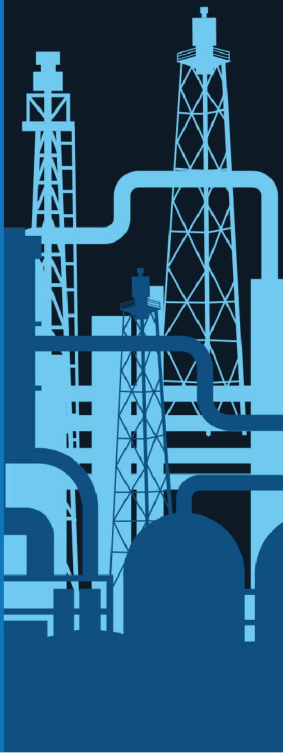
FACULTY OF ENGINEERING AND ARCHITECTURE

# Industrial Symbiosis Enabling Resource Circularity and Climate Neutrality in the Process Industry

**Francisco Mendez Alva**



Doctoral dissertation submitted to obtain the academic degree of
Doctor of Engineering

**Supervisors**
Prof. Greet Van Eetvelde, PhD - Prof. Lieven Vandevelde, PhD
Department of Electromechanical, Systems and Metal Engineering
Faculty of Engineering and Architecture, Ghent University

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*"The growth of knowledge depends entirely upon disagreement."— Karl Popper*

I am grateful to all people that made possible the present work and allowed my knowledge to grow.

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*Francisco*

*Ghent, 7 October, 2022*

**Erinnerung.**

Willst du immer weiter schweifen?
Sieh, das Gute liegt so nah.
Lerne nur das Glück ergreifen,
Denn das Glück ist immer da.

W.J. Goethe

**Remembrance.**

Do you always want to wander further?

See, the Good is so close.

Just learn to seize your fortune,

As happiness is always there.

W.J. Goethe

# SUMMARY (ENGLISH)

In the last decade, a number of reports and policy recommendations at global and European levels have paved the way to firm actions regarding greenhouse gas (GHG) emissions and resource depletion. The overall aim was and is to prevent major and irreversible consequences to the environment, ecosystems, and human society (Rockström et al., 2009; IPCC, 2018). A crucial initiative was the Paris Agreement at the Climate Change Conference in 2015, where 195 countries jointly committed to limit global temperature rise below 2°C, aiming for 1.5 °C (European Commission, 2016b; Guiot & Cramer, 2016). It triggered a series of policy and strategy actions taken by the European Commission (EC) to enhance the transition towards a more sustainable economy. The most recent strategy in this area is the EU Green Deal (European Commission, 2019c), resulting in the Climate Law (European Commission, 2020f), which enshrines 2050 climate neutrality. Concerning resource preservation, the most critical initiative is deploying the circular economy concept, growing its policy relevance in Europe (European Commission, 2020b) and involving industry, society and academia as a whole.

A key strategy to reach such regional goals is industrial symbiosis (IS). Multiple directives from the European Commission mention industrial symbiosis and its relation to resource efficiency, although few are specific regarding IS as focal area; instead, industrial symbiosis is included as support to the primary aims of some directives (CEN-CENELEC, 2018). One of the best examples is the 2018 Amendment to the Waste Framework Directive (2008/98/EC) passing into law calls for member states to promote sustainable use of resources and industrial symbiosis (European Commission, 2018).

Process industries (cement, chemicals, steel, etc.) are the foundation of the European economy, transforming raw materials into building blocks for strategic products and applications in today's society. Such transformation requires intensive energy and resource utilisation, implicating substantial amounts of waste and emissions. The current situation of these industries is not aligned with the region's circular economy (CE) and carbon neutrality goals. Therefore, the process industry requires transforming into a carbon and resource-neutral industry by grasping new business and technology solutions.

The concept of circularity provides economic opportunities that, together with the ambitious European policy goals, enable an unprecedented market space for collaboration across industries. Public institutions and sector associations already study such opportunities to draw concrete visions and roadmaps for 2050 through transition technologies and IS. The present work explores new interactions and exchanges of the process industry across sectors, including cities (urban-industrial symbiosis), at multiple scales. In the academic literature, methodologies and tools that are able to explore systematic combinations of sectors are still lacking. Furthermore, very few of the current industrial symbiosis tools are designed to integrate technical and non-technical factors.

Therefore, the main research questions of this thesis can be expressed as follow:

How to systematise the exploration of cross-sectoral collaborations (IS) in the process industries?

How to investigate challenges and opportunities beyond the technological aspects?

On a regional/cluster level, chapter 2 elaborates on the concept of hubs for circularity (H4C) and provides a methodology to apply clustering algorithms to geo-located industrial installations and emissions databases. DBSCAN clustering allowed to identify urban-industrial clusters with a cross-sectoral perspective and to determine indicators in terms of the distance between sites and the minimum number of sectors per cluster. Insights in specific regions are given, including industrial sector analysis. Further in the chapter, a framework for circular economy in the processes industry is developed enabling systematic analysis of options for industry to form effective clusters and more sustainable regional networks. The study has laid the foundation for developing a flexible tool that provides relevant data on industrial clustering and industrial symbiosis potential in Europe. When elaborated further, the tool could support and accelerate the implementation of hubs for circularity in Europe. Expanding the dataset with more industrial sectors and a wider variety of streams and exchanges can be considered a next step towards an enhanced map of potential hubs.

On a case-by-case analysis level of IS, chapter 3 focuses on reported synergies across process industries to build an IS case-base, a tool for bottom-up valorisation of by-products and waste from industries, including urban communities. Based on this case-base, IS profiles were conceptualised and developed for key industries (cement, chemicals and steel), enabling a top-down approach for the identification of synergies that provides insight into shareable resources, sustainability impact and technological possibilities. Furthermore, a matching method for sectors is proposed to explore further options enriching the IS case-base prospects. The research also pointed to the

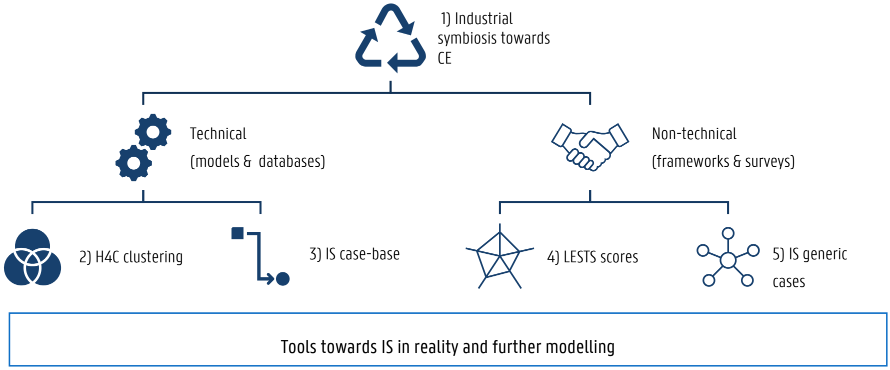
optimisation potential of the IS profiles and to the possibility of widening the involved sectors. Although cement, chemicals and steel have an intense energy demand and emissions footprint, the process industry is under-represented with only three sectors. Hence for instance paper, glass sectors and power plants were recommended for inclusion, along with other energy and carbon-intensive process industries.

From a non-technical perspective, the work is based on survey methods and results developed and obtained across the ECM research group (LESTS). In chapter 4, LESTS tools proved useful for barrier screening for IS initiatives and suitable to complete technical analysis of IS via process engineering. The tools also allowed the extension of initial screening into the evaluation of the different stages of an IS project. Overall, the work includes the design and application of scores to evaluate symbiosis in clusters considering legal, economic, spatial, technological and social aspects. Further research is suggested by linking LESTS analysis to specific modes of symbiosis organisations (exchange or mutualisation). Providing a non-technical factor profile for each type of symbiosis is perceived to facilitate the adoption of symbiosis projects by solving non-technical barriers.

In chapter 5, the concept of an IS generic case is developed to promote the replicability of collaborations in the process industry. Twenty-one generic IS cases are presented with a range of key topics for symbiosis, bringing insights into strategic collaborations for process industries. Furthermore, the generic cases are substantiated with a methodology to apply the game theory tool to IS cases. The game theory approach is introduced to improve collaboration among industries by analysing cooperation strategies, aiming to avoid prisoner dilemma situations. The research showed that applying game theory could be developed further by utilising such tools in existing industrial clusters. They could generate the data required for strategic evaluation of potential IS projects, thus advancing collaboration in clusters.

It can be concluded that technical and non-technical factors are essential in assessing industrial symbiosis. A technical base provides the starting point for contextual (clustering) and specific (cross-sectoral synergies) industrial symbiosis potential. However, the technical base alone has critical shortcomings due to the demanding collaborative nature of symbiosis projects. An industrial cluster or regional synergy with a high technical potential for collaboration may never result in more than an academic exercise if the organisation's capabilities for symbiosis are not triggered. The novel tools, methodologies and insights on industrial symbiosis as part of the principle of circularity open new lines of research and provide support to unleash the potential of process industries towards a circular and carbon neutral economy.

**Keywords:** clustering; circular economy; industrial ecology; industrial symbiosis; methodology; process industry



# SAMENVATTING (DUTCH SUMMARY)

In het afgelopen decennium hebben een aantal rapporten en beleidsaanbevelingen op mondiaal en Europees niveau de weg vrijgemaakt voor krachtige beleidsmaatregelen inzake de uitstoot van broeikasgassen (BKG) en de uitputting van grondstoffen. Het algemene doel was en is het voorkomen van grote en onomkeerbare gevolgen voor het milieu, de ecosystemen en de samenleving (Rockström et al., 2009; IPCC, 2018). Het Akkoord van Parijs op de Klimaatconferentie in 2015 was een cruciaal initiatief hiertoe. 195 landen hebben zich gezamenlijk verbonden om de wereldwijde temperatuurstijging tot 2°C te beperken, en zich zelfs te richten op 1,5°C (Europese Commissie, 2016; Guiot & Cramer, 2016). Dit leidde tot een reeks strategische beleidsacties van de Europese Commissie (EC) om de overgang naar een duurzame economie te versterken. De meest recente strategie op dit gebied is de EU Green Deal (Europese Commissie, 2019), die resulteerde in de EU Klimaatwet (Europese Commissie, 2020b), waarin klimaatneutraliteit in 2050 werd verankerd. In parallel werd een even cruciaal initiatief genomen inzake het behoud van grondstoffen, met name de introductie van het concept circulaire economie. Dit concept wint aan beleidsrelevantie in Europa (Europese Commissie, 2020a) en omvat zowel de industrie, de samenleving als de academische wereld.

Een belangrijk middel om circulaire doelen te bereiken is industriële symbiose (IS). Meerdere richtlijnen van de Europese Commissie vermelden symbiose en de relatie met grondstoffen efficiëntie, maar slechts weinig referenties gaan specifiek in op IS toepassingen. Industriële symbiose wordt vooral vermeld ter ondersteuning van de primaire EU-doelstellingen (CEN-CENELEC, 2018), met als een van de beste voorbeelden de wijziging van de Kaderrichtlijn Afvalstoffen (2008/98/EG). Deze richtlijn werd in 2018 in een wet omgezet, waarin de EU-lidstaten worden opgeroepen om duurzaam gebruik te maken van grondstoffen en om industriële symbiose te bevorderen (Europese Commissie, 2018).

De procesindustrie (cement, chemicaliën, staal, enz.) vormt de basis van de Europese economie; ze transformeert grondstoffen tot bouwstenen voor strategische producten met ruime toepassingen in de huidige samenleving. Dergelijke transformaties vereisen echter een intensief gebruik van energie- en hulpbronnen, wat gepaard gaat met aanzienlijke hoeveelheden afval en emissies. Het profiel van deze sectoren is vandaag niet in lijn met de Europese lange-termijn doelstellingen inzake circulaire economie (CE) en koolstofneutraliteit. Daarom moet de procesindustrie worden getransformeerd naar een koolstof- en grondstof-neutrale industrie door nieuwe commerciële en technologische oplossingen toe te passen.

Het concept circulariteit biedt economische kansen die, samen met de ambitieuze Europese beleidsdoelen, een ongekende marktruimte voor samenwerking tussen industriële sectoren mogelijk maken. Overheidsinstellingen en sectorverenigingen zoeken opportuniteiten om via transitietechnologieën en IS concrete visies en roadmaps voor 2050 uit te tekenen. Het voorliggend werk speelt hierop in door nieuwe interacties en uitwisselingen in de procesindustrie te onderzoeken, binnen en tussen sectoren, in synergie met woongebieden (stedelijk-industriële symbiose), en zelfs op verschillende niveaus. In de wetenschappelijke literatuur ontbreken momenteel immers methodieken en tools die in staat zijn om systematisch interacties binnen en tussen sectoren te verkennen. Bovendien zijn zeer weinig bestaande IS-tools ontworpen om zowel technische als niet-technische factoren te integreren.

Daarom gelden als belangrijkste onderzoeksvragen van dit proefschrift:

- Hoe sectoroverschrijdende samenwerkingen (IS) in de procesindustrie systematisch verkennen?
- Hoe uitdagingen en kansen ruimer onderzoeken dan enkel op technologisch vlak?

Op regionaal clusterniveau gaat hoofdstuk 2 dieper in op het concept van hubs voor circulariteit (H4C). Het werk biedt een methodologie om clusteralgoritmen toe te passen op industriële installaties, meer bepaald op grond van locatiegegevens en emissiedata. Via DBSCAN-clustering was het mogelijk om stedelijk-industriële clusters te identificeren met een sectoroverschrijdend perspectief en om indicatoren te bepalen op grond van de afstand tussen industrielocaties en het minimumaantal sectoren per cluster. Er worden inzichten gegeven voor bepaalde EU-regio's, inclusief een volledige industriële sectoranalyse. Dieper in het hoofdstuk wordt een raamwerk voor de circulaire economie ontwikkeld, toegepast op de procesindustrie. Dit maakt een systematische analyse van opties per sector mogelijk om effectieve clusters en duurzamere regionale netwerken te vormen. De studie legde de basis voor de ontwikkeling van een flexibele tool die relevante data genereert inzake industriële clustering en het potentieel voor industriële symbiose in Europa. Na verdere uitwerking zou deze tool de implementatie van hubs voor circulariteit kunnen ondersteunen en zelfs versnellen. Als eerste stap hiertoe kan de uitbreiding van de dataset met meer industriële sectoren en een ruimer aanbod van stromen en uitwisselingen overwogen worden, zodat een verbeterd overzicht van potentiële hubs wordt verkregen.

Via een case-by-case analyse richt hoofdstuk 3 zich op gerapporteerde synergiën tussen procesindustrieën. Hieruit wordt een zogenaamde IS case-base samengesteld, een tool voor bottom-up valorisatie van industriële bijproducten en afval, inclusief stedelijke gemeenschappen. Op basis van deze case-base worden IS-profielen uitgewerkt voor primaire sectoren zoals cement, chemicaliën en staal. Hierdoor kan een top-downbenadering gevolgd worden voor de identificatie van synergiën inzake deelbare hulpbronnen, met vermelding van impact op duurzaamheid en technologische alternatieven. Tot slot wordt een matchingmethode voor sectoren voorgesteld om verdere opties te verkennen die de IS case-base kunnen verrijken. Het onderzoek wijst ook op het optimalisatie-potentieel van de IS profielen en op de mogelijkheid om meer sectoren in de methode op te nemen. Hoewel de cement-, chemie- en staalsector een intense energievraag en emissie-afdruk hebben, is de procesindustrie ondervertegenwoordigd met slechts drie sectoren in de studie. Daarom wordt aanbevolen om bij voorbeeld papier, glas en energiecentrales toe te voegen in de studie, samen met andere energie- en koolstof-intensieve industrieën.

Vanuit een niet-technologisch perspectief is het werk gebaseerd op onderzoeksmethoden en resultaten die zijn ontwikkeld binnen de ECM-onderzoeksgroep (LESTS). In hoofdstuk 4 wordt het nut van LESTS-tools bewezen, niet enkel voor het screenen van barrières die symbiose-initiatieven kenmerken, doch ook als aanvulling op de technische IS-analyse via proces engineering. LESTS maakt het ook mogelijk om een initiële screening uit te breiden naar een evaluatie van de verschillende stadia van een IS-project. Het hoofdstuk gaat dieper in op het definiëren en toepassen van scores om symbiose in clusters te evalueren door juridische, economische, ruimtelijke, technologische en sociale aspecten te analyseren. Als verder onderzoek wordt voorgesteld om een LESTS-analyse te koppelen aan specifieke vormen van symbiose-organisaties (uitwisseling of mutualisatie). De uitbreiding naar niet-technische factorprofielen per type symbiose wordt geacht de adoptie van symbioseprojecten te verbeteren, precies door niet-technische barrières op te lossen.

In hoofdstuk 5 wordt het concept van een generieke IS-case ontwikkeld om de reproduceerbaarheid van samenwerkingen in de procesindustrie te bevorderen. Eenentwintig generieke IS-cases worden gepresenteerd rond een aantal typische symbiosethema's; ze geven dieper inzicht in het strategisch samenwerkingspotentieel voor de procesindustrie. De generieke IS-cases worden onderbouwd door de methodiek van de speltheorie toe te passen. Deze benadering wordt geïntroduceerd om de wisselwerking tussen industrieën voor te stellen; door de samenwerkingsstrategieën te analyseren wordt beoogd om 'prisoner dilemmas' te vermijden. Het onderzoek toont aan dat het toepassen van de speltheorie verder uitgebreid kan worden door deze in te zetten in bestaande industriële clusters. Hierdoor kunnen gegevens gegenereerd worden die nodig zijn voor de strategische evaluatie van potentiële IS-projecten, om zo de samenwerking in clusters bevorderen.

Er kan worden geconcludeerd dat zowel technische als niet-technische factoren essentieel zijn bij de beoordeling van industriële symbiose. Een technische basis vormt het startpunt voor de bepaling van het potentieel inzake contextuele IS (clusteren) en specifieke IS (sectoroverschrijdende synergieën). De technische basis alleen schiet echter tekort gezien het veeleisende collaboratieve karakter van symbioseprojecten. Een industriële cluster of regionale synergie met een hoog technisch potentieel voor samenwerking zal nooit meer dan een academische oefening zijn als de partners niet worden gestimuleerd om hun IS capaciteit om te zetten in effectieve projecten. De innovatieve tools, methodologieën en inzichten inzake industriële symbiose die hier worden aangereikt als onderdeel van het circulariteitsprincipe openen nieuwe onderzoekslijnen en geven een aanzet om het transitiepotentieel van de procesindustrie naar een circulaire en koolstof-neutrale economie effectief te ontketenen.

**Sleutelwoorden:** clusteren; circulaire economie; industriële ecologie; industriële symbiose; methodologie; procesindustrie

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## ABBREVIATIONS

| | |
|---|---|
| CE | Circular Economy |
| AISBL | Association internationale sans but lucratif (International Non-Profit Organisation) |
| CSR | Corporate Social Responsibility |
| CEAP | Circular Economy Action Plan |
| CEFIC | European Chemical Industry Council (in French Conseil Européen des Fédérations de l'Industrie Chimique) |
| DBSCAN | Density-based spatial clustering of applications with noise |
| EC | European Commission |
| EIIs | Energy Intensive Industries |
| EMF | Ellen MacArthur Foundation |
| EPOS | Enhanced energy and resource Efficiency and Performance in process industry Operations via onsite and cross-sectorial Symbiosis |
| ETS | European Trading System |
| EU | European Union |
| HAC | Hierarchical Agglomerative Clustering |
| H2020 | Horizon 2020 |
| H4C | Hubs for Circularity |
| H2020 | Horizon 2020 |
| IE | Industrial Ecology |
| IS | Industrial Symbiosis |
| LESTS | Legal Economic Spatial Technical Social |
| NACE | Nomenclature statistique des activités économiques dans la Communauté européenne |
| NE | Nash Equilibrium |
| n.e.c. | Not Elsewhere Classified |
| P4Planet | Processes4Planet partnership |
| PD | Prisoner's Dilemma |
| PPP | People Planet Profit |
| PV | Photo Voltaic |
| RTO | Research and Technology Organisation |
| SPIRE | Public-Private Partnership in the European process industries sectors of ceramics, cement, non-ferrous metals, chemicals, minerals, refining, steel, water and engineering |
| U-IS | urban-industrial symbiosis |
| VPP | Virtual Power Plant |
| WACC | Weighted Average Cost of Capital |

# CHAPTER 1 INTRODUCTION TO INDUSTRIAL SYMBIOSIS, CIRCULAR ECONOMY AND THE PROCESS INDUSTRY

This chapter provides insight into the relevance of the research scope and motivation. Firstly, it introduces the importance of the circular economy (CE) and industrial symbiosis (IS) according to the latest European policy landscape. It presents a review of industrial symbiosis concepts and challenges, followed by highlighting the significance in the process industry in terms of energy and resource consumption and emission reduction potential. Finally, the scope and motivations of the research are presented.

## *1.1 INDUSTRIAL SYMBIOSIS AND THE CIRCULAR ECONOMY IN A EUROPEAN CONTEXT*

In the last decade, a number of reports and policy recommendations at global and European levels have paved the way to take firm actions regarding greenhouse gas (GHG) emissions and resource depletion to prevent major and irreversible consequences to the environment, to ecosystems, and to human society (Rockström et al., 2009; IPCC, 2018). A crucial initiative was the Paris Agreement at the Climate Change Conference in 2015, where 195 countries jointly committed to limit global temperature rise below 1.5°C (European Commission, 2016b). It triggered a series of policy and strategy actions taken by the European Commission (EC) to enhance the transition towards a more sustainable economy. The most recent strategy in this area is the EU Green Deal (European Commission, 2019c), resulting in the Climate Law (European Commission, 2020f), which enshrines 2050 climate-neutrality into law. Concerning resource preservation, the most important initiative is the deployment of the circular economy concept, growing its policy relevance in Europe (European Commission, 2020b) and involving industry, society and academia as a whole.

A key strategy to reach such regional goals is industrial symbiosis. Multiple directives from the European Commission mention industrial symbiosis and its relationship to resource efficiency, although few are specific to industrial symbiosis as a focus; rather, industrial symbiosis is included as support to the primary aims of the directives (CEN-CENELEC, 2018). One of the best examples is the 2018 Amendment to the Waste Framework Directive (2008/98/EC) passed into law calls for member states to promote sustainable use of resources and industrial symbiosis (European Commission, 2018).

The CWA 17354 IS workshop agreement listed some of the most relevant documents:

- In 2012 the EC commissioned practical guidelines in the framework of the Smart Specialisation Platform set up by the European authorities. It included concrete recommendations and examples of good practice, showing potential ways to facilitate discussion between public authorities and stakeholders, including industrial symbiosis (European Commission, 2012).
- In 2014 the EC published the Green Action Plan for SMEs to turn environmental challenges into business opportunities. In the document, a key concept is the 'synergy economy', promoting the valorisation of waste and by-products (European Commission, 2014a).
- In 2016, the European Environmental Agency published a knowledge base for the circular economy, including symbiosis as a business model. The report touches on four dimensions of a circular economy (VITO, 2016):
  1. concept and benefits.
  2. main enabling factors and transition challenges.
  3. metrics for measuring progress.
  4. contextual issues that would require attention from research or policy.

  The report on circularity also clarifies the overlapping and complementary relationship with the green economy and common topics on waste management, waste prevention and resource efficiency (Figure 1.1).

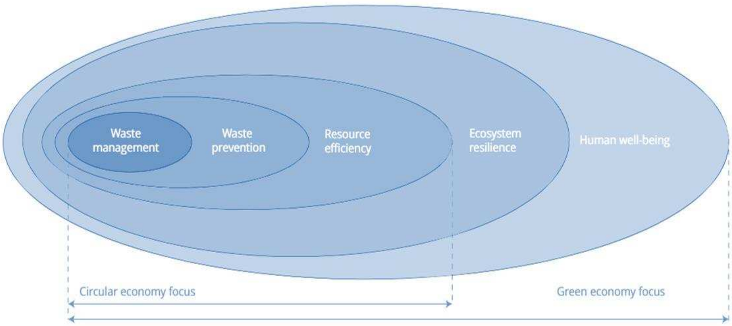



Figure 1.1 Circular and green economy: overlaps and complementarity (adapted from VITO, 2016).

- In 2018, the EC published a study that mapped the different aspects of IS to foster cooperation towards a more sustainable and integrated industrial system. The study recommended the establishment of an EU-level ‘platform of platforms’, a trading platform for cross-boundary synergies, and a centre for excellence to develop additional IS capabilities (Domenech et al., 2018).
- A recent policy initiative is the EU taxonomy, aiming to develop a funding scheme for the transition towards the circular economy considering climate ambitions (European Commission, 2020e). The proposal consists of a thematic classification that directly and indirectly may trigger industrial symbiosis across industries.

Sector associations and companies require cross-sector collaboration towards the ambitions of regional challenges. In order to facilitate such collaborations, the SPIRE initiative has been the contractual Public-Private Partnership (cPPP) active between 2014 and 2020 and dedicated to innovation in resource and energy efficiency in process industries. SPIRE has transitioned to the Processes for Planet (P4Planet) initiative (2021-2027), a new co-programming partnership under Horizon Europe. In its strategic agenda, industrial symbiosis is defined as ‘long-term commitments across the boundaries of individual organisations when dealing with waste and by-products, embedded in the concept of Hubs for Circularity (H4C)’ (A.SPIRE aisbl, 2022). H4C involves multiple stakeholders building an ecosystem to develop the circular economy (A.SPIRE aisbl, 2022).

The circular economy is conceptualised in Europe as a regenerative economic system that keeps the use of resources within the planetary boundaries while reducing the footprint of consumption (European Commission, 2020b). The CE framework aims to decouple economic growth from natural resource depletion and environmental degradation (Masi et al., 2017). Implementing such a framework creates profitable opportunities where value creation integrates environmental performance, joining improved energy and material productivity with the access and creation of green market places (L. M. Fonseca et al., 2018).

The Ellen Macarthur Foundation (EMF, 2013), one of the foremost promoters of the concept, established three actionable principles related to the circular economy concept: (1) the preservation of natural capital, referring to the control of non-renewable resource stokes and the balance of resource flows; (2) the optimisation of resource yields, referring to the (re-)circulation of products, components, and material in use at the highest utility; and (3) the fostering of system effectiveness, referring to the assessment and management of externalities. Also, the sustainable product policy framework (European Commission, 2020b) addresses circularity in three aspects: designing sustainable products, empowering consumers, and interrelating production processes.

The CE model has gained attention and attraction in the last 15 years (Ranjbari et al., 2021). It aims at replacing the linear economy that follows the 'take, make and dispose off' principle by 'closing the loop'. The linear economic model exposes the finite supply of raw materials such as resource scarcity and price volatility (EMF, 2015; Masi et al., 2017). Limited supplies also increase material dependency, especially in the European Union where resource consumption is high e.g., energy per square km$^2$ or per capita. According to the CE action plan (CEAP) on critical raw materials (European Commission, 2016a), the European industry is dominated by the manufacturing and the process industry compared to the extractive industry. The need for access to primary sources, including ores, concentrates and processed or refined materials, is vast and crucial for European industries' wealth – even its survival – and the associated jobs and economic benefits. However, most primary raw materials are produced and supplied from non-European countries, indicating a supply risk (European Commission, 2016a). Such risk has supported the idea to start valorising waste and grow a more circular model.

The circular economy also plays a critical role in helping to reduce climate change (Material Economics, 2019; Sarja et al., 2021), enabling goods and services with lower emissions. Based on the ladder of Lansink (Lansink, 2017), the CE policy in Europe integrates the principle of preserving the value of materials with a cascade approach, leaving energy recovery as the last option (omitting disposal) thus avoiding unnecessary emissions (Lansink, 2017). The merging of economic and environmental goals has led the CE concept to become one of the most prominent sustainable development models in academic and policy domains (Kusch, 2015; Lansink, 2017).

To implement the CE concept, action from diverse stakeholders is critical. Critical actors are industries (physic-chemical transformation processes in the economy) and cities establishing symbiotic relations toward higher levels of circularity (Feiferytė-Skirienė & Stasiškienė, 2021; Sun et al., 2020). The relevance of cities in creating industrial hubs for circularity is high. Although cities occupy only around 3% of the planet's surface, the concentration of the population in urban areas is over 50% and is still expected to rise to almost 70% by 2050 (United Nations Environment Programme, 2018). Such concentration of people leads to intensification of resource demands and waste production. Hence, the collaboration between cities and industries is vital for the European climate and circularity agenda to reach common goals.

## *1.2 CIRCULAR ECONOMY IN AN URBAN-INDUSTRIAL CONTEXT*

Industrial sectors and urban centres can collaborate towards a circular economy (A. SPIRE, 2019). Synergies among industries, including urban districts, are an organic way forward (Figure 1.2). Urban districts refer to "the close spatial proximity of areas with a high population density" (Joint Research Centre (European Commission), 2019). The EU had a high urbanisation rate of 72% in 2015 and a population density of 3 000 residents per km$^2$ (Joint Research Centre (European Commission), 2019). Moreover, high-density urbanised areas have implications for industries in terms of product/service demands and the availability of qualified professionals. Also, European cities enable a concentrated demand for industrial products and recirculate resources back to the industry at scale. In terms of energy use, at a global level, cities are attributed about 70% GHG emissions (including mobility) while being especially vulnerable to the impacts of climate change (Joint Research Centre (European Commission), 2019). Hence, the collaboration between cities and industries towards common goals is a key component towards a circular economy.

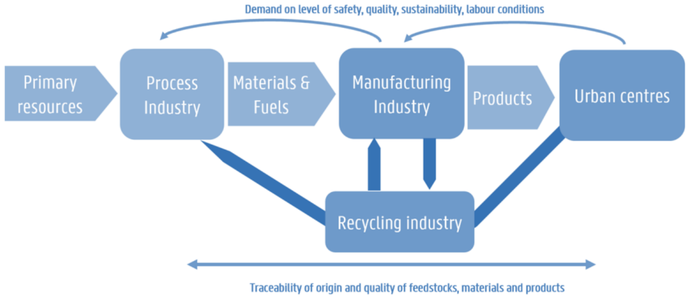



Figure 1.2 Hubs for circularity focus on the relation of different units for circularity with an industrial focus (A. SPIRE, 2019).

On the industry side, energy-intensive industries (such as steel, cement, chemicals and refining.) provide the material and energetic building blocks to virtually any sector (A. SPIRE, 2019; HLGEEIs, 2019). Therefore, they concentrate massive amounts of energy, resources, waste and emissions in industrial sites and clusters. Such a profile makes the process industry significant in environmental impact and economic development. One of the key features enabling the sector's transition to a net-zero economy is its clustering capacity (especially chemicals and refining). It not only enhances competitiveness (Elser and Ulbrich, 2017; Ketels, 2007) but also answers socio-environmental questions by making effective synergies between different processes and sectors or communities in a specific region (Cervo, 2020; Lowe & Evans, 1995).

### 1.2.1 CONCEPT OF INDUSTRIAL SYMBIOSIS

Industrial symbiosis is, in principle, a metaphor coming from biological symbiosis (Van Eetvelde, 2018). The first academic mention of symbiosis is attributed to Albert Frank, a German scientist, who proposed symbiosis to refer to the mutualistic relationship observed in lichens (Cohn, 1877). Two years later, Anton de Bary, a German mycologist, defined symbiosis as 'the living together of unlike organisms' (Bary, 1879). The conceptualisation of symbiosis was based on the observation of the behaviour of organisms that establish a relation in close proximity and with a qualitative distinction between them.

In biology, symbiosis is not always about mutual benefits. The outcome of interaction can be of three types: beneficial, neutral or harmful, leading to six possible types of relations between organisms (Figure 1.3). Relationships range from neutralism to mutualism. In neutralism, organisms live together without apparent benefits or harms (0/0). In agonism, one organism thrives at the cost of the other (+1/-1). In a commensalism relation, one organism benefits from the other without providing any benefit. Finally, both organisms benefit from the relation in mutualism (Martin & Schwab, 2012). Weng et al. (2018) distinguished two types of mutualisms: symmetric and asymmetric, referring to the distribution of the benefits and arguing that symmetric mutualism tends to be the most sustainable mode of symbiosis, as both species share benefits in similar proportion (Weng et al., 2016).

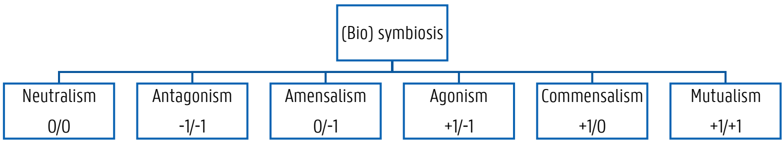



Figure 1.3 Diagram of the six possible types of symbiotic relationship, from mutual benefit (+1,+1) to mutual harm (adapted from (Martin & Schwab, 2012).

Symbiosis is not an exotic exception but the basis of all living systems (Vester, 2019). Etymologically, the word comes from the Greek translated as 'living together' (Van Eetvelde, 2018), suggesting the essential simplicity of the concept common to living communities at multiple scales. A basic example at the human scale are the respiratory particles inside our cells, the so-called mitochondria, relics of primitive bacteria that provided energy balance in exchanging nutrients networks (Vester, 2019).

Industrial symbiosis brings a cultural/human dimension to the type of relation in symbiosis: the possibility to choose/aim for the most sustainable type of symbiosis for industrial development. The concept of industrial symbiosis in the academic literature is traced back to the seminal article by Frosch and Gallopoulos in Scientific American (Erkman, 1997; Frosch & Gallopoulos, 1989), where the authors envisioned “industrial ecosystems” in which “the consumption of energy and materials is optimised, and the effluents of one process serve as the raw material for another process”. Various manufacturing sectors have incorporated these principles into standard operating procedures for far longer, as in the case of chemical industrial complexes (Van Eetvelde, 2018). Recently, industrial symbiosis has gained increasing attention in production economics with reducing waste, emissions and primary resources consumption as the first areas of interest, becoming a mainstream approach for delivering the circular economy (Ranjbari et al., 2021).

Baldassarre et al. (2019) proposed the synthetic conceptualisation of IS from a circular economy and industrial ecology perspective. On the one hand, IS focuses on business viability and operations (circular economy). On the other hand, it focuses on understanding energy and material flows with their associated environmental impacts (industrial ecology). However, reaching a common understanding of IS presents different challenges due to diverse actors and situational factors involved (Boons et al., 2017). The concept builds from the mutual interaction of various entities initiated by a variety of drivers (Van Eetvelde, 2018; Abreu and Ceglia, 2018). Boons et al. (2017) proposed terminology for IS as a process of connecting flows among industrial actors, trying to address the complexity of the concept by defining different dynamic models. A further attempt to establish standard IS principles was made in a documented CEN-CENELEC workshop with academic and non-academic participants (CEN-CENELEC, 2018). A recent bibliographical study with a selection of more than 600 articles over a period of 30 years (Mallawaarachchi et al., 2020) proves that the sustainability of material and energy interactions has been central to the concept. IS has been expanded extensively in the last five years to include non-material resources, contextual factors (cultural, political, spatial, etc.), and the impact of externalities.

A general conceptualisation of industrial symbiosis is as a specific relationship formed between two or more different units (industries, sites, cities) according to a specific cooperation mode under a particular pressure context (economic, legal), to improve the capacity to survive of the involved units (CEN-CENELEC, 2018; Wang et al., 2021). Typically industrial symbiosis includes resource valorisation and re-valorisation of waste, but the approach can be extended to services such as shared logistics and infrastructure (Lombardi & Laybourn, 2012; Van Eetvelde, 2018) in most cases, with technology-centred business cases. Figure 1.4 shows a summary of the main aspects of IS.

| **Industrial symbiosis** | ***Highlight*** | ***References*** |
|---|---|---|
| Relational goal | *business (need) / policy (duty)* | (Chertow, 2007; Van Eetvelde, 2018) |
| Competitive advantage | *response to pressure (people, planet, profit)* | (Domenech et al., 2019;<br>EPOS project, 2019; SCALER project, 2019) |
| Non-traditionally related industries | *units (regions, sector, sites)* | (Massard, 2011; Kerdlap et al., 2020;<br>Azevedo et al., 2021) |
| Collective approach | *cooperation mode<br>(top-down, bottom-up)* | (CEN-CENELEC, 2018; Cervo, 2020) |
| Resource (re-)valorisation | *tech centred business model<br>(mass/energy/info-> exchange/pool)* | (Lombardi and Laybourn, 2012;<br>Albino and Fraccascia, 2015;<br>Ogé et al., 2019) |

Figure 1.4 Summary of the key aspects of industrial symbiosis in the academic literature (adapted from CEN-CENELEC, 2018).

The establishment of industrial symbiosis requires a relational goal. At the level of individual companies, this goal can be driven mainly by a wish, a need or a duty (Van Eetvelde, 2018). A genuine wish to collaborate is the most straightforward and often most fruitful synergy between business partners. A need to collaborate relates to the economic pressure faced by a company in a cluster or region embedded in competitive markets. Such pressure can be a pull (reaching an opportunity) or a push (overcoming a threat). At the same time, a duty to collaborate is related to a legal or compliance requirement for operating more efficiently resulting from stricter legislation. Companies nearby can articulate relational goals to satisfy such needs and duties. Empirical findings suggest that the initial period of self-organised IS is based on economic efficiency and/or meeting regulatory conditions (Chertow, 2007).

IS provides a competitive advantage in the network's economic, social and environmental outcomes (Domenech et al., 2019). Such outcomes, integrated as business cases, have been a consistent aim of several European projects. As key example, the EPOS project emphasised the need for specific (Cervo et al., 2019) and generic IS cases (EPOS project, 2019). The SCALER project proposed 100 proto-business cases for the process industry considering economic, social and environmental aspects (SCALER project, 2020c).

In terms of the IS scales, Massard (2011) proposed a nested model. The model distinguishes regional resource synergies from eco-industrial parks. The regional scale describes the relations among eco-industrial parks involving shared services and by-product exchanges in a region. The park scale includes the shared infrastructure, services and by-products exchange within a single industrial park (Massard, 2011). Kerdlap et al. argue that different perspectives and scales are essential in industrial symbiosis, proposing three levels: network level (related to park management, policy, and urban planning), entity level (companies) and resource flow level (specific resource) (Kerdlap et al., 2020), giving a higher definition to the industrial park level of Massard. Azevedo et al. expanded the scale across regions on a common ground of legislation, standardisation, incentives, metrics and targets (Azevedo, Henriques, et al., 2021).

According to the CWA 17354 IS workshop agreement, there are four main non-mutually exclusive approaches or cooperation modes to industrial symbiosis depending on contextual factors (CEN-CENELEC, 2018):

1. Self-organisation: a bottom-up approach resulting from direct interaction among industrial actors, without any external coordination, generally motivated by business concerns arising from context, including resource risk, pending legislation, and economic gains.
2. Strategic planning: a top-down approach where networks are formed following a central plan or strategic vision. The approach has been applied to existing industrial parks and industrial areas of a city. It includes attracting new businesses to regeneration sites or purpose-built developments.
3. Facilitated: an approach where a third-party intermediary coordinates the activity, working with organisations to identify opportunities and bring them to fruition. By engaging with organisations from all sectors, the practitioner enables the flow of information across sectoral boundaries; practitioners often provide technical support to overcome technical or regulatory barriers associated with synergies.

4. ICT-supported: an approach that makes use of information and communication technologies to compensate the market failure of information in relation to resource efficiency, improving information flow between actors. Recently web-based waste exchanges have proliferated as the technology has developed.

The initial cooperation mode in IS depends on the cluster context. A two-axis quadrant provides orientation: on the vertical axis, the level of external pressure in the region (resource risk, pending legislation, economic gain/loss) is represented. The horizontal axis represents the level of communication among industries in the cluster or region (Figure 1.5). If the pressure is high and there is a good level of communication, the companies will tend to self-organisation. The Kalundborg industrial park case is a benchmark example of such an approach, enabling symbiosis in a relatively small and well intercommunicated Danish park upon a substantial resource supply risk of water (Jacobsen, 2006). A high external pressure situation with a low level of communication tends towards a strategic planning intervention. Chinese industrial parks with an energy-intensive industry tend towards strategic planning to approach IS (Yu et al., 2015; Zhu et al., 2007). If the pressure is insufficient to trigger strategic planning or self-organisation, clusters tend to approach symbiosis through facilitated workshops to explore potential synergies and foster business relations. If the level of communication is already high, ICT tools tend to be encouraged to approach IS or build at least some initial capacity for industrial collaboration. However, passive online waste exchanges have had minimal uptake in Europe and around the world, which is attributed to their inability to meet the specific information needs of industrial users (including classification, distribution and timing issues) (Maqbool, Alva, et al., 2019)

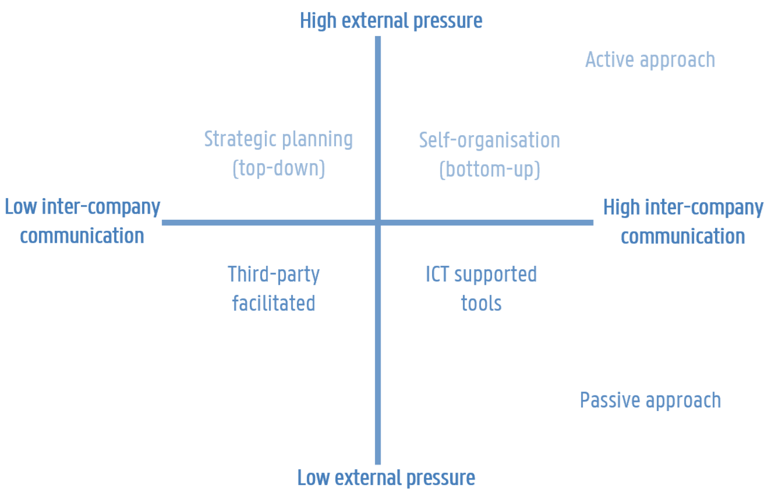



Figure 1.5 Industrial symbiosis coordination can take different approaches depending on cluster context (adapted from CEN-CENELEC, 2018).

In IS networks, resource (re-)valorisation builds on a technology-based business model. Innovative products, alternative materials, or services can be developed (Lombardi & Laybourn, 2012; Ogé et al., 2019). Albino and Fraccascia, 2015 proposed six different business models oriented to industrial symbiosis considering cost savings in operations and possibly generating additional revenue streams. The involved technologies are related to the type of stream to be valorised and the valorisation pathway (Dias et al., 2020; Mendez-Alva, Cervo, et al., 2021). The valorisation of resources occurs by direct exchange of resources between different companies or by organising a pool of resources. The former is the typical case of IS (steel slag from the cement industry). The latter is related to organised waste management to concentrate a quantity and diversity of resources until reaching a profitable level.

### 1.2.2 INDUSTRIAL CLUSTER MODEL

The circular economy can be approached at multiple levels in an industrial context. It can address opportunities at single process, sites, industries, clusters, regions and nations. Due to the cross-sectorial potential, industrial clusters, have a major relevance. Implementing the circular economy requires industrial symbiosis as a central strategy, where industrial clusters organisation and management are key (A. SPIRE, 2019; Accenture, 2021).

A hub or cluster refers to a geographical area with high industrial density, defined by the spatial proximity of industrial sites and the number of sites (further discussed in chapter 2). The principle objective is to join forces to create mutual wins. Such symbiosis can be organised on countless topics and growingly covers all three pillars of sustainability, starting from business profit in economies of scale and scope, expanding to environmental wins such as exchanges of streams and likewise generating social gains such as local employment or community integration (Chertow, 2007; Chertow et al., 2008; Van Eetvelde, 2018). Figure 1.6 illustrates the concept of a cluster, its connections and potential to create synergies. Synergies are value propositions across multiple entities that take advantage of their complementarity, leading to benefits that could not be reached by the actors individually. In clusters, such value propositions emerge from the spatial proximity, size and (process) diversity of the local industries. The valorisation of by-products or waste streams is a typical objective of a hub or cluster. Recirculation of under-used resources is fundamental to the circular economy (Baldassarre et al., 2019; Domenech et al., 2019; Mendez-Alva, De Boever, et al., 2021), closing resource loops within and across value chains (cross-sectoral synergies). Section 2.4.3 illustrates the concept of circularity in the process industry.

The effect of the contextual factors in the development of industrial clusters is critical for symbiosis (Weng et al., 2016). They provide the drivers for collaboration to companies and clusters. However, changes in the context can also diminish collaboration potential (Weng et al., 2016). In a positive context for collaboration, symbiosis may be an effective strategy to grasp the opportunity or reduce the change risk. Boons et al. suggested four underlying conditions shaping the development of IS: technical, economical, geo-spatial and institutional (Boons et al., 2017). Technical conditions refer to the physical resources and processes available in the region. They are the base of the economic conditions related to the sensibility of industrial actors to net benefits. Geo-spatial conditions refer to the location of clusters and actors (spatial proximity is a typical example); such spatial conditions are inseparable from social/institutional ones enabling policy interventions and collaboration capabilities (Boons et al., 2017). With a focus on industrial cluster assessment, Van Eetvelde proposed five angles (LESTS) for cluster assessment (Van Eetvelde, Delange, et al., 2005; Van Eetvelde, 2018), adapted as follows for the purpose of this thesis:

1. **L**egal: institutional capabilities for establishing contracts.
2. **E**conomical: maximising benefits in a partnership (economies of scale and scope).
3. **S**patial: regional planning related to the cluster's location.
4. **T**echnical: physical resources and processes available in the cluster.
5. **S**ocial: Responsible impact on surrounding communities.

The outcome of such holistic assessment leads to LESTS factors as enablers and barriers for collaboration in clusters.

From an industrial actor perspective, the contextual pressure for symbiosis can be overall economic or legal. Economic pressure refers i.a. to the availability of the supply of resources required to operate (related to technical and spatial conditions) and the demand of the production in the market. Legal pressure refers i.a. to articulating social or ecological concerns into policies (related to spatial and social conditions) that directly affect industries and clusters (permits, norms, audits, taxes, etc.).

Economic and legal pressures are related to the ecosphere through the technosphere. The ecosphere refers to biologically available resources (including inorganic geo-cycle and local ecosystems). As a subsystem, the technosphere contains the stocks and flows of resources mainly controlled or caused by humans (Ayres & Ayres, 2002). Changes in the ecosphere, overlapping with the technosphere, generate legal and economic pressure in industries. For example, the environmental degradation of rivers due to industrial pollution may lead to unprecedented legal permits requirements. On the other hand, the scarcity of critical raw materials may disrupt industries, making prices unaffordable for some industries. Thus, ecosphere impacts visible in the technosphere affect industrial symbiosis development.

Under pressure, units of a cluster can respond in two ways: internally or externally (Figure 1.6). An internal response makes relevant the capacity of the unit to optimise their core business under changing circumstances. It tends towards gradual change due to urgent matters that affect the business in the short term. An external reaction makes relevant the potential to develop joint efforts with other units to spread the risks associated with strategic positioning. This tends towards niche innovation related to long-term transition goals of the industry. Both internal and external responses can be leveraged through industrial symbiosis.

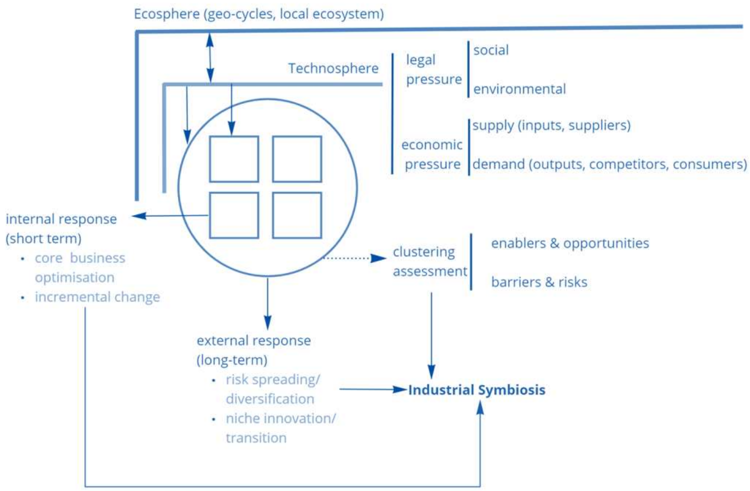



Figure 1.6 Nested model of clustering relates IS with key pressures and strategic responses (adapted from Van Eetvelde, 2018 and Ayres and Ayres, 2002).

IS supports optimisation and transition of business models. Schaltegger et al. studied business model transition towards sustainability, proposing two fundamental directions (Schaltegger et al., 2016):

- Optimisation: incremental changes adapting to the customers' demands, competition or changes in the legislation (e.g., district and industrial heating networks).
- Transition: strategic approach aiming for radical innovation in niche markets (e.g., pilot projects through public-private partnerships).

Optimisation is closer to mass-market transformation reaching widespread markets, this tends towards technological upgrades. Transition is about the gradual upscaling from a niche to a mass-market business model (Schaltegger et al., 2016). This results in two types of symbiosis: optimisation (type 1) and transition (type 2) symbiosis (

Figure 1.7).

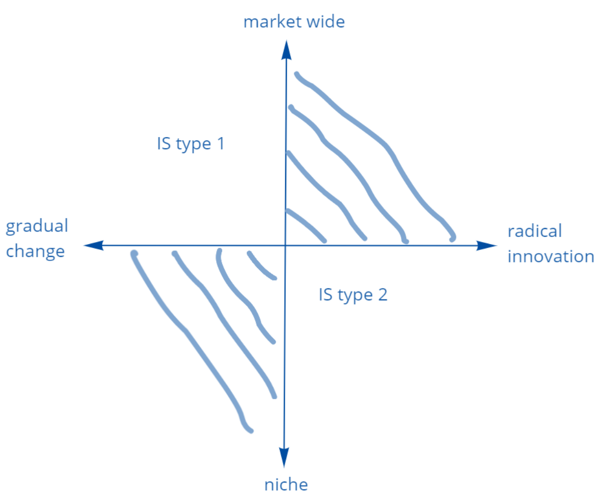



Figure 1.7 Types of symbiosis from a business model perspective (adapted to IS from Schaltegger et al., 2016).

A final aspect of IS in a cluster is its development cycle. Maqbool et al. proposed a model for the life cycle of an IS project distinguishing stages in industrial symbiosis to organise its life cycle (Maqbool, Alva, et al., 2019). The IS cycle has five stages (Figure 1.8).

Firstly, an identification stage takes place in three ways:

1. The development of process innovation (e.g., transform waste or by-products).
2. The matchmaking of output resources as input for others not previously established (a new type of steel slag to produce new cement products).
3. The replication of the reported synergies (e.g., mimicking of established synergies).

Once an IS opportunity is identified, a cluster-based assessment involves legal, economic, spatial, technological and social aspects (LESTS). The third stage is finding a solution for the multiple barriers by identifying opportunities in the various LESTS dimensions. When the main barriers have been addressed, the implementation stage follows with a specific management scheme (self-organised, third-party support or top-down) and the implications for the manufacturing systems regarding safety, quality, production, and others. As soon as the project is ongoing, it is essential to document the process and start a continuous improvement cycle to deal with barriers after implementation and to identify new synergies (Maqbool, Alva, et al., 2019).

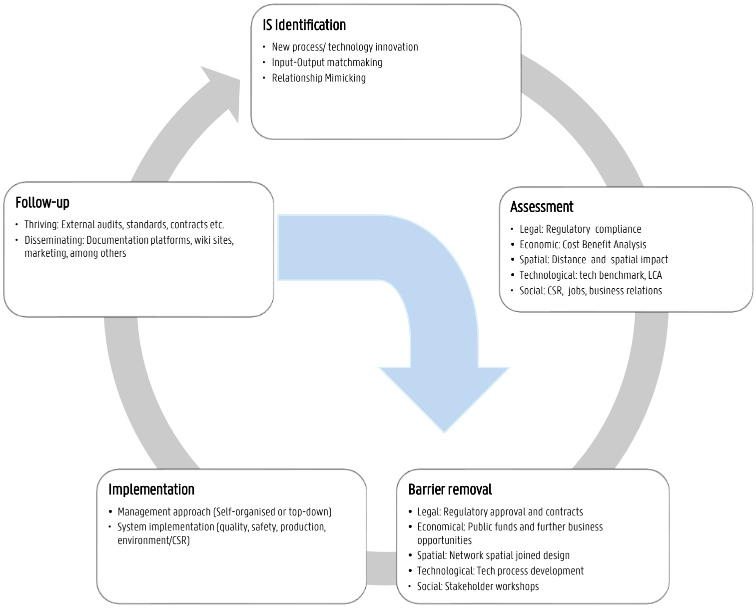



Figure 1.8 Five stages of any industrial symbiosis project lifecycle, adapted from Maqbool et al. (2019).

### 1.2.3 HUBS FOR CIRCULARITY (H4C)

Climate change and resource intensity are some of the most challenging problems humanity faces today. To prevent escalation, action is needed on all levels of society (European Commission, 2019c, 2020b; IPCC, 2018). An important actor in this field is the public-private partnership P4Planet, an association of process industries, research institutions and other organisations aiming for a circular and climate neutral economy in Europe (A.SPIRE aisbl, 2020). One of the prominent accelerators for this transformation is the concept of hubs for circularity. In these hubs, energy, materials, services, infrastructure and information are shared with the aim of achieving climate and resource neutrality (A.SPIRE aisbl, 2020). Such a self-sustaining economic ecosystem involves a manifold of regional stakeholders from industry, civil society, local authorities, and research organisations (universities and RTOs) to deploy full-scale urban-industrial symbiosis and circular economics (A.SPIRE aisbl, 2020).

In the academic literature, there are two main concepts related to H4C: zero waste hubs and urban-industrial symbiosis. Zero waste hubs originated in 1997 (Connett, 2013; Friedmann et al., n.d.), focusing on industrial waste but not restricted to industry boundaries. The concept builds on considering waste as an under-used resource proposing a hierarchy for end-of-life use based on the ladder of Lansink (Lansink, 2017). True to this approach, Accenture (Accenture, 2021) developed a strategy for hubs in Europe targeting net-zero emissions with a focus on energy-intensive industries. The second concept, urban-industrial symbiosis (Feiferytė-Skirienė & Stasiškienė, 2021; Sun et al., 2020), introduces synergies among industries and cities, acknowledging the importance of urban collaboration to reduce the environmental impact in a region effectively. Such a strategy becomes more prominent as the distance between industries, traditionally established in suburban areas, reduces due to the expansion of cities in regions around the world (Lu, 2020).

Global megatrends on European production-consumption systems boost the motivation for circular initiatives (VITO, 2016). Firstly, increasing urbanisation opens the scope for replication in other regions, as industrial solutions found in the EU may be replicable. Secondly, accelerating technologies would bring opportunities inside and outside the EU for digitalising processes and collaborations. Thirdly, the increasingly multipolar world would require Europe to adapt to potential changes in the supply change together with the increasing global competition for resources. Finally, increasing environmental issues and climate change urge for more effective solutions require a superior level of collaboration among stakeholders.

H4Cs involve multiple stakeholders building an ecosystem to develop the circular economy strategies (Figure 1.9).

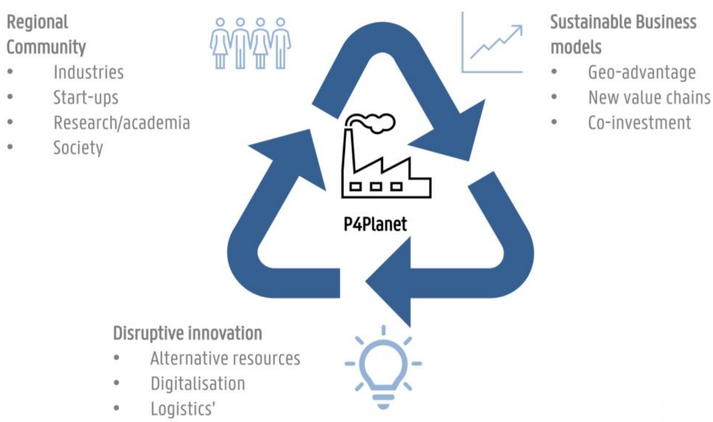



Figure 1.9 Key components of a Hub for Circularity building on the P4Planet partnership (A. SPIRE, 2020).

Industrial symbiosis provides frameworks and tools to develop relationships across sectors, especially in industrial clusters. The formation of relationships can be driven by the opportunities in the circular economy (both legal and economic), bringing benefits to the diversity of stakeholders involved in the H4C initiative.

In this context, IS plays its role as a business archetype based on a cooperative network to provide a competitive advantage based on shared resources (infrastructure, by-products, and joint services) (Baldassarre et al., 2019; Chertow et al., 2008). Such an approach creates value from waste while improving resource efficiency (Van Eetvelde, 2018). Jacobsen (2006) provided an in-depth analysis of the Kalundborg cluster, presenting quantitative insights on the economic and environmental performance enabled by IS. The author clarifies that economic motivations are often generated upstream and downstream, beyond the value of exchanged by-products, thus encouraging the dual perspective of individual sites and collective value chains.

The business model of industrial symbiosis enables financial value creation. Cash flows and the cost of capital (often WACC) are critical for an organisation (McKinsey & Company, 2020). Cash flow can increase by increasing revenue (new markets or products) derived from by-product valorisation or by improving the return on invested capital (ROIC) originated from the competitive advantage of IS (Figure 1.10). A project increases the value of an organisation only when the ROIC exceeds its cost of capital with or without a revenue increase (McKinsey & Company, 2020). Therefore, the financial assessment of IS projects is critical to their viability.

From a financial perspective, the challenge for IS projects is to deliver a rate of returns higher than the cost of capital to justify the opportunity cost for the required capital allocation. Also, IS projects compete in limited capital allocation industries, which calls for clarifying the financial and non-financial benefits in the business case.

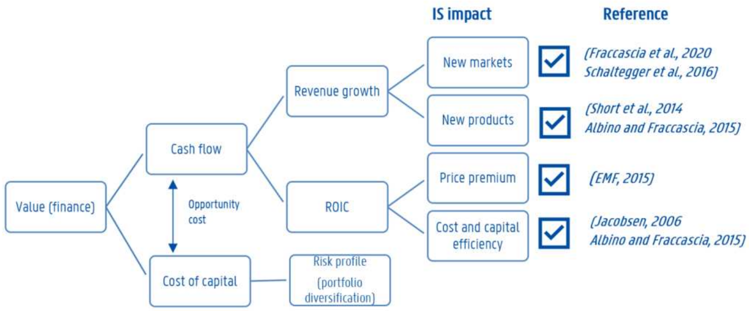



Figure 1.10 Industrial symbiosis impacts financial value creation (adapted from (McKinsey & Company, 2020)).

The IS impact on revenue growth comes from sustainable business innovation by valorising under-used resources to develop new products (Short et al., 2014) or to enter new markets with non-new products due to improved economic, social or environmental performance (Fraccascia et al., 2020; Schaltegger et al., 2016).

IS can also impact the return level by enabling a price premium in the context of the circular economy (EMF, 2015) or by enabling lower operation costs and higher utilisation of capital assets (Albino & Fraccascia, 2015). Jacobsen (2006) made an initial quantification of the success case of Kalundborg in Denmark.

The financial assessment of IS projects is often challenging as the financial requirements across companies and industries may differ substantially. In order to reduce the relevance of such differences, partnering with not-for-profit organisations (including regional authorities) to increase the chances of sustainable value generation is often encouraged in IS initiatives as third-party partners, especially when urban centres are involved (A. SPIRE, 2019; Domenech et al., 2019).

Symbiosis can make a difference towards circularity objectives in at least three ways (Domenech et al., 2019):

1. By creating opportunities to increase the re-utilisation of components and materials through the use of by-products and waste to substitute primary raw materials. Cases include many types of chemicals, plastics, woods of different qualities, biomass, redundant stock, reusable construction materials but also water, steam and energy.
2. By reducing structural waste through the optimal use of underutilised resources and assets (including infrastructure, buildings and space). The shared exploitation of water or waste treatment facilities in a cluster is a generic example of an IS case, while the techno-economic study of such facility in a particular cluster is a site-specific case.
3. By promoting projects to reduce the overall volume of waste and emissions generated by manufacturing activities, which amounts to several million tonnes of landfill diversion and GHG emissions saved. Such projects facilitate symbiosis activity in Europe.

In addition to circular gains, IS can also directly support climate change goals, for instance by valorising carbon emissions, storing CO2, using biomass or sharing green power investments. These examples are driven by enhanced efficiencies in carbon and energy management with direct impact on the transition towards climate and resource neutrality. Likewise IS can leverage climate change goals by reducing indirect emissions through saving energy, feedstock use or transport (EPOS project, 2019h; SCALER project, 2020b), but the impact requires a complex value chain assessment which is out of the scope of this thesis.

Industrial symbiosis inherently aims at advancing the competitiveness of companies through added value creation. Such IS value can be added in multiple dimensions. From an economic perspective, most typical are enabling cost reduction strategies based on energy, material or emission efficiency, or realising additional revenue streams from the valorisation of under-used resources (CEN-CENELEC, 2018). A second dimension is environmental, enabling reduced dependency on critical resources (energy, raw materials, water) while generating less waste and emissions.

Growingly, also the third pillar of sustainability gains ground, in particular in urban-industrial clusters. The social dimension creates value by integrating with communities, offering additional sources of employment such as joined greenkeeping of industrial parks; or simply by enabling new business relations, in particular in cross-sectoral clusters. Across all three sustainability dimensions, competitiveness benefits most from creating new business opportunities linked to alternative uses of existing by-products and waste streams, whether resulting from industrial partners or from neighbouring communities (CEN-CENELEC, 2018). In this way, IS facilitates demand-led innovation in the current transition economy, connecting industry with academia as well as governments and society to address real-time innovation (Domenech et al., 2018). Figure 1.10 shows how IS impacts financial value creation in particular.

Sustainability in IS refers to establishing multidimensional synergies across different industries (beyond financial value). Such synergies can be economical, social, or environmental, as emphasised in recent European projects and studies (SCALER project, 2020; EPOS project, 2019). The economic synergies result from the generation of marketplaces for under-used resources creating revenue streams and cost savings (Albino & Fraccascia, 2015). The social impact often refers to generating jobs and enhancing relationships with communities surrounding the industries. This aspect is particularly relevant for urban industrial symbiosis, fulfilling mainly the infrastructure needs of urban areas related to energy and material flows (European Commission, 2019a; Ažman Momirski et al., 2021). In terms of environmental performance, the synergy point lies in material and emissions efficiencies promoting resource conservation and avoiding associated environmental impacts (Axelson et al., 2021). Such efficiencies, however, are not always granted due to circular economy rebound effects (Zink & Geyer, 2017), symbiotic rebounds (Figge & Thorpe, 2019), and/or additional by-product processing needs (Mohammed et al., 2018).

## 1.2.4 PROCESS INDUSTRY PROFILES

The circular economy aims to balance supply and demand of goods and services while considering planetary boundaries. Such a balance enables industries and societies to strive for climate and resource neutrality. The role of basic materials used to manufacture any physical good in our daily life is often ignored when referring to the societal impact on environment, particularly the challenges related to the circular economy and climate change (Gerres, 2022). Emission and energy-intensive processing and production often take place in industrial plants, which are out of sight during our daily life, and might even be situated on the other side of the globe.

Only a few highly emission-intensive processes cause most direct industrial emissions. Specifically, the production of basic materials such as cement, iron and steel, chemicals, aluminium, and paper was responsible for 71% of European direct industrial emissions in 2018 (Gerres, 2022; WRI & WBCSD, 2004) with intense energy demand profiles. Manufacturing causes minor direct emissions compared to the production of basic materials. Process industries, having energy-intensive input, have a significant role to play in the context of policy goals towards climate and resource neutrality (HLGEEIs, 2019).

In 2018, the total direct GHG emissions from Energy-Intensive Industries (EIIs) in the EU represented 15% of EU-28 total GHG emissions (European Commission, 2020c). In the meantime, between 1990 and 2015, EIIs reduced their GHG emissions by 36%, accounting for 28% of the total economy-wide emission reductions by the EU (Wyns et al., 2018). These decreases are related to technical factors, such as improvements in energy efficiency and resource innovation like the use of biofuels (assuming emissions compensation), but also to non-technical influences such as lower production levels following the economic crisis of 2008 (Wyns et al., 2018). Similar factors were found in a Canadian study, finding five change drivers for $CO_2$ emissions in the industry: activity level, industry structure, energy intensity, fuel mix, and emission factors (Talaei et al., 2020). Among EIIs, chemicals, steel, and cement industries represented ca. 65% of the $CO_2$ industrial emissions in the EU ETS in 2018 (de Bruyn et al., 2020). Such basic materials are currently responsible for the largest share of industrial emissions (Figure 1.11). Thus, improving these three sectors' energy and resource efficiency is significant for achieving the EU's climate goals.

The role of the chemicals, steel, and cement sectors in the EU is crucial in terms of transitioning towards climate-neutrality; it also implies global competitiveness and regional circularity due to their high energy and resource demand and impact on productivity and employment levels.


Figure 1.11 Share of basic materials production in the direct emission balance of the EU industry (adapted from Gerres, 2022).

In 2018, the chemicals industry in Europe represented 20.7% of the world output sales in euros (CEFIC, 2020a). The sector is a supplier to virtually every other industry in Europe, producing about 330 Mt of product per year (Elser & Ulbrich, 2017) but also generating $CO_2$ emissions at 27% of the total industrial $CO_2$ emissions in the EU ETS in 2018 (de Bruyn et al., 2020). Many efforts have been made to reduce process emissions via energy efficiency in the last decades. The energy consumption per production unit in the chemical industry, including pharmaceuticals, was nearly 55% lower in 2017 than in 1991 (CEFIC, 2020a). One of the key features enabling the sector's lower carbon transition is its clustering capacity. This not only enhances competitiveness (Elser & Ulbrich, 2017; Ketels, 2007) but also answers socio-environmental questions by making effective synergies between different process units and sectors or communities in a specific region (Cervo, 2020; Lowe & Evans, 1995).

In the EU, the steel sector accounted for 10% of the world output (metric tonnes) in 2019 (EUROFER, 2020). Steel is fundamental for both the manufacturing and the construction industry and thus for the logistic development of any region. Such importance implies a high demand for raw materials and an equally high amount of emissions. The industry requires about two tonnes of material (iron ore and coke) to produce one tonne of steel (World Steel, 2019). In 2018, the steel sector made up for 22% of the total industrial $CO_2$ emissions in the EU ETS (de Bruyn et al., 2020). In contrast, the EU steel industry has reduced its energy consumption by 50% over the last 40 years, thanks to higher scrap recycling levels and a decrease in production (European Commission, 2014b).

In 2018, the production of cement in EU-28 represented 4.4% of the total world production (metric tonnes) (CEMBUREAU, 2019). Cement is fundamental for building durable structures since it is a hydraulic binder in concrete (Elser & Ulbrich, 2017). The $CO_2$ emissions from the sector in Europe take up a 21% share of the total industrial $CO_2$ emissions in the EU ETS in 2018 (de Bruyn et al., 2020). An important aspect of this industry is its ability to use fuels derived from waste and biomass to produce heat in its kilns. In Europe, this amounts to ca. 40% of the fuel supply for thermal energy in the grey clinker production (De Beer et al., 2017). Between 1990 and 2017, the EU-28 cement industry has reduced its gross $CO_2$ emissions per tonne of product by 13% (CEMBUREAU, 2019).

Regarding GHGs emissions, onsite energy generation (fuel emissions) and process emissions (other chemical reactions) are the main contributors (Gerres et al., 2019).. Process industries have similar energy intensity and emission profiles (Figure 1.12). Regarding energy intensity, the thermal energy demand has the largest share across industries (compared with electricity), with aluminium production having the highest total energy demand according to the Best Available Techniques (BAT).

Due to stricter energy and emissions policy demands in all industrial sectors, technologies applicable to multiple sectors are relevant. Based on a review of sector roadmaps and public reports, Gerres et al. (2019) listed the technology across sectors with the potential reduction range according to the public reports, having CCS and electrolysis as the most promising technologies across industries (Figure 1.13). The authors highlighted challenges for the implementation and the need for cross-sectorial symbiosis to enable the required energy and climate infrastructure (Gerres et al., 2019).

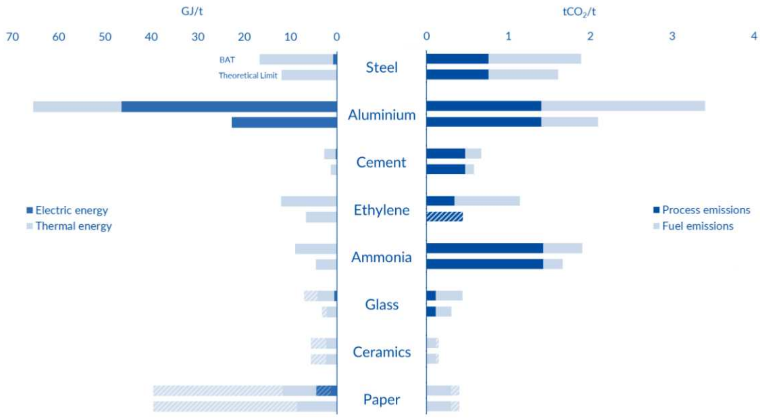



Figure 1.12 Energy intensity and direct emission profiles of conventional production routes in the process industry (Gerres, 2022).

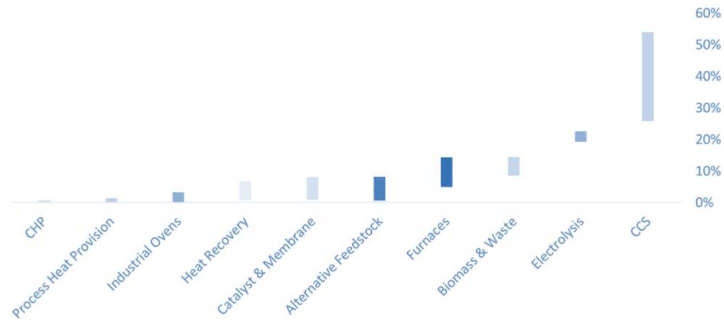



Figure 1.13 Key technological abatement options across the process industry and their min/max potential for total industrial GHGs emission reduction (adapted from Gerres et al., 2018).

In the last 15 years, over 130 million euros have been invested in Europe to develop tools that enable a broad implementation of industrial symbiosis (Maqbool et al., 2019); and still, there is potential for further exploitation (Azevedo et al., 2020; Neves et al., 2020). Barriers related to non-technological factors such as low trust among partners, lack of information, and non-supportive environmental legislation have been highlighted (Neves et al., 2019; Van Eetvelde, 2018; Golev et al., 2015a). In order to fill the information gap, several studies and projects have been done, building databases and reports to reference IS cases using various approaches. In 2002, Pellenbarg (2002) published a study on the concept of sustainable business sites focusing on the Netherlands . With a similar site-based approach on eco-industrial parks, Susur et al. (2019) presented an overview of 104 sites located worldwide. Neves et al. (2020) made a literature review of more than 500 papers from cases around the world, showing that China and the USA are the countries with the highest number of studies. Still, most of the analysed cases are in Europe. In one of the latest studies on IS databases, Jato-Espino and Ruiz-Puente (2020) performed an analysis of open access IS databases clarifying links between different sectors with a focus on correspondence, network, and correlation analysis. It provides a solid base to explore further IS cases for sectors of main relevance towards resource and climate neutrality, such as chemicals, steel, and cement.

The state-of-the-art of IS research projects in EIIs have a wide range of applications but also show converging approaches. Recent European projects have focused on the identification of IS cases at different levels (Maqbool, Alva, et al., 2019). The MAESTRI project developed a knowledge depository targeting practitioners that aim at IS replication (Benedetti et al., 2017; Evans et al., 2017). The EPOS project generated a collection of generic cases for replication in cross-sectoral clusters (EPOS project, 2019). The SCALER project published several reports on 100 synergy schemes with an estimated added value of 8 billion euros for the EU and a significant reduction of the environmental impact (Azevedo et al., 2020). Such European projects have taken a sectoral approach towards regional replication. In the EPOS project, blueprints of various industrial sectors have been developed to enable communication and optimisation between sites and sectors with differing activities (Cervo et al., 2020; EPOS project, 2019a).

## *1.3 THESIS OBJECTIVES, SCOPE AND OUTLINE*

### 1.3.1 OBJECTIVES AND RESEARCH QUESTIONS

The central objective of the present work is to explore industrial symbiosis as an enabler for industries in the transition towards carbon neutrality and the circular economy. Specifically, process industries are energy-intensive industries requiring a high level of transformation to align with the ambitions of the regions (EU). Although each sector has its specific needs, cross-sectoral collaborations (joint infrastructure and by-product exchange) offer effective options to enable the required transformations.

The research questions of the thesis are:

1. How to systematise the exploration of cross-sectoral collaborations (IS) in the process industries?
2. How to investigate challenges and opportunities beyond the technological aspects?

The first question is addressed by the research on regional clustering (chapter 2), considering generic cases of symbiosis (chapter 5), and by the research on the industrial symbiosis profile of selected industries based on extensive databases of cases.

The research on non-technical clustering factors (LESTS) in chapter 4 and the application of game theory tools to facilitate collaboration (chapter 5) address the second question.

### 1.3.2 RESEARCH OUTLINE

Critical gaps exist across projects aiming for future circular and carbon-neutral scenarios, such as advanced industrial symbiosis. The lack of studies on cross-sectoral collaboration that relate symbiosis with the circular economy, specifically for the process industry, is the gap addressed in this work. The research provides frameworks, models, and cases to identify the potential for cross-sectoral collaboration and developed tools that include non-technical factors when addressing and advancing industrial symbiosis (Figure 1.14).

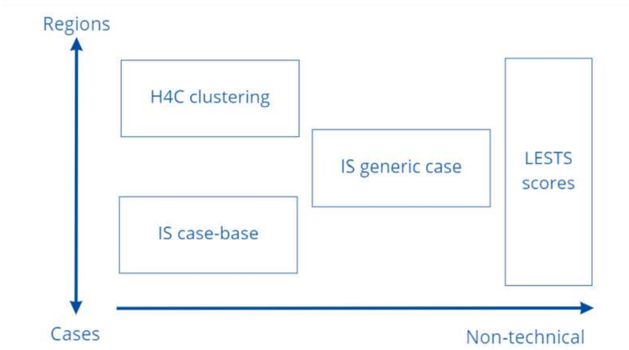



Figure 1.14 Thesis content scope towards regions and non-technical aspects.

In chapter 2 of the thesis, the concept of hubs for circularity is elaborated by using clustering algorithms applied to geo-located data of industrial installations and emissions (peer-reviewed article (Mendez-Alva, De Boever, et al., 2021)).

In chapter 3, the thesis focuses on IS sector profiles to build an IS case-base, a tool for the bottom-up valorisation of by-products and industrial waste (peer-reviewed article (Mendez-Alva, Cervo, et al., 2021)).

In chapter 4, the thesis focuses on the design and application of LESTS scores to evaluate symbiosis in the cluster, taking into account legal, economic, spatial, technological and social implications (based on reviewed contributions to EPOS project deliverables D5.4 and D4.3).

Chapter 5 presents the concept of IS generic cases to promote replicable synergies for the process industry (based on reviewed contributions to EPOS project deliverable D1.3). Furthermore, the game theory is used to bridge the collaboration gap back to the concept of hubs for circularity, opening additional research lines toward economic approaches for H4C.

### 1.3.3 OVERVIEW OF THE WORK DONE

The present research work originated and developed in European research projects with a prominent IS component (EPOS, H4C, AIDRES, and TRILATE). This work contributes to critical research gaps relevant to the needs of industrial clusters and regions towards their circular and climate ambitions.

The goal of the H2020 EPOS project (2015-2019) was to enforce the competitiveness of the EU industry by gaining cross-sectoral knowledge and investigating cluster opportunities using an innovative Industrial Symbiosis (IS) platform that was developed and validated during the project (EPOS project, 2019a). To this purpose, the work developed 21 IS generic cases for selected sectors (Deliverable 1.3), supported the advancement and implementation of LESTS surveys in the toolbox (Deliverable 4.3) as well as matchmaking methodologies for industrial symbiosis in the process industry (Deliverable 5.4). Research results led to a journal article on IS industrial profiles (Mendez-Alva, Cervo, et al., 2021) and co-authorship of three other papers. The first article related to ICT tools for industrial symbiosis (Maqbool, Alva, et al., 2019), the second article concerned an IS study case in the UK Hull region (Cervo et al., 2019), and the third article described a methodology to develop IS business relations (Ogé et al., 2019). In 2018, the author participated in the CWA workshop on industrial symbiosis as a contributor (CEN-CENELEC, 2018), joining the development of the first set of guidelines on IS in Europe with a standardisation institution. Chapters 1, 3 and 5 include the research contributions to the EPOS project.

Chapter 2 includes the research contributions to the H4C project. Building from the EPOS and CWA experience, the contribution to the H4C initiative was to conceptualise how to bring industrial and urban stakeholders together to close resource loops, with urban-industrial symbiosis and circular solutions as core elements (A. SPIRE, 2019; Mendez-Alva, De Boever, et al., 2021). The research results lead to a journal article on how clustering methods can advance the development of the H4C concept (Mendez-Alva, De Boever, et al., 2021). Starting in 2020, the author represented the ECM research group in the CircLean project, a network of IS academics and practitioners aiming to develop a community of practice and an EU-wide platform for industrial symbiosis and circular economy (CircLean, 2020), proving academic feedback on the development of their IS tools.

Chapter 3 includes background research maturated in the AIDRES project. Building from H4C research and EPOS inspired, the goal of the AIDRES project (commissioned by the EC) provided the next level of necessary data to develop a sharper picture of potential pathways for industries at their respective sites and in their respective industrial clusters in Europe (VITO et al., 2022). Developing further the research in EPOS, the work led to developing insights related to the circular economy of the AIDRES selected industries and their symbiosis potential. Different technology pathways and geographical locations of industrial installation were considered across Europe, leading to results presented at international conferences.

Finally, the ongoing TRILATE project aims at investigating Belgian needs for energy transport infrastructure in order to guarantee the security of supply to industrial clusters. In this project, the author's research focused on clustering algorithms and IS profiles, which is now further developed by the ECM group.

Table 1.1 Overview of the work done.

| Chapter | Research focus | Related Project (s) | Author's publications |
|---|---|---|---|
| **1 Introduction** | • Review and articulation of key concepts (circular economy, symbiosis, clustering and process industries), including visualisation diagrams | EPOS, H4C, AIDRES, TRILATE | I-III, VIII, X |
| **2 H4C: Clustering options** | • Hubs for Circularity conceptual insights<br>• Methodology for clustering algorithm application<br>• Maps and database of urban-industrial clusters in Europe<br>• Circularity framework for the process industry | H4C | IV, VII, IX |
| **3 IS case-base: Industrial symbiosis profiles** | • Exiting IS databases overview<br>• Methodology to develop IS profiles<br>• IS case-base (new database to facilitate elaboration of profiles)<br>• Method for cross-sectoral matchmaking<br>• Sustainability, technological and organisational challenges | EPOS, AIDRES | V,VI |
| **4 LESTS tools: management of organisational aspects of IS** | • LESTS scores: application in the process industry including cities<br>• LESTS matrix: application for multiple project stages | EPOS, AIDRES | II-III |
| **5 IS generic cases: collaboration schemes for industrial regions** | • Method to elaborate IS generic cases<br>• 21 IS generic cases<br>• Exploratory strategic analysis for generic cases | EPOS, AIDRES | VII |

The list of publications related to this thesis can be found in appendix 1.

Table 1.1 provides an overview of the research with focus on the novelty per chapter. In the regional approach for the study of IS opportunities (chapter 2) the novelty lies in the development of a new methodology to cluster industrial sites and cities based on the E-PRTR and the Eltis datasets, respectively. The method supports the selection of databases for testing the performance of clustering algorithms of increasing complexity (K-means, HAC, DBSCAN) to return potential hubs for circularity across Europe. This resulted in a novel framework for circularity in the process industry (section 2.4.3). The sectoral approach to systematically investigate symbiosis (chapter 3) led to developing industrial symbiosis profiles for key process industries and systematising the documented IS cases into an IS case-base. Regarding the investigation of organisational capabilities (chapter 4), the application of the LESTS method in industrial clusters and cities for symbiosis cases enables a new tool, which includes indicators at three focus levels: stream, company and cluster. Finally, the concept of IS generic cases is presented as an innovation result in chapter 5, providing a method for developing a wider range of cases ready for replication across Europe. The generic case-base is supplemented with a prescriptive application of basic game theory tools in order to trigger strategic analysis and enable early detection of potential social dilemma.

# CHAPTER 2 H4C: CLUSTERING OPTIONS FOR CIRCULARITY

Building from is the concept of industrial symbiosis (IS) in chapter 1 and the approach toward a circular economy (CE) in the context of process industries, Chapter 2 focuses on the development of IS on a regional level, exploring clustering techniques to identify potential hubs for circularity (H4C) across Europe. This chapter embeds the article' Hubs for Circularity: Geo-Based Industrial Clustering towards Urban Symbiosis in Europe', published in the peer-reviewed journal 'Sustainability'.

The study explores the concept of hubs for circularity in the context of the P4Planet programme preparation, providing a methodology and insights on the geographical distribution of urban-industrial hubs and the conceptual approach of circularity in the context of hubs involving process industries. The chapter is complemented with a review on recycling for key sectors (glass, steel and plastics), as this strategy is key to reducing energy, feedstock and emissions in the mentioned sectors.

## *2.1 CLUSTER ANALYSIS FOR IDENTIFICATION OF HUBS FOR CIRCULARITY (H4C)*

The implantation of H4Cs addresses the circular economy's aims at a meso-level, where industrial clusters are expected to have industrial symbiosis (IS) as central strategy (A. SPIRE, 2019; Accenture, 2021). Clustering analysis is used to explore together the concepts of H4C and IS.

Cluster analysis is an exploratory analysis tool that finds structures and patterns in data sets. Clustering algorithms are unsupervised learning algorithms that identify patterns from untagged data (Sinharay, 2010). According to Estivill and Castro (Estivill-Castro, 2002), there is a top-down and bottom-up view to clustering. In the top-down approach, clustering is the process of segmenting a heterogeneous population into a number of homogeneous subgroups. In the bottom-up view, clustering is defined as "finding groups" in a dataset by a specific similarity criterion. These should be grouped into the most homogeneous groups possible, maximising the difference between groups and minimising the differences among the elements of each group. However, given the diversity of methods and purposes, other views and classification strategies are possible (Berkhin, 2006).

Relevant examples of applying clustering methods range from identifying groups of indicators across frameworks to the segmentation of regions and industries according to certain parameters. Superti et al. (Superti et al., 2021) organised circularity indicators into common groups using hierarchical clustering based on a selection of circular economy projects and frameworks. Dunkelberg et al. mapped the German plastic industry using clustering analysis to support waste heat utilisation strategies (Dunkelberg et al., 2019). Arbolino et al. identified homogeneous regions to improve the monitoring and evaluations of regional waste policies (Arbolino et al., 2018) based on economic indicators. Although these applications relate to the circular economy, none entered into developing multi sector hubs, including industries and cities.

Recent European projects on industrial symbiosis potential in regions indicate the importance of geo-based data. An initial approach in the EPOS project led to the mapping of process industries with high potential for industrial symbiosis (EPOS project, 2019h). The procedure was further elaborated in the SCALER project adding potential exchanges among the industries in a specific area (SCALER project, 2020b). This regional approach is turned into an implementation strategy in the INCUBIS project, where incubators are located around Europe to promote symbiosis, mainly focusing on industrial waste heat utilisation (INCUBIS project, 2020). The hub approach is taken forward by the P4Planet partnership supported by the European Commission (A.SPIRE aisbl, 2020), considering the geospatial character for clustering as crucial.

Different clustering methods have differing degrees of complexity. The method compared three algorithms on a set of location data of European industrial facilities (E-PRTR): K-means clustering, hierarchical agglomerative clustering (HAC) and density-based spatial clustering of applications with noise (DBSCAN) (Mendez-Alva, De Boever, et al., 2021). The first, K-means, is one of the simplest methods capable of both supervised and unsupervised clustering based on the number of clusters 'K' in a given a dataset (Berkhin, 2006). Due to its simplicity and versatility, it is one of the most used clustering methods. The second one, HAC, enables bottom-up clustering based on the distance between points or similarity criteria (Rokach & Maimon, 2005). Finally, DBSCAN allows for a more sophisticated clustering based on the distance between data points and restrictions about the number of connecting points to each point in a cluster (Schubert et al., 2017). By selecting this range of methods, researchers can explore the suitability of clustering methods for a first identification of hubs.

Using clustering methods to define regions that can become hubs for circularity can provide useful information for identifying regional circular economy strategies, fostering industrial symbiosis and involving a maximum number of cities. This chapter aims to make a first-of-a-kind explorative analysis of how clustering methods can support the identification of regions with high potential for developing hubs for circularity involving multiple industries and cities.

The approach of this study is two-fold: in a first phase, the clustering methods are investigated and compared using both general statistical validation techniques as well visual inspection of the data. In a second phase, the method that is best suited for hubs identification, based on the nature of the data, is selected and used to generate insights on clustering for circularity.

## 2.2 STAGES TOWARDS H4C INSIGHTS

A five-step cyclical methodology was developed to identify H4Cs using clustering algorithms as shown in Figure 2.1. With the goal set, the checks required to verify a suitable database were defined and the clustering algorithms for comparison and selection described. To end, the circularity indicators were identified in order to enable insights and develop a mapping tool to visualise the clusters.

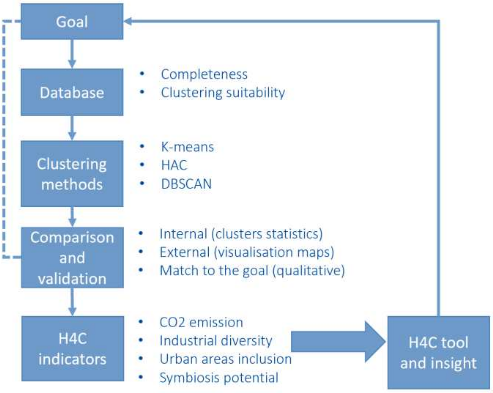



Figure 2.1 Methodology: using clustering methods to identify hubs for circularity.

### 2.2.1 GOAL: ESTABLISH COMMON GROUND AND EXPECTATIONS

The study explored options for defining circularity regions in Europe using different clustering methods. It focused on the distribution of industries and cities as they are critical stakeholders.

The definition of regional circularity is broad, but the core element is the geographical aspect of the concept. The building blocks considered for this exploration are industries in Europe as reported in the European Pollutant Release and Transfer Register (E-PRTR) (European Commission, 2020d), supplemented with information on the concentration of urban areas from the EU Urban Mobility Observatory (European Commission, 2021). Spatial clustering techniques allow to identify groups of location points. They are of a specific size and concentration that are not able to appear randomly and show a visible similarity between each other.

### 2.2.2 DATABASE: ANALYSE THE AVAILABLE DATA

Information related to the location of an industry was the starting point of this study. The data on industrial facilities, retrieved from E-PRTR, include all 27 European Union member states and Iceland, Liechtenstein, Norway, Switzerland, and the United Kingdom. The register contains data on main pollutant releases to air, water and land of more than 30 000 industrial plants. These facilities cover a total of 65 economic activities across 9 industrial sectors. Besides categorising plants in the above sectors, E-PRTR also supports classification according to the economic nomenclature used by the EC (NACE) to define industrial sectors. In this study, data were collected by choosing a set of 24 NACE-coded activities (European Commission, 2020d). The database considered solid thanks to the broad range of industries, the relevance of the pollutants for clustering into H4Cs and the continuous improvement of the reporting since 2007 (European Commission, 2020d).

With the database selected, the suitability for clustering methods requires to be checked. The cluster tendency assessment (Datanovia, 2021a) evaluated whether or not the data have non-random structures. Such evaluation was necessary because the algorithms group any type of data, regardless of the data structure. In this step, first a visual inspection was done to assess the generation of meaningful clusters, and then the Hopkins statistic was calculated, yielding the probability of a uniform data distribution (Lawson & Jurs, 1990).

For the analysis itself, open-source Python libraries were used, in casu the Py-clustertend package to assess cluster tendency (Lachheb, 2019/2021; Open Source Libs, 2021).

### 2.2.3 METHODS: IDENTIFY RELEVANT CLUSTERING ALGORITHM

As introduced above, three representative cluster methods were selected, known to have increasing sophistication: K-means, HAC and DBSCAN. K-means and HAC require to determine the optimal number of clusters. Specifically, for this research, the authors used two different methods: the elbow method (Datanovia, 2021c) and the average silhouette method (Ketchen & Shook, 1996). The results of these three methods can vary, hence choosing the right value (if existing) relies on direct inspection of the clustering results. The K-means method served as pilot for testing the methods for an optimal number of clusters.

In hierarchical agglomerative clustering (HAC), the clustering is performed from a bottom-up perspective. Each data point starts in a potential cluster, and clusters are merged using a proximity measure such as distance or similarity. The algorithm also requires either a specification of the number of clusters or a distance threshold at which clusters will no longer be merged. The second option is excellent for the H4C application since it allows to specify clusters with a certain distance range (Estivill-Castro, 2002; Rokach & Maimon, 2005). The algorithm in Scikit-learn for the HAC method does not support haversine distance (scikit-learn developers, 2007) as a distance metric, but this can be solved by generating a precomputed distance matrix that calculates circle distances between all data points. This, however, considerably increases the computational complexity of this algorithm. The HAC algorithm has different linkage criteria. The single linkage criterion has the ability to form clusters of non-spherical shape as compared to circular clusters in other linkage criteria. Likewise, it is able to create larger clusters with a tendency to split such clusters into groups of multiple smaller clusters. Therefore, the single linkage for HAC was selected. The results of the HAC method with a distance threshold of 25 kilometres criteria are discussed below.

DBSCAN requires two main parameters (Schubert et al., 2017) to be set. The first is the epsilon value (EPS) that determines the distance between two data points needed to be considered part of a cluster. Two data points that lay within EPS range of each other are called neighbours. The second parameter is called minPoints and sets the minimum number of data points required to define a dense region or cluster. Parameters can be chosen intuitively: the EPS parameter can be transformed into an exact range in kilometres, which allows to choose a specific range. The minPoints parameter allows to determine the minimum number of industrial sites to be identified as a cluster with the rest of the data points categorised as outliers. The DBSCAN algorithm classifies data points (i.e., industrial locations) into three types in order to process outliers. The first one covers the core points: it contains at least the minimum number of points (minPoints; including the point itself) as neighbours with radius EPS. The second type is the border point that is reachable from a core point, with less than minPoints number of points within the neighbouring area. Finally, the outlier point is a point that is not a core point and not reachable from any core point (Schubert et al., 2017). The results of the DBSCAN method with a distance threshold of 25 kilometres and minPoints=5 are used for visualisation in next sections.

Here again, open-source Python libraries were used to perform the analysis. They include Scikit-learn, a free software machine learning library and the main library used for the clustering methods (Scikit-learn developers, 2021; VanderPlas, 2017d); NumPy, one of Python's fundamental libraries for scientific computing (VanderPlas, 2017a); and Pandas, an open-source data analysis and manipulation tool (VanderPlas, 2017b).

### 2.2.4 COMPARISON: SELECT VALIDATION OPTIONS FOR EACH METHOD

The next step in the selection process was to compare the three algorithms via cluster validation statistics and visualisation. Cluster validation is a technique that evaluates the quality of the clustering results (Datanovia, 2021b). Three categories, internal, external and relative cluster validation (Brock et al., 2008; Charrad et al., 2014) are distinguished. The first only uses internal information to indicate the quality of the clustering by applying the average silhouette score. In the second category, the clustering results are visualised on a map of Europe, thus offering crucial spatial insight on how the clustering is performed. Lastly, relative validation techniques evaluate the clustering by changing the values of the clustering parameters (sensitivity), which is in essence a combination of the internal and external validation technique. This last validation option was used for DBSCAN since the silhouette score was not suitable for the type of clustering (density-based) performed.

Table 2.1 shows the overview of the clustering algorithms and validation methods applied. The validation results are discussed and used to evaluate and compare the algorithms and select the appropriate algorithm for further application.

Table 2.1 Types of validation applied to the selected clustering algorithms.

| Clustering method | Internal validation (Silhouette score) | External validation (Visual maps) | Relative validation (Parameter sensitivity) |
|---|---|---|---|
| **K-means** | X | X | |
| **HAC** | X | X | |
| **DBSCAN** | | X | X |

### 2.2.5 INDICATORS: INCLUDE ADDITIONAL PARAMETERS FOR H4C

In a next step, the research gathered statistics and insights on the results of the clustering. Additional parameters are added to the data model alongside the geolocation used at first: data on industrial activities of the facilities, data on European cities, $CO_2$ emission data of the industry sites, and industrial symbiosis options across sectors.

Data on European cities provided helpful information on how clusters are located in relation to the urban zones in order to account for urban-industrial symbiosis. City data were included as data points into the model. Data are gathered from Eltis (European Commission, 2021), Europe's main observatory on urban mobility, covering all cities in the EU, including Norway and the UK but excluding Iceland, Switzerland and Liechtenstein. Eltis is a central place for the exchange of information, knowledge and experience on European cities. It allows filtering of data points based on the population in a city centre as well as larger urban zones such as communities.

In this study, cities were defined by having a density of more than 1 500 inhabitants per square km and more than 50,000 inhabitants according to European standards for a city centre (Joint Research Centre (European Commission), 2019). From the Eltis dataset, data points were chosen for larger urban zones with populations of more than 100,000 inhabitants. Data on urban areas in Switzerland, Iceland and Liechtenstein are gathered from the OECD, again for populations of at least 100 000 inhabitants. In total 567 data points were collected (Joint Research Centre (European Commission) et al., 2019).

$CO_2$ emission data associated with industrial sites are included in the E-PRTR (European Commission, 2020d). Not all installations listed in the register have an associated value for emissions due to varying reporting policies, but most large emitters are included. These are useful to visually identify and tag them, either within or outside of the potential clusters.

Potential synergies across process industries or in urban-industrial clusters were a vital part of the result analysis. A preliminary list of IS synergies was extracted from the published Insights of the Horizon 2020 project EPOS. The documents summarise relevant outcomes for the H4C study, such as EPOS Insight #17 on industrial symbiosis. It discusses high-potential cross-sectoral cases and their impact in Europe, identifying 20 different generic IS cases (EPOS project, 2019h). Such cases can be generalised across sector profiles of the process industry, such as in steel, cement, chemical, mineral and engineering sectors (Mendez-Alva, Cervo, et al., 2021). The list of 20 cases was applied to a specific cluster to grasp the size of the (potential) cross-sector collaboration in the cluster with a simple matchmaking approach based on the presence of sites corresponding to the sectors in all possible generic cases.

Again, open-source Python libraries were used to perform the analysis. including Matplotlib, a library for creating data visualisations (VanderPlas, 2017c); Folium, facilitating data visualisation on interactive leaflet maps (Story, 2013); and Seaborn, another data visualisation library that is based on Matplotlib (VanderPlas, 2017c).

## *2.3 CLUSTERING APPLICATION AND RESULTS*

In this section, the collected data was analysed according to each methodology, comparing the clustering algorithms and assessing the type of clusters and insights found per selected algorithm. After selecting the final algorithm, the identified clusters were analysed to gain insight on their profile and their potential as hub for circularity.

### 2.3.1 DATABASE: E-PRTR INSIGHTS

In a first explorative analysis, the E-PRTR database was used for localising industrial sites in Europe. To test the suitability of the database, the author evaluated the uniformity of the installation distributions. Through visual inspection (Figure 2.2), cluster formation was observed in known industrial hubs such as port areas (Antwerp, Rotterdam, etc.) or the Ruhr area. This was further verified by the Hopkins statistic.

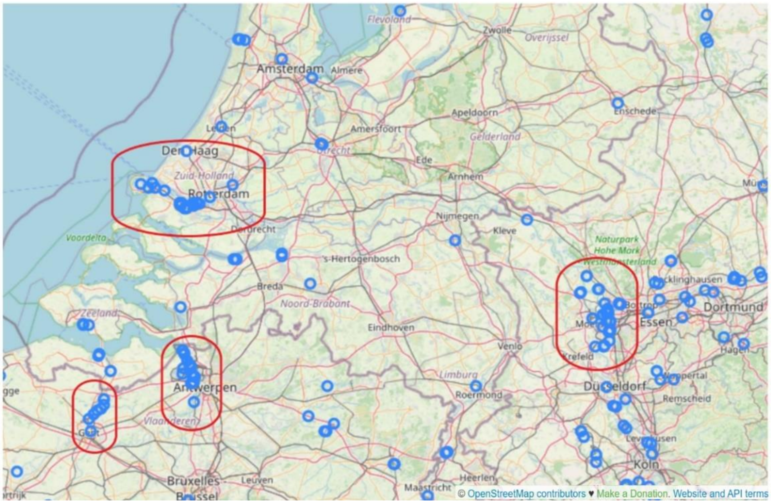


Figure 2.2 Initial visual inspection of the dataset (E-PRTR) shows groups of industrial facilities.

The Hopkins statistic was used as a statistical test with the null hypothesis stating that the data are uniformly randomly distributed (Datanovia, 2021a; Qiu & Cao, 2016). A value close to zero means that the data are not uniformly distributed and clustering will be meaningful (Lachheb, 2019/2021). For higher values (starting from 0.5) data are too uniformly distributed and clustering is not considered useful for the problem. The calculated value of the Hopkins statistic on the E-PRTR database is 0.01187, indicating a very high tendency towards clustering.

### 2.3.2 CLUSTERING METHOD: DBSCAN

K-means, HAC and DBSCAN, were applied to the database. The methods outlined in the methodology section (2.2.3) were used, namely the average silhouette score method for internal validation. Visualisation of the results is presented for external as well as relative validation (variation of parameters) mechanisms. In section 2.2.4, Table 2.1 shows the overview of the validation methods per algorithm.

K-means

The method requires a priori the number of clusters. By using the elbow method, seven clusters were found as the optimal. K-means uses the Euclidean distance as distance metric, however since geolocation coordinates are not linear, this method does not return entirely accurate results. As shown in Figure 2.3, the size of the clusters is too large to be practical for articulating local hubs (they are too few and too large to be realistic). In the figure only five colours can be identified, due to the excessive agglomeration of datapoints in such clusters. Two additional colours suggested marginal clusters for datapoints spread in continental African and American locations associated to European countries.

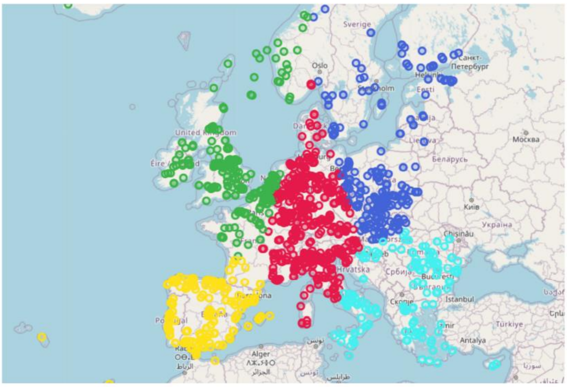



Figure 2.3 K-means clustering visualisation; using the elbow method, the optimal number of clusters is 7(=K).

The opposite, i.e., a high value for the optimal number of clusters, is found using the average silhouette score method. It resulted in up to 1 000 clusters, divided in intervals of 50 with a coefficient optimum at 700 clusters. The coefficient shows least variation between 600 and 850 clusters, in a range of 0.64 to 0.65, peaking at 700 clusters. Such wide variation makes it difficult to identify a feasible number of clusters and thus the realistic potential for hubs for circularity.

The average silhouette method returned very high values as optimal number of clusters, but they present either a large range of options or a high degree of sensitivity to the numbers of clusters from the industrial database. This was confirmed in extra visualisations showing that certain neighbouring data points were still grouped into different clusters while closely grouped data points were often clustered correctly. Upon further comparison, K-means was discarded as algorithm for determining the optimal number of clusters.

Hierarchical agglomerative clustering (HAC)

The HAC algorithm requires a specification of a distance threshold at which clusters are no longer merged. For HAC, a precomputed distance matrix was needed to calculate the circle distances between all data points, which considerably increased the computational complexity of this algorithm. The results of the HAC method used a distance threshold of 25 kilometres for different linkage criteria, referring to the average distance for symbiosis between sites in the United Kingdom (Jensen et al., 2011).

Figure 2.4. shows the output of the HAC algorithm zooming in on Western Europe (UN-SD, 2021). The trilateral industrial zone (western Germany, South Holland and Flanders) is clearly visible from the plot. The large cluster in western Germany, next to the ports of Antwerp (pink), Rotterdam (purple) and also Ghent (grey), and a long cluster geometry (blue) in the centre of Belgium are identified. The downside to such chained cluster effect is that the endpoints are distanced further from each other than the data points in other clusters.

The algorithm generated 628 unique clusters, with the largest cluster consisting of 103 data points. The silhouette score for the single linkage method with a 25-kilometre range is 0.548. The results with HAC are preferred over K-means because of the ability to influence the clustering based on a distance threshold, and the unnecessity to determine a priori the number of clusters.


Figure 2.4 Visualisation of clusters generated by the HAC algorithm with 25 km threshold.

DBSCAN

From the start, the DBSCAN algorithm was considered to have several advantages to make it suitable for the H4C application: the automatic detection of noise and robustness to outliers and parameters are intuitive, easy to set and offer the needed control over the outcome of the algorithm. In this study, a range of 25 kilometres (EPS) was chosen and a set of 5 minimum points (minPoints). The distance parameter was chosen based on the input from literature on the median distance for a symbiotic relationship (Jensen et al., 2011). The minimum number of points was chosen on experimental evidence from previous projects and studies aiming for clusters of a significant size and impact (Chertow, 2007; EPOS project, 2019h).

With DBSCAN, 92 clusters were identified using 969 of the 1918 data points, the other half being categorised as not clustered, thus noise data. The silhouette score for these results is -0.0158, since the method is not made to validate noise-labelled points. It assumes that each data point is clustered, thus filtering out the noise would make the score very high since all clusters would be well-defined when non-clustered data are left out. Alternative internal validation methods are available (Moulavi et al., 2014), but they are not applicable for comparison with the other two methods (K-means and HAC).

Regarding the external validation, the DBSCAN results were visually very similar to HAC clustering with the single linkage criterion. The linear cluster is of particular interest due to its unconventional shape (Figure 2.5). While it may seem undesirable to have clusters in a linear shape, it is clear that all data points are reachable through the cluster core points. A downside of this linearity, however, is that the endpoints can be reached by core points in other clusters, meaning that the locations can be part of multiple clusters at the same time. This makes DBSCAN not fully deterministic (Schubert et al., 2017), but additional testing confirmed that the frequency of returning linear clusters was too low to have a significant effect on the results.

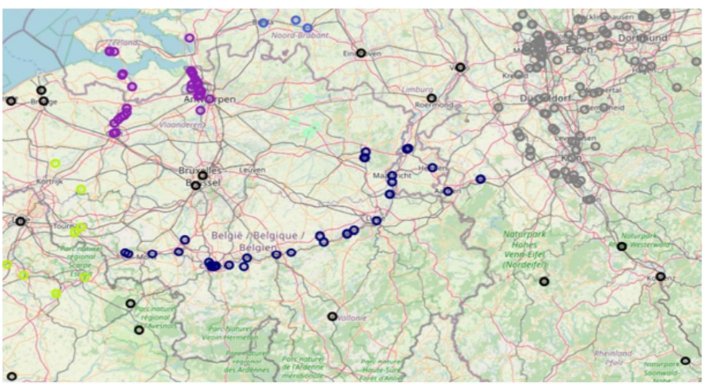



Figure 2.5 DBSCAM clustering with radius of 25 km and 5 minPoints, showing various geometries for clusters, identified dark blue cluster along the Maas River

Regarding the relative validation of the algorithm, the results were sensitive to the minimum number of datapoints to form a cluster. This follows the intuitive trends: with an increasing minPoint parameter and decreasing distance between points (range), more outlier data points were identified and less clusters were found; the results being more sensitive for lower numbers of minPoints compared to higher numbers.

The exploration confirmed that the advantages of the DBSCAN algorithm are manifold: it has automatic detection of noise, it shows robustness to outliers, its parameters are easy to set, and it provides indirect and in-built influence over the outcome of the algorithm.

DBSCAN was chosen over the HAC algorithm, primarily because the minimum point parameter in DBSCAN assures that all core points within a cluster are reachable from one another, which is imperative for hubs that aspire circularity. Hence it becomes a condition on the density of data points, an option that is not available when using HAC. The latter gives no guarantee that a minimum number of other data points will be present within a radius around a certain data point.

### 2.3.3 INDICATORS: CHARACTERISATION OF (CIRCULAR) INDUSTRIAL CLUSTERS

For incentivising hubs for circularity, five indicators were used in collaboration with P4Planet (A.SPIRE aisbl, 2020): clusters by country, by sector, by synergy, urban-industrial clusters and zero-carbon clusters. The clusters by country and by sector are presented following the DBSCAN output, and additionally by adding cities as actors for clustering. Also the impact of clusters is shown in terms of $CO_2$ emissions and finally the author evaluated the potential number of synergies for the largest cluster in the database using the matrix of generic cases from the EPOS project (EPOS project, 2019h; Mendez-Alva, De Boever, et al., 2021).

*Clustering overview (size, countries and sectors)*

In order to understand the structure of the clustering results,

Figure 2.6 shows the size of the identified industrial clusters, with only 8 clusters having more than 20 installations (data points). A prominent outlier in western Germany with 103 data points is shown on the right side of the figure.

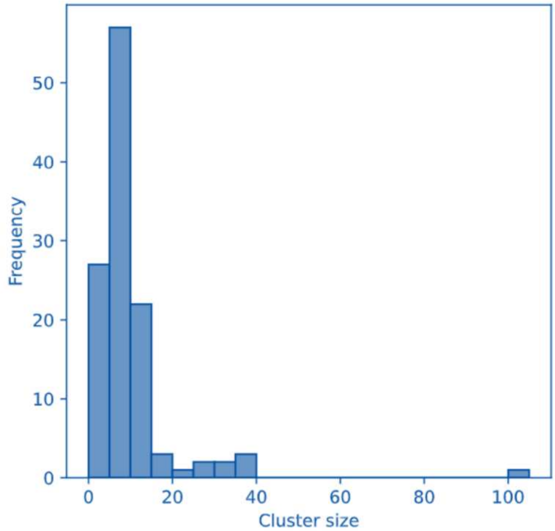



Figure 2.6 Frequency of cluster sizes, showing an outlier with more than 100 datapoints in Western Germany.

Figure 2.7 shows the number of clusters per country. Clusters that span over multiple countries are added to each country individually. The figure shows a distribution disparity between western and eastern Europe.

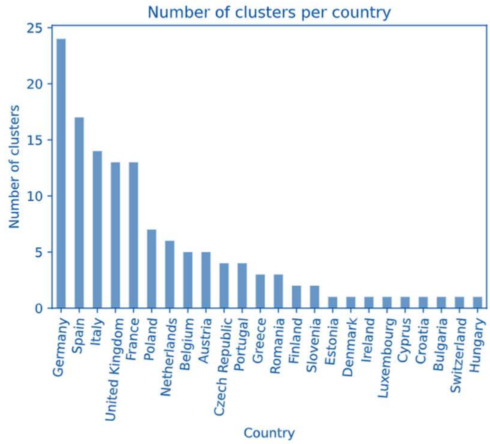



Figure 2.7 Distribution of clusters per country, evidencing a disparity between western and eastern Europe.

The largest number of clusters is found in Germany (24), followed by Spain (17), Italy (14), the UK (13) and France (13). Some smaller western European countries have only one cluster, in some cases even involving installations in other countries. It is noted that the dataset is a subset of the total industrial facility population, thus the actual number may be higher considering sites beyond the subset reported in the database.

Table 2.2 shows the number of industrial sites clustered per industrial activity and the total number of sites corresponding to each activity in the database. Facilities in aluminium and electricity production, and in manufacturing of cement, lime or plaster all show a relatively low percentage of clustering. They return an average between 45% and 60%, whilst the petrochemical sector scores higher with more than 70% clustering.

Table 2.2 Clustering per industrial type, showing some sectors with 100% of their installations in clustered (glues, industrial gases, man-made fibres, ceramic products and precious metals).

| Industry Type | Amount clustered | Total | Percentage clustered |
|---|---|---|---|
| **Aluminium production** | 21 | 45 | 47% |
| **Copper production** | 3 | 9 | 33% |
| **Extraction of natural gas** | 2 | 16 | 13% |
| **Lead, zinc and tin production** | 5 | 7 | 71% |
| **Manufacture of basic iron and steel and of ferro-alloys** | 97 | 159 | 61% |
| **Manufacture of cement** | 165 | 366 | 45% |
| **Manufacture of dyes and pigments** | 6 | 7 | 86% |
| **Manufacture of fertilisers and nitrogen compounds** | 15 | 31 | 48% |
| **Manufacture of glues** | 1 | 1 | 100% |
| **Manufacture of industrial gases** | 25 | 25 | 100% |
| **Manufacture of lime and plaster** | 65 | 110 | 59% |
| **Manufacture of man-made fibres** | 2 | 2 | 100% |
| **Manufacture of mortars** | 1 | 1 | 100% |
| **Manufacture of other ceramic products** | 1 | 1 | 100% |
| **Manufacture of other chemical products n.e.c.** | 4 | 8 | 50% |
| **Manufacture of other inorganic basic chemicals** | 47 | 65 | 72% |
| **Manufacture of other organic basic chemicals** | 77 | 99 | 78% |
| **Manufacture of plastics in primary forms** | 16 | 24 | 67% |
| **Manufacture of refined petroleum products** | 94 | 130 | 72% |
| **Manufacture of synthetic rubber in primary forms** | 1 | 2 | 50% |
| **Other non-ferrous metal production** | 1 | 2 | 50% |
| **Precious metals production** | 1 | 1 | 100% |
| **Production of electricity** | 453 | 807 | 56% |

*Urban clusters*

The addition of European urban zones and cities shows to increase the clustering opportunities. The number of clusters goes from 92 to 119 clusters, implying 254 additional industrial facilities clustered, but also indicating that industrial facilities are located close to cities. Therefore, the addition of urban parameters is proven useful for the data analysis, offering the potential for exploring and exploiting urban-industrial symbiosis.

Table 2.3 shows clustered cities per country. The algorithm groups about 40% of the cities. The higher numbers are for densely populated countries like Belgium and the Netherlands, with over 65% of the cities clustered. Countries with low population and industrial density, like Norway and Sweden, show limited to no cities clustered.

Table 2.3 Overview of the clustered cities per country, showing the countries with the highest percentage of cities clustered (Belgium, Germany, the Netherlands, etc.).

| Country | Number of cities | Number of cities clustered | Percentage clustered |
|---|---|---|---|
| **Belgium** | 8 | 6 | 75% |
| **Germany** | 81 | 57 | 70% |
| **Netherlands** | 25 | 17 | 68% |
| **Cyprus** | 3 | 2 | 67% |
| **Spain** | 61 | 37 | 61% |
| **Austria** | 5 | 3 | 60% |
| **Greece** | 10 | 6 | 60% |
| **United Kingdom** | 96 | 56 | 58% |
| **Ireland** | 2 | 1 | 50% |
| **Slovenia** | 2 | 1 | 50% |
| **Portugal** | 17 | 7 | 41% |
| **France** | 74 | 30 | 41% |
| **Italy** | 46 | 16 | 35% |
| **Czech Republic** | 6 | 2 | 33% |
| **Croatia** | 4 | 1 | 25% |
| **Denmark** | 4 | 1 | 25% |
| **Poland** | 30 | 6 | 20% |
| **Switzerland** | 10 | 2 | 20% |
| **Finland** | 6 | 1 | 17% |
| **Romania** | 24 | 4 | 17% |
| **Hungary** | 13 | 2 | 15% |
| **Bulgaria** | 8 | 1 | 13% |
| **Estonia** | 2 | 0 | 0% |
| **Georgia** | 1 | 0 | 0% |
| **Iceland** | 1 | 0 | 0% |
| **Latvia** | 1 | 0 | 0% |
| **Lithuania** | 4 | 0 | 0% |
| **Luxembourg** | 1 | 0 | 0% |
| **Malta** | 1 | 0 | 0% |
| **Norway** | 2 | 0 | 0% |
| **Slovakia** | 5 | 0 | 0% |
| **Sweden** | 13 | 0 | 0% |
| **Ukraine** | 1 | 0 | 0% |

*Carbon dioxide emissions*

Using $CO_2$ emission data from E-PRTR a pro-rata comparison was made showing the percentage of total $CO_2$ emissions per country in blue and the percentage of industrial installations clustered in the country in red (

Figure 2.8). The Benelux region heads the table with the highest number of groups, indicating the high potential of the region for developing hubs. The figure clustered $CO_2$ emissions per country. 100% in the red bar indicates that all the data points of the corresponding country were clustered. 100% in the blue bar represents the emission of the clustered installation for that country.

France and Germany have a similar profile. In France only 56% of the data points are clustered (red), although that percentage accounts for 77% of the total $CO_2$ emissions. Germany highlights 90% of total $CO_2$ emissions clustered compared to 77% clustered data. This indicates that most large emitters in these countries have the potential to articulate hubs for gaining value from emissions.

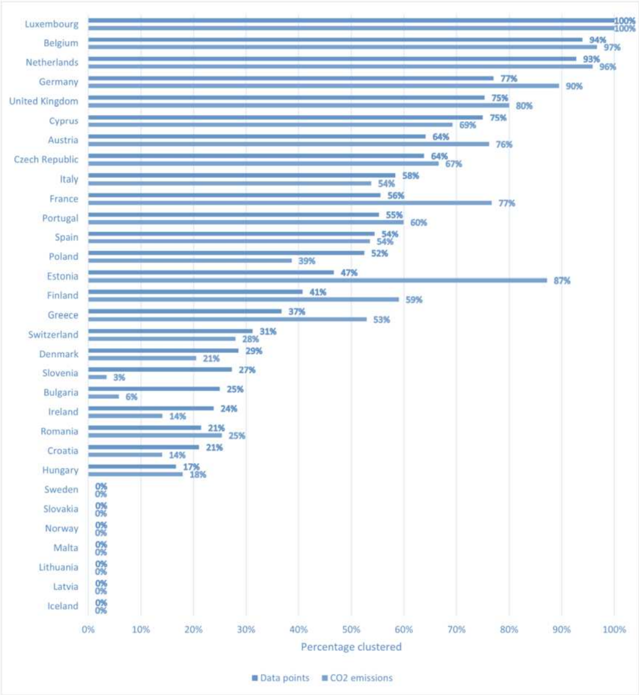



Figure 2.8 Clustered $CO_2$ emissions per country, indicating the top countries with clustered installations (Luxemburg, Belgium, the Netherlands, Germany, etc), and the corresponding share of $CO_2$ emissions for the clustered installations (blue bar).

It is observed that the largest $CO_2$ emitters in western Europe are clustered (indicated by the colours in Figure 2.9 and per country in

Figure 2.8), while most eastern European large emitters are not (indicated in black on the map). Also, in southern Europe, various large emitters are seen to be isolated. Such regional differences indicate that the hubs for the circularity concept is likely to vary from region to region.

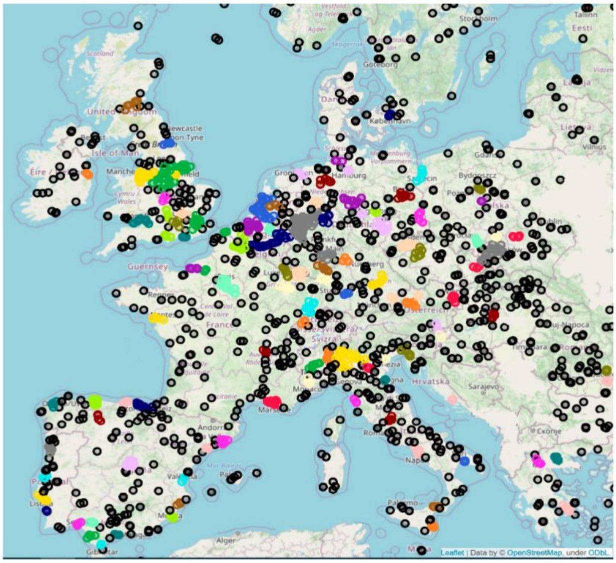


Figure 2.9 DBSCAN clustering with radius 25 km and 5 minPoints, where hubs are indicated with colours (non-clustered installations with black).

*Potential synergies*

To finalise, the cross-sectoral symbiosis matrix from H2020 EPOS project (EPOS project, 2019h) was used to roughly estimate the number of potential collaborations between industries of different sectors. The matrix was applied to the western Germany cluster, showing that for several sector combinations, numerous industrial symbiosis opportunities were highlighted. 408 cross-sectoral combinations were identified based on the EPOS generic cases (method in section 2.2.5) between sites in the chemical and steel sectors, each combination having 17 different IS cases. Table 2.4 gives a full overview of the cases per sector pair and the total number of cases in western Germany (cluster #39 in the database).

Table 2.4 Synergies overview for the western Germany cluster using the generic IS matrix.

| Sector combination | Number of potential synergies | Number of cross-sectoral combinations |
|---|---|---|
| **Chemical-District** | 8 | 576 |
| **Chemical-Steel** | 17 | 408 |
| **Steel-District** | 8 | 408 |
| **Chemical-Mineral** | 7 | 144 |
| **Mineral-District** | 2 | 144 |
| **Chemical-Cement** | 16 | 120 |
| **Cement-District** | 7 | 120 |
| **Steel-Mineral** | 6 | 102 |
| **Steel-Cement** | 15 | 85 |
| **Cement-Mineral** | 8 | 30 |

This way to quantify the number of potential synergies is the first step towards identifying symbiosis opportunities between different industries in a cluster. The analysis was performed by using a simplified matrix that did not include all relevant sectors nor all potential cases. The author recommends a more elaborated matrix with more cases and sectors to yield a more realistic synergy potential per industrial facility as well as per cluster as a whole.

## *2.4* H4C concept further development

In this section, the clustering results are compared with the outcomes of the H2020 projects and discussed in view of implementing hubs for circularity. Non-technical factors that are critical to the development of industrial hubs are examined.

### 2.4.1 BENCHMARKING CONCEPTS

In the EPOS project, a first attempt was made to map the potential for industrial symbiosis in the process industry in Europe using a geographical base (EPOS project, 2019i). This approach was further developed in the (SCALER project, 2020a), leading to a map of 100 synergy cases involving 18 industrial sectors operating across Europe.

A first point of comparison concerns the distance between sites for successful symbiosis. The average distance between coupled sites in SCALER was around 1 000 km. Geographical density levels were used in a radius of 100 km computed by GIS software, arguing that such distance was still within the local transport standards for materials trading (SCALER project, 2020a). The clustering method proposed in this study enables a flexible selection of distances, currently set at 25 km but allowing for shorter or longer distances. With a 25 km distance, around one-third of the emissions do not correspond to clustered facilities for 2017 (Appendix 2-A). This indicates that higher distances are convenient to enable a higher emission reduction potential using clustering strategies. Additionally, the proposed method ensures a minimum number of sites in the selected distance, which enhances the possibilities for exchange.

The SCALER study identified several areas of high industrial density based on the number of sites within a 100 km radius: Benelux, western Germany, northern France, northern Italy, Valencia-Castellon in Spain and the UK Midlands. These regions were also detected with DBSCAN, meaning that sites are also surrounded by at least four other sites in a radius of 25 km. Since the E-PRTR database has a central role in both studies, similar results were expected, however, the DBSCAN method also enabled the identification of clusters of diverse geometry at different regional scales. Such clusters often have a connection with geographical presences such as ports, rivers, capital cities, etc. Clusters with similar geographical features can often capitalise on similar strategies to develop a more efficient hub implementation. In Figure 2.5, the algorithm identifies the dark blue cluster along the Maas River flowing from Belgium to the Netherlands.

In terms of industrial symbiosis, the SCALER results present a broader top-down approach while this study enables a more local bottom-up approach. The SCALER project mapped 39 synergies involving 18 sectors at the European and regional level, missing the local cluster level. In this study, a more focused approach was used mapping 20 synergies covering 5 sectors for a specific cluster. Such approach can be used to explore the potential of cross-sectoral collaboration in any other cluster, complementing the results of SCALER and providing a specific methodology and database to support further research that promise relevant benefits for the regional development. According to the broader SCALER study, the potential benefits are situated in around 22 billion euros of added value, 5 billion euro of added tax, 230 000 new direct jobs, 11.5 billion euros in savings related to waste management and 2.5 billion $m^3$ of water saved (SCALER project, 2020a). In addition, the symbiosis implementation would save around 91 million tons of $CO_2$ (SCALER project, 2020a).

A fundamental remark towards both the SCALER and the current study is the database used to identify hubs. E-PRTR lists installations in terms of energy and emissions, but there is still a significant number of industrial installations not included due to a smaller size or lower level of energy or carbon intensity (SCALER project, 2020a). These industrial sites need also to be considered, especially in regions with lower industrial densities, i.e., when large installations seem to be in isolation. Smaller companies could find business opportunities in the concentration of resources from larger installations. Also, small companies could facilitate collaboration and thus help create the industrial ecosystem needed to form a hub for circularity, supporting, for example, the link to cities.

Regions with a high density of industrial activity can develop superior levels of energy and material efficiency; however, this is subject to contextual factors. A Japanese study, based on spatial econometrics for paper and cement industries, indicates that there are not only sectoral variations related to the effects of industrial density but also a diversity of factors that may lead to positive and negative effects at an increasing industrial concentration (Tanaka & Managi, 2021). Some symbiosis studies and projects such as EPOS include contextual factors beyond techno-economic assessments, including legal, spatial and social aspects (EPOS project, 2019a), thus acknowledging the relevance of non-technical factors. In order to develop hubs for circularity, industrial density should only be considered as starting point; additional critical factors should be taken into account to assess the implementation and the impact of hubs for circularity.

### 2.4.2 RANKING OF CLUSTERS WITH AN INDUSTRIAL SYMBIOSIS INDEX

The resulting clusters can be ranked considering an index (equation 1) that integrates their production capacity and the diversity of sectors involved. The index is based as an indication for economies of scope and scale in symbiosis taking into account (Akar et al., 2022; M. Morales et al., 2021). Economies of scale increase symbiosis potential due to the volume of resources available, meaning that the larger the production site, the higher the possibilities to develop economies of scale in symbiosis. Economies of scope increase the symbiosis potential based on the diversity of industries in a region, opening the range of options for valorising waste and by-products. Based on economies of scale, the potential for symbiosis is relatively higher in regions with higher production. On the other hand, economies of scope can develop in regions producing a diverse output (multiple sectors) (Walls & Paqin, 2015).

Equation 1 IS index for clusters

$$IS\ index\ for\ cluster\ i = \sum_{sector\ j}^{n_i} \frac{Cluster\ production_j}{Max\ production_j}$$

$Cluster\ production_j = Production\ (kt) of\ sector\ j\ in\ cluster\ i$

$Max\ production_j = Highest\ production\ (kt)\ of\ sector\ j\ accros\ all\ clusters$

$$n_i = number\ of\ sectors\ in\ cluster\ i$$

The index was successfully applied in the AIDRES project for the selection of the demo cases for symbiosis in the database (VITO et al., 2022).

### 2.4.3 CE-IS STRATEGIES FOR THE PROCESS INDUSTRY

The European Waste Hierarchy Framework Directive (European Commission, 2008), in combination with the original Ladder of Lansink (Lansink, 2017), offers a basic approach for developing an implementation framework for circularity in hubs. Such a framework does not only set a preference default for projects but also enables the identification of specific symbiosis cases tailored for process industries.

Theoretical circular economy frameworks tend to be comprehensive, involving as many sectors as possible. They range from the original 4Rs strategy (reduce, reuse, recycle, recover) to more than 12Rs (European Commission, 2020a). Some R-verbs mainly apply to end-users of specific products and thus have minor relevance to industry. On the other hand, more implementation-oriented approaches limit the number of strategies to a minimum. A good example is the 3Rs strategy from the UN in the Asian-Pacific region to promote sustainability principles (United Nations, 2013).

Ramsheva used the Ellen MacArthur's 'Circular economy system diagram' to illustrate the link of IS partnerships to the CE for the cement sector only, including 11 cases (materials, heat, alternative fuels, among others) in three main categories (reuse, pre-consumer and end-consumer recycle), without integrating the categories into a specific framework for the industry (Ramsheva, 2021). Gerres et al. proposed an industrial categorisation approach based on an input-output model (process inputs, improvements and outputs) combined with the type of resources in systems (feedstock, energy carrier, information) in order to identify different categories for reducing carbon emissions (Gerres et al., 2019). However, this approach does not support priority orientation compared with other frameworks such as the Ladder of Lansink.

This study proposes a simple frame for the European process industry based on the 4Rs strategy. In Figure 2.10, industrial sectors are represented with a dual role as source and sink of resources. For each sector, the 4Rs strategy is defined in view of incentivising circularity.

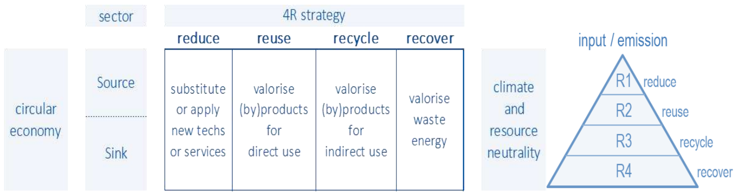



Figure 2.10 Circular economy strategies for the process industry, indicating a simple framework to design implementation strategies.

At the top of the ladder, to **reduce** resource inputs and emissions, industries can jointly invest in renewable energy production or engage in shared infrastructure or services. To **reuse** materials, by-products and bio-based feedstock play a significant role in replacing virgin inputs. To **recycle**, mechanical and/or chemical reprocessing of waste streams is required, with steel, glass and plastics as key examples. Finally, to recover energy, heat cascading, upgrading and conversion are considered with the use of alternative fuels from materials that would otherwise be discarded. Among key abatement areas across sectors are recycling of primary materials, flue gas recycling, alternative feedstock, bio-waste use, (green) hydrogen, heat recovery and Combined Heat and Power (CHP), added with monitoring and control strategies, and including potential product substations (Gerres et al., 2019).

The reduce priority (R1) requires technological breakthroughs to enable unprecedented energy, materials and emissions efficiency. It may also lead to substantiating the demand for service approaches for end-products, such as repairing, refurbishing, remanufacturing and repurposing business strategies across multiple product categories (construction materials, renewable energy infrastructure, etc.), developing new materials that cope with such demand while maintaining economic, environmental and social responsibility. R1 strategies enable circularity with virtually any sector, from process industries to urban centres with innovation ecosystems of small to medium-sized enterprises (SMEs).

A CE framework for the process industry requires a cascading approach at multiple levels. The foundation industries provide the basic materials for virtually any product society demands. Such industries require energy- and resource-intensive processes. Therefore, the focus of the process industry should be on applying the 4Rs strategy on energy and materials to enable closing loops (Figure 2.10). The application of circularity strategies in the process industry starts within a site or sector (internal optimisation), then continues with close partners such as other process industries or also communities in geographical proximity to establish energy or material loops. In the circular economy, the idea of closing loops refers to the broader re-valorising of discarded/underused streams. This includes post-consumer products and their components in close distance to the 'waste' source (EMF, 2015; Stahel, 1982), under the assumption that such re-valorisation can be more efficient and effective considering local advantages and needs. When the application of the 4R strategy is not feasible at the level of post-consumer products (level 1 in

Figure 2.11) or product components (level 2), effective valorisation options may be found at the level of basic materials (level 3) and energy content (level 4) in the process industry (L4 and L3)—applying such circularity cascading promises to develop more effective and efficient pathways toward carbon neutrality, avoiding a significant fraction of new infrastructure costs and energy demand (Agora Energiewende, 2022).

Figure 2.11 4Rs strategies: First and second levels should be assessed before applying Rs strategies to levels of process industries.

Also, the different regions demand differing implementation strategies towards hubs for circularity in Europe. The variation between west and east Europe, and also north and south, offer the possibility to use strategies for deployment in broader regions with similar characteristics. To reduce (R1), a primary example is northern Europe with opportunities for hubs related to wind energy, while in the south, the potential is more on the use of solar energy applications for their industrial profiles, making use of joint investment schemes for shared infrastructure. In western regions, the high density of industrial facilities might enable innovation based on spatial proximity, developing pilot projects and taking advantage of the many R&D centres in the region and global energy innovation trends (Elsevier, 2021). On the other hand, scattered facilities in eastern Europe may trigger development policies to transfer technology and innovation, developing hybrid hubs for innovation. They could also expand their network to actors that do not match the E-PRTR database, such as SMEs of high relevance due to their diversity and flexibility. Such regions may also advance top-down approaches promoted by the regional governments to create conditions for circularity. In that sense, invigorating changes in the waste legislation could be an enabler for hub development, and when integrated with energy and emissions directives, even towards a broad implementation of the circular economy.

### 2.4.4 COMPARING OPTIONS FOR IMPLEMENTATION

With the aim of implementing circularity centres, a set of enabling frameworks is discussed.

A starting option is the ETS Innovation Fund framework from the European Commission. The fund requires a series of sequential steps, each with success criteria. The stages run from proof of concept to pilot plant, then commercial demonstration, and finally scale up and roll out of a technology (European Commission, 2019b). Such a scheme could be used to launch specific symbiosis projects in the scope of hubs for circularity, although the scheme misses the critical collaboration aspects essential to the development of hubs.

A symbiosis readiness level frame was developed based on the technology readiness level scheme (Directorate-General for Research and Innovation (European Commission) & Sommer, 2020). It includes aspects of collaboration, such as the relevance of the partners in the proof-of-concept phase and their indication of interest at an early stage. The maximum readiness level is a resilient partnership, keeping the collaboration priority until the last stage (Directorate-General for Research and Innovation (European Commission) & Sommer, 2020).

Former SPIRE projects developed implementation tools focusing on barriers and enablers. For industrial symbiosis in process industries, the EPOS project used the LESTS scores to assess and identify progress at three levels (region, cluster and resource) across five different dimensions: legal, economic, spatial, technical and social incentives (EPOS project, 2019j). Similar approaches have been developed based on risk identification related to internal and external factors in the domain of non-technological aspects for symbiosis (J. D. Henriques et al., 2021). Such methods aim to develop mitigation actions that increase the potential for success of the project.

In the CARBON4PUR project, a two-stage methodology is outlined towards implementing and replicating symbiosis cases related to $CO_2$ utilisation (Barascu et al., 2021). The first stage covers hard criteria: a regional selection is based on specific preconditions that can be qualitative (partners and resource types) or quantitative (proximity, resource flows quantities). In the second stage, soft criteria are added, developing a better understating of the context in physical and societal terms. This stage considers, for example, access to finance, skilled workforce, supporting institutions, regional market profile, local entrepreneurial culture and public support policies. Similarly, the CarbonNext project proposes a framework for a fully integrated and intensified value chain (DECHEMA, 2017). Five main components are considered: synergy (what is exchanged), physical aspects (distances, infrastructure, etc.), legislation, public support and economic aspects. Both approaches take into account factors that support the selection of regions; therefore, they can be helpful in the planning and implementation of hubs for circularity. It is argued that the use of multiple IS platforms is convenient due to the multiple goals and life stages of symbiosis projects (Barile et al., 2021).

### 2.4.5 CONCLUSION ON THE USE OF DATA CLUSTERING METHODS FOR H4C

The hubs for circularity concept, introduced by the P4Planet partnership, is a key pillar of Europe's roadmap towards achieving the circular and climate objectives in the Green Deal. Hubs for circularity aim to bring urban and industrial stakeholders together to create collaborations through urban-industrial symbiosis. The development of such hubs facilitates the practical implementation of resource and climate neutrality by exchanging materials, waste streams, energy and more. This chapter provided an attempt to identify locations for hubs based on urban-industrial symbiosis centred around energy-intensive industries. By comparing different clustering methods and validation schemes, it was concluded that the DBSCAN algorithm provided core insights to identify potential hubs for circularity in Europe.

The study has laid the foundation for developing a flexible tool that provides relevant data on industrial clustering and industrial symbiosis potential in Europe. When elaborated further, the tool could support and accelerate the implementation of hubs for circularity in Europe. Expanding the dataset with more industrial sectors and a wider variety of streams and exchanges can be considered a next step towards an enhanced map of potential hubs. Further research could focus on integrating a machine-learning algorithm to include affinity parameters beyond distance and the number of surrounding points (Davis & Aid, 2022). Although obtaining the required data is recognised as the basic challenge, the digital revolution across industries looks promising to identify further opportunities for developing circularity solutions (Barile et al., 2021).

# CHAPTER 3 IS CASE-BASE: INDUSTRIAL SYMBIOSIS PROFILES IN ENERGY-INTENSIVE INDUSTRIES

Chapter 3 transitions from the regional clustering level (chapter 2) to a case-by-case approach discussion of technical synergies for cross-sectoral industrial symbiosis. This chapter embeds the article: 'Industrial symbiosis profiles in energy-intensive industries: sectoral insights from open databases' (Mendez-Alva, Cervo, et al., 2021), published in the Journal of Cleaner Production.

The study explores IS databases and proposes the concept of a case-base for industrial symbiosis with its corresponding methodology for key selected sections in the process industry: chemicals, cement and steel. The chapter is complemented with research on the matchmaking of energy and material streams (section 4.4) for IS, based on the research developed in the scope of the EPOS project (EPOS project, 2019a).

## *3.1 INDUSTRIAL SYMBIOSIS IDENTIFICATION TOWARDS CROSS-SECTOR PROFILES*

The key aspect of sustainability in IS refers to establishing multidimensional synergies across different industries. Such synergies can be economical, social, or environmental, as emphasised in recent European projects and studies (SCALER project, 2020; EPOS project, 2019). The economic synergies result from the generation of marketplaces for underused resources creating revenue streams and cost savings (Albino & Fraccascia, 2015). The social impact often refers to generating jobs and enhancing relationships with communities surrounding the industries. This is of special relevance for urban industrial symbiosis, fulfilling mainly infrastructure needs of urban areas related to energy and material flows (European Commission, 2019a; Ažman Momirski et al., 2021). In terms of environmental performance, the synergy point lies in material and emissions efficiencies promoting resource conservation and avoiding associated environmental impacts (Axelson et al., 2021). A recent bibliographical study with a selection of more than 600 articles over a period of 30 years (Mallawaarachchi et al., 2020) proves that the sustainability of material and energy interactions has been central to the concept. IS has been expanded extensively in the last five years to include non-material resources, contextual factors (cultural, political, spatial, etc.), and the impact of externalities.

Resource efficiencies towards effective environmental impact reduction are not always granted. Studies have shown that circular economy rebound effects (Zink & Geyer, 2017), symbiotic rebounds (Figge & Thorpe, 2019), and additional by-product processing needs (Mohammed et al., 2018) may prevent the translation of resource efficiencies into environmentally friendly options. Thus, the assessment of IS opportunities at different stages of IS projects is required, from the initial identification to the ongoing documentation (Maqbool, Alva, et al., 2019; Yeo et al., 2019). The database collection developed in the present study focuses on the first stage of identifying sustainable cases for IS, where a first screening of the sustainable impact due to links among sectors is presented.

This chapter aims at integrating successful approaches from state-of-the-art projects and IS database research to perform an exploratory analysis of industrial symbiosis in key industrial sectors by making use of public IS databases and using standard classifications for industrial activities (e.g., NACE), resources categories, and selected statistics. The objective is to conceptualise and apply industrial sector profiles for IS in terms of cross-sectoral collaborations. Such profiles specify the role a sector plays in the synergy, the partnership and the resources involved. They also define what technologies could enable IS and help to provide insights on the sustainability of the cases.

In the following section, methodological aspects are detailed, such as the definition of sector profiles, the approach to IS in the context of data processing, the selection and validation process for IS cases, and the method for categorising exchanges. In section 3, the results are presented per sector in terms of categories of exchanged resources and partnering sectors, including a focus on the interlinks between sectors, the related technologies, and sustainability insights per sector. In section 4, a discussion is raised about missing links among process industries, next to a broader perspective of sustainability in IS cases. The section includes the learnings gained by developing the IS profiles and working with public databases; such learnings are integrated into a new method for continuous improvement. Finally, section 5 presents overall conclusions summarising the main research findings and indicating further research lines.

## 3.2 METHOD TO DEVELOP IS PROFILES AND INSIGHTS FROM DATABASES

The process to develop sector profiles from IS database collections is illustrated in Figure 3.1. It starts with sector standardisation, which consists of three sub-steps: selection of industrial sectors (chemicals, steel, or cement), selection of a suitable standard code for economic activities (NACE for Europe), and definition of the sectors in the selected code. The next stage concerns the selection of IS database collections. The MAESTRI knowledge depository (Benedetti et al., 2017; Evans et al., 2017) is used as the central collection as there currently is no other suitable semi-standardised IS database. The EPOS generic cases (EPOS project, 2019) and the SCALER synergies (SCALER project, 2020c) are supplementary references. In the next stage, the findings are validated, with consistency checks and clustering of terms taking place. This results in sector profiles that specify the role a sector plays in the synergy, the partnership, and the resources involved in the IS case. In the final stage, cross-sectorial links are made in terms of technologies and sustainability, as explained in the following sections.

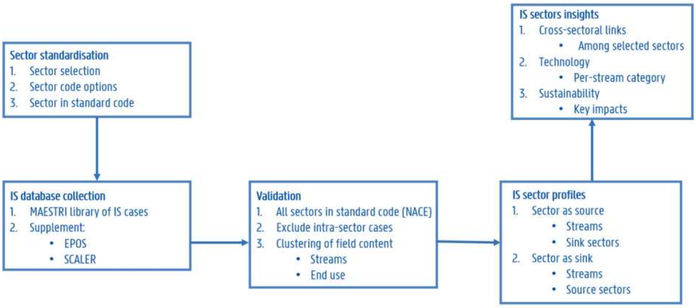



Figure 3.1 Sector profile generation scheme to define and present IS for EIIs.

### 3.2.1 SECTOR STANDARDISATION

The first step of the methodology is sector standardisation. Industrial IS actors are grouped per the corresponding sector according to NACE codes to enable the use of relevant databases (MAESTRI). For the cement and steel sectors, single NACE codes are available and are C2351 and C2410, respectively, while for the chemicals sector, several NACE codes are used (C19, C20, C21, C22) based on the work of Cervo (2020). Urban districts or cities were included as a sector without a standard code (Not Applicable or NA).

### 3.2.2 IS DATABASE COLLECTION

The second step of the methodology is the IS database collection. A systematic comparison of public access IS databases (Jato-Espino & Ruiz-Puente, 2020) highlighted that the MAESTRI project collection (Evans et al., 2017) could be used as the main source of information due to its completeness and traceability. The MAESTRI database contains 424 binary synergy cases (two sectors per case) and provides a structure using standardised schemes (NACE, European waste codes, among others) with clearly linked references. This database was designed as a tool for systematic filtering of cases to promote IS among companies (Benedetti et al., 2017). The selection criterion was to include publicly reported cases already labelled as industrial symbiosis to promote IS solutions by mimicking existing cases and extending their replication potential (Benedetti et al., 2017).

The MAESTRI database provided a starting point. It was filtered for the NACE codes of the selected sectors, which led to 210 cases. Additional cases were included following the MAESTRI's selection criterion to fill the gaps among sectors across the different resource categories, amounting to 252 cases in total (Appendix A). In particular, 16 binary cases were added from the EPOS generic cases and 26 more cases were taken from the SCALER dataset. In this study, the tool is used to build a database of cases, a so-called case-base suited for developing insight on IS at a sector level, not only by bringing statistical analyses but also by understanding drivers and barriers related to exchanges among sectors in terms of technology and sustainability. Table 3.1 provides a general overview of the databases.

Table 3.1 Collected IS databases characteristics. They share the common goal of replication of IS cases across Europe.

| Project | Goal | Regional scope | Date | Sectors per case | # Cases | # Selected cases | Reference |
|---|---|---|---|---|---|---|---|
| **MAESTRI Library** | EU replication | World | 2017 | 2 | 424 | 210 | Evans et al., 2017 |
| **EPOS IS case watch** | EU replication | Europe | 2019 | 3-5 | 21 | 16 | EPOS project, 2019 |
| **SCALER 100 synergies dataset** | EU replication | Europe | 2019 | 2 | 100 | 26 | SCALER Project, 2020 |

As compared to the MAESTRI database, which has no geographical restriction, the EPOS case collection was developed for specific industrial clusters and technologies in Europe (EPOS project, 2019). Similarly, SCALER 'synergy types' aim at replication and add a deeper level of techno-economic assessment plus an environmental appraisal (SCALER project, 2019). The three databases together bring variety to the aggregated database and enhance the IS identification capacity.

### 3.2.3 VALIDATION

The third step of the methodology is the validation of the collected cases. The MAESTRI database (Evans et al., 2017) included NACE codes for each IS case. A revision of the codes was done for the cases involving chemicals, steel, and cement industries. A resource category was developed grouping streams from different sectors. A first category was called 'energy', grouping sub-functions such as heating & cooling, fuel substitution (for heat generation), and electricity where its generation takes place as part of the synergy. Other streams were categorised as 'by-product' or 'waste', both functioning as (raw) material inputs. The waste category refers to any other material input with a specific European Waste Code as defined in the MAESTRI database. As the final category, 'water' was chosen despite the fact that water streams often have simultaneous functions as energy or by-product. However, when a specific use of water was reported in the synergy with energy use (heating or cooling), the stream was classified in the energy category.

The following method was used to classify each stream (across cases) into the above categories:

1. Is the stream substituting an energy input (heating/cooling/fuel/electricity) in the reported IS case?
    - Yes: Classify as Energy.
    - No: Go to 2.
2. Does the stream involve mainly water?
    - Yes: Classify as water.
    - No: Go to 3.
3. Does the stream have a waste code?
    - Yes: Classify it as waste.
    - No: Classify as a by-product (ranked by sender/status before the symbiosis happens).

Finally, a consistency check of terminology was performed for resource types, stream names, sector allocations, and references.

For the present research, IS cases are exclusive collaborations between different sectors; therefore, intra-sectoral cases are not included as part of the validation. Chertow et al. (2008) made a distinction between industrial symbiosis activities occurring in two types of systems: single industry-dominated clusters and multi-industry ones. They pointed out that in the latter, most activities are done in isolation. However, due to the variety of resource inputs and outputs, there may be a high potential for symbiosis, as evidenced in the Kalundborg model. Therefore, it is crucial to focus on cross-sectorial collaborations to enhance industrial exchanges.

### 3.2.4 SECTOR IS PROFILES

The fourth step of the methodology is the creation of sector profiles. Binary synergy models are used to represent industrial symbiosis and organise case studies (Figure 3.2). In such models, each sector can have two roles for the other sector: either as a source or a sink for a specific stream. A source role implies the supply of a stream to the other sector; a sink role receives a stream from the other sector. To emphasise a network approach, the terms 'sink' and 'source' for sectors were selected, reflecting different methods for optimising networks of resources (Kastner et al., 2015).


Figure 3.2 Synergy model: Industrial sector as a resource source and as a sink.

Therefore, the IS profile of a sector represents the collection of streams and partnering sectors based on case frequency. The profile is dual due to the binary model for IS roles: a sector can operate from both sides of an IS case, as a source or as a sink.

### 3.2.5 SECTOR IS INSIGHTS

The fifth and final step of the methodology consists of analysing the relations across sectors in terms of enabling technologies and sustainability insights.

The first objective is to specify the synergies among the main sectors of analysis: chemicals, steel, and cement. A matrix (Table 3.3), including the three sectors complemented with urban district profiles, is built to clarify any connection and identify the type of relation in terms of role (source, sink, or both).

Secondly, enabling technologies refer to the technical processes that act upon the streams to enable symbiosis. Such technologies can be as simple as transport needs or as complex as implementing emerging processes at scale, such as installing carbon capture units.

Lastly, technology aspects are closely related to the sustainability insights of the different cases. Relevant insights in the results section are developed in the context of IS identification in relation to the central resource to the synergy and the technology. The insights aim to screen a sustainable case.

## *3.3 IS PROFILE PER SECTORS, TECHNOLOGY, AND SUSTAINABILITY*

Results are presented with a top-down approach, starting in section 3.3.1 with the overview of the IS profiles of the main sectors. In section 3.3.2, a more in-depth sector-by-sector analysis is done for chemicals, steel, cement, and urban districts, respectively.

### 3.3.1 OVERVIEW PER SECTOR

Table 3.2 gives an overview of the sector profiles in terms of role (sources or sinks) and stream category (energy, waste, by-product, water).

Table 3.2 EIIs sector profiles overview. Each sector has a dual role (source and sink) across four resource categories.

| Sector | Role | %* | # IS cases per category | | | | Number partnering sectors |
|---|---|---|---|---|---|---|---|
| | | | **Energy** | **Waste** | **By-product** | **Water** | |
| **Chemicals** | Source | 44% | 18 | 8 | 26 | 15 | 23 |
| | Sink | 56% | 32 | 29 | 19 | 7 | 23 |
| **Steel** | Source | 72% | 15 | 36 | 6 | 3 | 14 |
| | Sink | 28% | 5 | 13 | 2 | 3 | 6 |
| **Cement** | Source | 19% | 5 | 3 | 3 | 0 | 7 |
| | Sink | 81% | 7 | 33 | 4 | 3 | 16 |
| **Urban** | Source | 69% | 2 | 16 | 0 | 4 | 6 |
| | Sink | 31% | 8 | 1 | 0 | 1 | 3 |
| ***% of IS cases for which the sector has the corresponding role** | | | | | | | |

A total of 252 synergy cases were categorised as waste, energy, by-product, and water. 41% of these cases concern waste, 27% energy, 21% by-product, and 11% water.

In the **waste** category, the most frequent streams are slag from steel furnaces (Appendix A), followed by waste plastics and fly ash streams. The most frequent **by-product** exchanges are carbon dioxide, hydrogen, and sludge with a strong participation of the chemicals sector.

In the **energy** category, heating networks and co-generation (electricity) cases are the most frequent. Heating and cooling processes account for 60% of the energy cases while electricity synergies represent 21%, involving chemical, steel, cement, aluminium, energy, and paper sectors in co-generation schemes. The remaining cases (19%) relate to the use of alternative fuels, making use of fuel gas, industrial waste, and packaging waste. Finally, **water** streams that are not related to energy processes are not frequent but still reported as process water.

Table 3.3 presents the links and gaps in terms of IS roles (sink or source) of the main sectors among themselves. In the table, the reference sector is either a sink or a source for the specific resource category in the header (waste, energy, by-product, and water). For example, chemicals is a waste sink for steel, cement, and urban districts, and also a source for synergies with cement. Table 3.3 shows gaps when there are no reported links between sectors for a specific category. The only gap common to all sectors is for valorising by-products in urban districts. This may be related to the legal status of by-products, an aspect that is further discussed in section 4.1.

Table 3.3 Main EIIs sectors have a role for each resource category. The sectors make synergies as a sink or source among themselves except for urban districts in terms of by-product cases.

| Reference sector | Waste | Energy | By-product | Water | Partnering sector |
|---|---|---|---|---|---|
| **Chemicals** | sink | both | both | both | Steel |
| | both | both | source | source | Cement |
| | sink | both | - | both | Urban |
| | | | | | |
| **Steel** | source | both | both | both | Chemicals |
| | source | both | sink | source | Cement |
| | both | source | - | sink | Urban |
| | | | | | |
| **Cement** | both | both | sink | sink | Chemicals |
| | sink | both | source | both | Steel |
| | sink | both | - | sink | Urban |
| | | | | | |
| **Urban** | source | both | - | both | Chemicals |
| | both | sink | - | source | Steel |
| | source | both | - | source | Cement |

## 3.3.2 IS SECTOR PROFILE

In this section, the IS sector profiles are presented with a higher level of details in terms of partnering sectors and resources used in the synergies.

### 3.3.2.1 Chemicals sector profile

Out of the 252 cases analysed (Appendix 3), the chemicals sector is involved in 154 of them (61%). This already highlights the key role of the chemical industry in implementing IS as this sector is able to transform and valorise a large variety of materials. **Table 3.4 and**

**Table 3.5 respectively display the results of the IS database analysis for the chemicals sector as a sink and as a source.**

Table 3.4 Chemicals sector profile, as a sink, has most frequent IS cases with energy supply, steel, and non-ferrous metal sectors.

| Sector | NACE | Energy | Waste | By-product | Water | Total cases |
|---|---|---|---|---|---|---|
| Electricity, gas, steam, and air conditioning supply | D35 | 19 | 0 | 0 | 4 | 23 |
| Manufacture of basic iron and steel and of ferro-alloys | C2410 | 6 | 4 | 3 | 1 | 14 |
| Other non-ferrous metal production | C2445 | 0 | 3 | 9 | 0 | 12 |
| Manufacture of pulp, paper, and paperboard | C1710 | 2 | 4 | 1 | 0 | 7 |
| Urban district | NA | 1 | 2 | 0 | 1 | 4 |
| Manufacture of cement | C2351 | 2 | 1 | 0 | 0 | 3 |
| Manufacture of sugar | C1081 | 0 | 2 | 1 | 0 | 3 |
| Growing of non-perennial crops | A0110 | 0 | 2 | 0 | 0 | 2 |
| Cutting, shaping and finishing of stone | C2370 | 0 | 0 | 2 | 0 | 2 |
| Distilling, rectifying, and blending of spirits | C1101 | 0 | 2 | 0 | 0 | 2 |
| Processing and preserving of fish, crustaceans, and molluscs | C1020 | 0 | 1 | 1 | 0 | 2 |
| Raising of other animals | A0149 | 0 | 1 | 0 | 0 | 1 |
| Water collection, treatment, and supply | E360 0 | 0 | 1 | 0 | 0 | 1 |
| Mixed farming | A0150 | 0 | 1 | 0 | 0 | 1 |
| Manufacture of paper and paperboard | C1712 | 0 | 1 | 0 | 0 | 1 |
| Aluminium production | C2442 | 1 | 0 | 0 | 0 | 1 |
| Manufacture of beer | C1105 | 0 | 1 | 0 | 0 | 1 |
| Manufacture of jewellery and related articles | C3212 | 0 | 0 | 1 | 0 | 1 |
| Manufacture of soft drinks; production of mineral waters and other bottled waters | C1107 | 0 | 1 | 0 | 0 | 1 |
| Production of electricity | D3511 | 0 | 0 | 0 | 1 | 1 |
| Manufacture of veneer sheets and wood-based panels | C1621 | 1 | 0 | 0 | 0 | 1 |
| Manufacture of food products | C108 | 0 | 0 | 1 | 0 | 1 |
| Growing of perennial crops | A0120 | 0 | 1 | 0 | 0 | 1 |
| Manufacture of other non-metallic mineral products | C230 0 | 0 | 1 | 0 | 0 | 1 |
| **Total cases** | | **32** | **29** | **19** | **7** | **87** |

Table 3.5 Chemicals sector profile, as a source, has most frequent IS cases with energy supply, cement, and non-ferrous metal sectors.

| Sector | NACE | By-product | Energy | Water | Waste | Total cases |
|---|---|---|---|---|---|---|
| Electricity, gas, steam, and air conditioning supply | D35 | 3 | 10 | 7 | 0 | 20 |
| Manufacture of cement | C2351 | 2 | 3 | 1 | 1 | 7 |
| Other non-ferrous metal production | C2445 | 4 | 0 | 1 | 0 | 5 |
| Manufacture of pulp, paper, and paperboard | C1710 | 3 | 0 | 1 | 0 | 4 |
| Aluminium production | C2442 | 3 | 0 | 0 | 0 | 3 |
| Manufacture of basic iron and steel and of ferro-alloys | C2410 | 1 | 1 | 1 | 0 | 3 |
| Treatment and coating of metals | C2561 | 3 | 0 | 0 | 0 | 3 |
| Manufacture of prepared feeds for farm animals | C1091 | 0 | 0 | 0 | 2 | 2 |
| Manufacture of soft drinks | C1107 | 1 | 1 | 0 | 0 | 2 |
| Growing of vegetables and melons, roots, and tubers | A0113 | 1 | 1 | 0 | 0 | 2 |
| Production of electricity | D3511 | 2 | 0 | 0 | 0 | 2 |
| Urban district | NA | 0 | 1 | 1 | 0 | 2 |
| Growing of cereals (except rice), leguminous crops, and oil seeds | A0111 | 0 | 0 | 1 | 1 | 2 |
| Waste treatment and disposal | E3820 | 0 | 0 | 1 | 0 | 1 |
| Manufacture of plaster products for construction purposes | C2362 | 1 | 0 | 0 | 0 | 1 |
| Mining of chemical and fertiliser minerals | B0891 | 0 | 0 | 1 | 0 | 1 |
| Mining support service activities | B99 | 1 | 0 | 0 | 0 | 1 |
| Water collection, treatment, and supply | E3600 | 1 | 0 | 0 | 0 | 1 |
| Other processing and preserving of fruit and vegetables | C1039 | 0 | 0 | 0 | 1 | 1 |
| Other business support service activities | N8299 | 0 | 1 | 0 | 0 | 1 |
| Manufacture of macaroni, noodles, couscous, and similar farinaceous products | C1073 | 0 | 0 | 0 | 1 | 1 |
| Mixed farming | A0150 | 0 | 0 | 0 | 1 | 1 |
| Manufacture of articles of concrete, cement, and plaster | C236 | 0 | 0 | 0 | 1 | 1 |
| **Total cases** | | **26** | **18** | **15** | **8** | **67** |

Among the 154 cases, circa one third (34%) involves the exchange of energy, over one quarter (29%) by-products, another quarter (24%) waste, and the remainder (13%) the exchange of water.

The energy sector (D35) exchanges most with the chemical industry, both from a source and sink side. This does not come as a surprise since chemical plants are highly energy-intensive and operate with power stations providing the utilities required to run the processes (Cervo, 2020).

Due to the wide variety of applications in the chemicals sector, a further fragmentation of the sector is shown in Figure 3.3 according to the previously selected NACE codes. Inorganic chemicals (C2013), petroleum products (C19), and fertilisers (C2015) are the most frequent segments within chemicals.

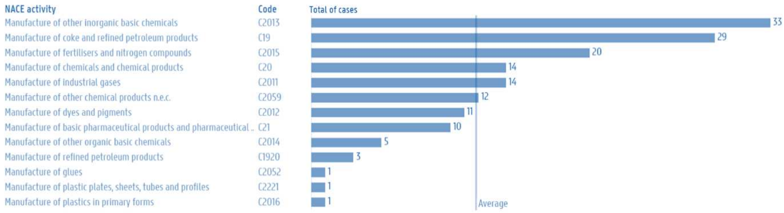



Figure 3.3 Chemicals segmentation for IS: Main chemical processes according to NACE activities include inorganic chemicals (C2013), petroleum products (C19), and fertilisers (C2015).

Considering the **chemicals sector as a sink**, one notices that the majority of exchanges (37%) involves energy. This is mostly explained by the tight relationships between the chemical industry and energy sectors (D35), as previously mentioned (mostly heat), but also by some interesting synergies with the steel sector (C2410) sending steam for heating purposes. Additionally, the chemical industry also receives many waste streams (33% of the sink exchanges), illustrating the capability of the chemical industry to transform waste into useful resources. Chemicals has also a growing number of by-product synergies with non-ferrous metal industries (C2445), since the streams have significant amounts of valuable metals for the chemical processes.

The manufacturing of other inorganic basic chemicals (C2013) is also frequently receiving streams (Appendix A). This can be explained by the fact that this category represents a multitude of chemical processes able to handle different types of streams (energy, by-product, and waste) and especially the multiple synergies with metal industries to recover the value from sludges and emissions. Also, the manufacturing of fertilisers (C2015) is one of the chemical processes that can take in a variety of wastes, such as organic residues, sludge, and sulphur (Appendix A). Last but not least, one can also notice specific exchanges, such as the valorisation of the gases produced during the steelmaking process by the chemical industry (Appendix A). These gases contain chemicals such as carbon monoxide or hydrogen that are readily used to synthesise new molecules (Bazzanella & Ausfelder, 2017).

Looking at the **chemicals sector as a source**, it is observed that the majority of exchanges (39%) relates to by-products. However, no particular industrial sector (except D35) is preferably receiving streams from the chemical industry. This phenomenon can be explained by the fact that the chemical industry is involved in the value chain of many different industries as it produces the building blocks that are used to manufacture new products. Some symbioses are also worth noticing (Appendix A), such as the use of carbon dioxide (produced by the chemical industry) by alumina refineries (C2442) to produce lime, which is used as an additive in the chemical process to improve product quality and reduce energy consumptions (Arıkan et al., 2019). Other promising cases include the use of $CO_2$ streams for mineralisation with applications that promise to keep the $CO_2$ in use for a longer term in the mineral (EPOS project, 2019), the steel (Huijgen et al., 2005), and the cement sectors (Huntzinger et al., 2009). Another interesting symbiosis is the recovery of hazardous by-products, such as caustic soda and hydrochloric acid, by galvanic treatment plants (C2561).

The **chemical industry** is typically involved in symbiotic relationships with urban areas. Chemical processes either produce or use heat (exo- or endothermic reactions) and thus can function as a heat sink or source for nearby cities or industrial clusters. This presents opportunities for either industrial steam networks or direct district heating networks. A textbook example of such a synergy is the Kalundborg eco-industrial park in Denmark, where a refinery is providing heat to the city (Jacobsen, 2006; Symbiosis Institute, 2019). In such network, pressurised water is often used as a medium to carry the heat from the chemical plant to the city, which also explains why the chemical industry can be seen as a source of water for urban districts.

Overall, the results indicate that IS and recycling waste have been part of the chemical industry's core business. The profile of the chemicals sector for symbiosis is very versatile. The chemical industry is used to partner with other sectors, such as energy providers or engineering companies, to be more resource-efficient and increase their performance. Furthermore, the chemical industry can process a large variety of materials and can play a significant role in advancing IS. However, this will require efforts to standardise streams involved in mutually beneficial exchanges, such as by defining quality standards and enabling new markets (CEFIC, 2020b; Elser & Ulbrich, 2017).

### 3.3.2.2 Steel sector profile

The steel sector is involved in 83 exchanges out of the 252 in the database (33%). Traditionally **steel has a strong source profile** providing slag and steam (waste heat) to other sectors. From Appendix A, the steel sector as a source is confirmed with 60 cases in total, prominently covering traditional resources. Table 3.6 shows that steel as a source primarily enables waste (36 cases) and energy (15 cases). The main sectors involved as sinks for steel streams are cement (C2351), chemicals (various), and other non-ferrous metal sectors (C2445). Overall, the steel sector is involved in waste exchanges, mainly supplying blast furnace slag and coke oven gas. In the cement sector, the use of steel slag has become common practice, while the use of steel streams in the chemicals sector brings new uses for steel residues (Giorgian, 2019; RESLAG project, 2015).

Table 3.6 Steel sector profile, as a source, has most frequent IS cases with cement, chemicals, and non-ferrous metal production sectors added with the urban district.

| Sector | NACE | Waste | Energy | By-product | Water | Total cases |
|---|---|---|---|---|---|---|
| Manufacture of cement | C2351 | 12 | 1 | 0 | 1 | 14 |
| Manufacture of other inorganic basic chemicals | C2013 | 4 | 5 | 0 | 0 | 9 |
| Other non-ferrous metal production | C2445 | 4 | 0 | 3 | 0 | 7 |
| Urban district | NA | 1 | 6 | 0 | 0 | 7 |
| Manufacture of other non-metallic mineral products | C2300 | 7 | 0 | 0 | 0 | 7 |
| Construction of roads and motorways | F4211 | 4 | 0 | 0 | 0 | 4 |
| Electricity, gas, steam, and air conditioning supply | D35 | 0 | 2 | 0 | 1 | 3 |
| Manufacture of coke and refined petroleum products | C19 | 0 | 0 | 2 | 0 | 2 |
| Manufacture of articles of concrete, cement, and plaster | C236 | 2 | 0 | 0 | 0 | 2 |
| Agriculture, forestry, and fishing | A01 | 1 | 0 | 0 | 0 | 1 |
| Construction | F4200 | 1 | 0 | 0 | 0 | 1 |
| Manufacture of fertilisers and nitrogen compounds | C2015 | 0 | 0 | 1 | 0 | 1 |
| Manufacture of chemicals and chemical products | C20 | 0 | 0 | 0 | 1 | 1 |
| Manufacture of industrial gases | C2011 | 0 | 1 | 0 | 0 | 1 |
| **Total cases** | | **36** | **15** | **6** | **3** | **60** |

Table 3.7 shows the **steel sector as sink** with 23 cases. Steel consumes waste (13 cases) mainly from urban districts (11 cases). Most energy synergies are with energy supply (3 cases). The few by-product synergies are with other EIIs (2 cases) and water again with urban districts. The main sectors involved as a source are urban districts, energy (D35), and cement industries (C2351), together with chemicals (various). Steel is a circular sink for waste steel in other sectors (4 cases), next to accepting waste plastics and home appliances (Appendix A). The increased collection and use of steel scrap promises to play a key role for the sector in the transition to a circular economy (Axelson et al., 2021).

Table 3.7 Steel sector profile, as sink, has most frequent synergies with urban district, energy supply, and chemicals sectors.

| Sector | NACE | Waste | Energy | Water | By-product | Total cases |
|---|---|---|---|---|---|---|
| Urban district | NA | 11 | 0 | 2 | 0 | 13 |
| Electricity, gas, steam, and air conditioning supply | D3500 | 0 | 3 | 0 | 0 | 3 |
| Manufacture of chemicals and chemical products | C20 | 0 | 1 | 1 | 1 | 3 |
| Manufacture of cement | C2351 | 0 | 1 | 0 | 1 | 2 |
| Aluminium production | C2442 | 1 | 0 | 0 | 0 | 1 |
| Manufacture of basic metals | C2400 | 1 | 0 | 0 | 0 | 1 |
| **Total cases** | | **13** | **5** | **3** | **2** | **23** |

According to Table 3.6 and Table 3.7, as also summarised in Table 3.3 for the main EII sectors, the **steel sector** has links with chemicals, cement, and urban districts mainly as a source of useful waste. A typical synergy is the use of steel by-products for construction materials in nearby urban areas. Steel is also a source of valuable waste for the chemicals and cement sectors (RESLAG project, 2015). For cement, the supply of steel slag is a typical synergy, while for chemicals, there are innovative applications that require additional research (Kriskova, 2013). Steel is also a source of energy for chemicals, cement, and cities, enabling heating networks. The energy integration with cement by establishing heating networks is an option highlighted in the EPOS project (EPOS project, 2019a), either as a direct exchange or by developing economies of scale to upgrade the heating profile for power production (Pili et al., 2020).

Thanks to the processing capacity in its furnaces, the sector is a sink for by-products from cement and chemicals. Steel industries not only make use of the energy recovery strategies, material reuse also adds new properties to the steel products (Plastics Europe AISBL, n.d.). The steel sector often utilises urban waste containing steel (World Steel, 2019). Finally, there are links between the steel sector and urban districts for energy to improve district heating (Li et al., 2016; Schweiger et al., 2019) and water cases (Colla et al., 2017; Li et al., 2016; Schweiger et al., 2019), the sector having roles both as a source and sink for synergies.

#### 3.3.2.3 Cement sector profile

The cement sector is involved in 58 cases of the 252 cases in the database (23%). Cement has a long tradition as a sink for secondary materials, exchanging mostly with steel. Table 3.8 shows that cement is a resource sink in 47 cases, valorising waste from different industries. Involved sectors are steel (C2410) and energy supply (D35), followed by urban districts and chemicals (C20). Cement is often a sink for furnace slag, fly ash, next to waste plastics (Appendix A). The concept of co-processing waste has been key in cement industries to keep a competitive position and establish sustainable business relationships with other sectors (Güereca et al., 2015).

Table 3.8 Cement sector profile, as sink, has most frequent IS cases with steel and energy supply sectors added with the urban district.

| Sector | NACE | Waste | Energy | By-product | Water | Total cases |
|---|---|---|---|---|---|---|
| Manufacture of basic iron and steel and of ferro-alloys | C2410 | 12 | 1 | 0 | 1 | 14 |
| Electricity, gas, steam, and air conditioning supply | D35 | 4 | 1 | 0 | 0 | 5 |
| Urban district | NA | 3 | 1 | 0 | 1 | 5 |
| Manufacture of chemicals and chemical products | C20 | 0 | 3 | 1 | 1 | 5 |
| Aluminium production | C2442 | 2 | 0 | 1 | 0 | 3 |
| Manufacture of paper and paper products | C1711 | 3 | 0 | 0 | 0 | 3 |
| Manufacture of food products | C108 | 1 | 0 | 1 | 0 | 2 |
| Other non-ferrous metal production | C2445 | 2 | 0 | 0 | 0 | 2 |
| Extraction of crude petroleum and natural gas | B6000 | 1 | 0 | 0 | 0 | 1 |
| Mining of coal and lignite | B5000 | 1 | 0 | 0 | 0 | 1 |
| Manufacture of coke and refined petroleum products | C19 | 1 | 0 | 0 | 0 | 1 |
| Waste collection, treatment, and disposal activities; materials recovery | E3800 | 0 | 1 | 0 | 0 | 1 |
| Manufacture of other organic basic chemicals | C2014 | 0 | 0 | 1 | 0 | 1 |
| Manufacture of pulp, paper, and paperboard | C1710 | 1 | 0 | 0 | 0 | 1 |
| Manufacture of basic metals | C2400 | 1 | 0 | 0 | 0 | 1 |
| **Total cases** | | **33** | **7** | **4** | **3** | **47** |

The higher relevance of the **cement sector as a sink,** as shown in Table 3.8, may be related to the high capability of energy and material recovery inherent to the manufacturing process of cement. Evidence of this is that as a sink, most of the synergies are related to material recovery based on waste, followed by the energy synergies where the use of alternative fuels is frequent. Such internal capability leaves little space for supplying under-used resources to other industries. However, a main issue of cement is the $CO_2$ production from non-combustion processes (Naims, 2016). The potential of such abundant underused resource is currently being explored in pilot projects (LEILAC project, 2020).

The profile of the **cement sector as a source** of resources is quite limited, with only 11 cases, as shown in Table 3.9. The cement sector is a source of energy (5 cases), waste (3 cases), and by-product (3 cases). The main sectors involved are energy supply (D35) and steel (C2410) together with chemicals (C20).

Table 3.9 Cement sector profile, as source, has most frequent IS cases with the energy supply, steel, and chemicals sectors.

| Sector | NACE | Energy | Waste | By-product | Total cases |
|---|---|---|---|---|---|
| Electricity, gas, steam, and air conditioning supply | D35 | 1 | 0 | 1 | 2 |
| Manufacture of basic iron and steel and of ferro-alloys | C2410 | 1 | 0 | 1 | 2 |
| Manufacture of chemicals and chemical products | C20 | 2 | 0 | 0 | 2 |
| Manufacture of articles of concrete, cement, and plaster | C236 | 0 | 1 | 1 | 2 |
| Manufacture of other non-metallic mineral products | C2300 | 0 | 1 | 0 | 1 |
| Urban district | NA | 1 | 0 | 0 | 1 |
| Manufacture of dyes and pigments | C2012 | 0 | 1 | 0 | 1 |
| **Total cases** | | **5** | **3** | **3** | **11** |

According to Table 3.8 and Table 3.9, as also summarised in Table 3.3 for the EIIs, the **cement sector** has links with chemicals, steel, and urban districts in terms of waste, mainly as a sink. Cement has strong links with chemicals enabling waste networks among the sectors (Jassim, 2017; Moreno-Maroto et al., 2017), based on the transformative capacity of both sectors. For this same reason, cement is a sink for waste from steel and urban districts (De Beer et al., 2017). Cement serves as a source and sink of energy, with urban districts mainly using district waste as fuel and providing heating services (IPP, 2013). Finally, in terms of by-products, the sector is a sink for chemicals with potential for $CO_2$ related synergies (Leeson et al., 2017).

### 3.3.2.4 Urban district profile

The urban profile is a collection of exchanges to and from facilities in cities (12% of the total cases). **Urban districts are mostly involved as a source** of resources, supplying waste (16 cases), water (4 cases), and energy (2 cases), as shown in Table 3.10. The main industrial sectors involved as sinks are steel (C2410), cement (C2351), and chemicals (various). Districts supply waste plastics, waste steel, and discarded home appliances as the most frequent cases.

Table 3.10 Urban district profile, as source, has most frequent IS cases with steel and cement sectors.

| Sector | NACE | Waste | Water | Energy | Total cases |
|---|---|---|---|---|---|
| Manufacture of basic iron and steel and of ferro-alloys | C2410 | 11 | 2 | 0 | 13 |
| Manufacture of cement | C2351 | 3 | 1 | 1 | 5 |
| Manufacture of chemicals and chemical products | C2000 | 1 | 0 | 0 | 1 |
| Manufacture of refined petroleum products | C1920 | 0 | 0 | 1 | 1 |
| Manufacture of coke and refined petroleum products | C19 | 1 | 0 | 0 | 1 |
| Manufacture of chemicals and chemical products | C20 | 0 | 1 | 0 | 1 |
| **Total cases** | | **16** | **4** | **2** | **22** |

**Districts have a limited profile as a sink** for resources, as shown in Table 3.11. However, a typical case relates to energy, where district heating networks integrate waste heat from EIIs. Water synergies are also relevant concerning water treatment infrastructure linked to several industrial facilities (Appendix A).

Attention is drawn to the low number of cases reported for renewable energy synergies despite the fact that such cooperative interactions have the potential to advance wind or solar energy projects, as some studies suggest (Butturi et al., 2019).

Table 3.11 Urban district profile, as sink, has most frequent IS cases with steel and chemicals sectors.

| Sector | NACE | Energy | Water | Waste | Total cases |
|---|---|---|---|---|---|
| Manufacture of basic iron and steel and of ferro-alloys | C2410 | 6 | 0 | 1 | 7 |
| Manufacture of basic pharmaceutical products | C21 | 1 | 1 | 0 | 2 |
| Manufacture of cement | C2351 | 1 | 0 | 0 | 1 |
| **Total cases** | | **8** | **1** | **1** | **10** |

## 3.3.3 CROSS-SECTOR PROFILE INSIGHTS

In this section, insights focused on symbiosis across sectors, using relevant technologies per category and building from cases that are common to the various IS profiles. The second part (3.3.2) presents the sustainability insights following the same categorical approach.

### 3.3.3.1 Insights with focus on technologies

This section analysed what technologies are most commonly applied in the above cases. The technologies are addressed at a higher level in terms of stream categories: energy, by-product, waste, and water; they apply to all sectors for both internal optimisations and symbiosis with others.

The by-product and waste categories share the same technologies; the distinction is dictated by legal rather than technical motivations. The technology reviews done in the European IS projects EPOS and SCALER are suitable for gaining insights on technical IS opportunities (EPOS project, 2019d; Azevedo et al., 2019).

*Energy technology options*

There are three types of energy synergies: heating & cooling, alternative fuels (primarily waste streams from other sectors with high caloric value), and electricity. Most of the 70 energy cases have a focus on waste heat symbiosis due to the wide range of temperature profiles in the process industry. Generic technologies to build cross-sector solutions have been highlighted in the EPOS and SCALER projects (Azevedo et al., 2019; EPOS project, 2019d), going from basic pinch point analysis to implementing absorption heat pumps or thermo-compressing processes to improve heating networks. Alternative fuel technologies can be subdivided according to the aggregation state of the stream: solid and non-solid. For solid streams, technology options are grate, fluidised bed, and rotary kiln incinerators. For non-solid waste, there are two general options: fuel cells and combustion engines (EPOS project, 2019d). A key limitation to use alternative fuels is that fuels often have an additional function as raw material that cannot be directly replaced (e.g., coke in steel furnaces). The upgrade of heat streams towards electricity production in co-generation systems is an alternative that takes place depending on the regional electricity market and the on-site capabilities of the sector. Examples of enabling technologies are Organic Ranking cycles and Kalina cycles (EPOS project, 2019d). Renewable electricity can also be sourced from wind turbines or photovoltaic panels at site, cluster, or regional levels (EPOS project, 2019).

Figure 3.4 summarises a non-exhaustive list of technologies. For further details on energy-related IS technology options and models, reference is made to the EPOS tech-watch (EPOS project, 2019d).

*By-product and waste*

Waste and by-product categories involve 156 cases. In terms of technology options, both categories are grouped as one because, in a circular economy, both can be reused as raw materials in other sectors. A frequent technological challenge in this regard is the purification of the stream and the separation of specific components as often only one substance (such as $H_2$, $CO_2$, etc.) or fraction in the stream is valuable for the other industry. Specific technologies and processes for each type of material are required to purify and separate the valuable fractions. Different levels of technological complexity apply depending on the process flexibility and product specifications. Some solutions are directly applicable, e.g., in case of only logistic needs, while others require multi-step mechanical and chemical processing (EPOS project, 2019d; Viganò et al., 2020).

In the database, the most frequent stream is slag from the steel industry. Slag from blast furnaces is used as a cement clinker substitute. Also, the alumina rich slag can be used directly in primary aluminium manufacturing through chemical processing (Azevedo et al., 2019). The mineral properties of slag enable its direct use as raw material, but depending on the end-use, the slag stream may require additional technologies (Azevedo et al., 2019). Streams rich in $CO_2$ are another key example, where calcium looping is one of the technology options to enable the sequestration of carbon emissions in the entire process industry (EPOS project, 2019d). Depending on the source and the specifications of the $CO_2$ stream (coal plant, cement kilns, steel furnaces, refineries, etc.), different options to capture and treat $CO_2$ apply such as pre-combustion integrated gasification combined cycle, vacuum pressure swing absorption (PSA), and amine-based solvent capture (Naims, 2016). It is believed, though, that this is an innovation area of key development and demonstrations in the next decade.

Another example is hydrogen as part of coke oven gas from steel, requiring PSA technology to reach the high levels of purity required in the chemical industry (Azevedo et al., 2019). The list of technologies can be as extensive as the number of streams considered. A case-by-case evaluation is required to define which technological option suits best the situation for each waste and by-product stream.

*Water synergies*

Finally, water synergies cover 26 cases. More efficient use of water sources is achievable through better water management, e.g., by recovery of water streams onsite, by integrating technologies for purification and optimal utilisation of available wastewater streams. Here too, separation and purification processes are key. There are mechanical, physicochemical, and biological techniques for the treatment of wastewater. Depending on the type of pollution, a combination of options may be required. In the case of sludge treatment, methanation, liquid waste incineration, and advanced systems for control, monitoring, and management can be considered to use sludge as alternative fuel options. Mechanical separation options range from filtration to electrocoagulation, while physicochemical techniques vary from chemical precipitation to electrolysis. Main biological techniques cover anaerobic filters and anaerobic membrane bioreactors (EPOS project, 2019d).

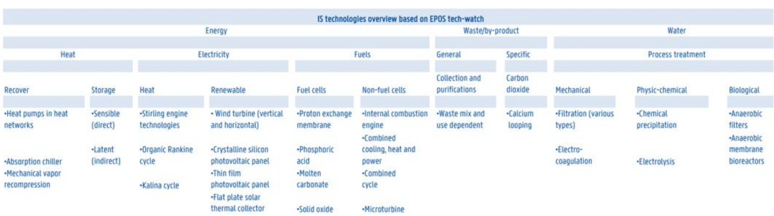



Figure 3.4 Overview of technologies for chemicals, steel, and cement sectors synergies.

### 3.3.3.2 Insights with focus on sustainability

This section presents critical sustainability aspects from different IS cases grouped per resource category. The insights focus on the environmental part of sustainability in terms of primary resource preservation and emission reduction.

For the **waste** category, circularity is the crucial sustainability driver. Substitution of raw materials such as minerals, metals, or plastics with under-used (by-)products avoids the extraction or use of additional primary resources. Such substitution may require different levels of reprocessing or reformulation, but it is understood that the higher the level of reprocessing, the most likely the sustainability aspects (both environmental and socio-economic) become uncertain (Figge & Thorpe, 2019; Mohammed et al., 2018). Therefore, the sustainability screening focuses on direct synergies that require no or low processing to allow for the synergy to take place.

A typical example has been given above when discussing the valorisation of steel slag in the cement industry (EPOS project, 2019c; Van Oss, 2015). Between 100-300 kg of slag is produced per tonne of steel, of which a significant fraction is used in the cement industry and an increasing fraction in the chemicals sector. Such substitution enables reductions in waste disposal cost and also generates an emission reduction of 0.3-0.6 tonne of $CO_2$ per tonne of slag substituting raw materials. Another example is the valorisation of coke in steam crackers. Further downstream, the use of waste plastic from industrial or residential sources as raw material for steel and cement industries is a promising raw material substitution with additional gains in energy due to a higher calorific value of the stream compared with traditionally used resources (EPOS project, 2019c). Another option in the waste category is the use of industrial inorganic residues enabling co-product valorisation in mineral and cement industries based on direct substitution (EPOS project, 2019c). Also, from the steel and chemicals sector, sludge and fly ash are potential streams to be used in the cement industry. Finally, urban sludge can be used as input for the cement industry; although it requires pre-treatment, it can substitute both raw materials and fuels. The range of IS cases substituting raw materials with under-used process streams is growing but still varies highly across sectors. The potential rises from 5% to 70% across the sectors such as chemicals, steel, minerals with engineering support (EPOS project, 2019), depending on the availability of supply and demand in the region and non-technical factors such as space available for storage, technological capability, economic conditions, support incentives, and social relevance (Maqbool et al., 2017; Van Eetvelde, 2018). The sustainability gains of valorising waste through industrial symbiosis lies in superior economic performance, lower demand for primary resources, and improved level of business relations in the cluster added with job creation.

For the **by-product** category, the sustainability advantage is similar to the waste category in the case of resource substitution. Often the difference lies in the concentration level of specific substances present in by-product streams. A keystream is $CO_2$, which is anticipated to become widely reused in a range of applications across industries, going from building blocks in the chemical industry over the use in fertiliser or mineralisation processes (EPOS project, 2019; CarbonNext project, 2018) to sequestration through enhanced oil recovery (EPOS project, 2019c). The potential valorisation and storage of captured $CO_2$ emissions from industrial processes ranges widely depending on the industry based on the process in place and the available technology options (CarbonNext project, 2018; IOGP, 2019; Naims, 2016). The energy recovery in $CO_2$ rich streams also plays a role in the sustainability performance of the synergy, as they frequently have high temperature levels. Cement kilns and blast furnaces in the steel sector are important sources that may well fit the chemicals opportunity to develop products with circular market demand (EPOS project, 2019c). In the EPOS project, hubs for upgrading captured $CO_2$ were proposed (EPOS project, 2019c) with a potential to reduce 20-40% of the treatment costs due to economies of scale. Overall, the sustainability gains of valorising by-products through industrial symbiosis are similar to those for waste streams lowering the demand for primary resources while reducing emissions and improving the level of business relations in the cluster.

In the **energy** category, the key substitution potential lies in primary energy resources having a final use for heating-cooling networks, electricity generation/use, and fuel switching. Related to heating networks, there is a potential to recover waste heat in the chemicals, steel, and cement sectors, leading to a reduction of energy consumption of 5-10% at the sector level (EPOS project, 2019b). In terms of alternative fuels (EPOS project, 2019c), savings of around 20-22 GJ per tonne of waste fuel are estimated for chemicals, steel, cement, and urban districts. For the steel industry, this corresponds to savings of 80-150 kWh of electricity per tonne of steel by turning waste heat into electricity (EPOS project, 2019c). The distance between plants remains a critical factor for heating networks (Bütün et al., 2019a; EPOS project, 2019c), balancing multi-site optimisation and conversion to electricity or for internal reuse. The sustainability gains of valorising under-used energy streams through industrial symbiosis lie in reaching economic opportunities that are not accessible without partners, unlocking the potential for non-traditional energy sources and developing business relations with additional stakeholders.

Finally, the **water** category refers to water networks that improve industrial water management. Water is a scarce resource, and optimal reuse of wastewater streams is evolving into common practice. By implementing water networks, there is a potential increase in efficiency of 10-50%, avoiding primary water sources (EPOS project, 2019c). In terms of common reuse of water, joint treatment facilities are known to advance the sustainable use of water among companies in an industrial park and in urban-industrial synergies. They create an economy of scale concerning building and operating the plants, generate lower demand on primary water and improve business relations across sectors (EPOS project, 2019c) .

Overall, the sustainability aspects in the IS cases focus on environmental performance. Economic impact estimations are often made, however, there are significant variations among sectors, regions and time periods that make a systematic comparison less suitable for the initial identification phase of IS. Social aspects are also mentioned in terms of potential growth, job creation and the creation of urban-industrial networks and communities. Again, such information is not detailed enough to distinguish between sector profiles, which is the aim of the present study.

## *3.4 LEARNINGS AND FUTHER DEVELOPMENT OF IS TOOLS*

The discussion of the analytic results presented above is held at three levels. The first-level focus lies on the gaps found in terms of synergies, technologies and sector classification. Secondly, the non-technological aspects of symbiosis projects and their sustainability gains are discussed from a management perspective. In a final section, the learnings are integrated into a method for continuous improvement of IS databases.

### 3.4.1 GAP ANALYSIS OF RESULTS

Three types of gaps are identified for enabling a better definition and further facilitation of cross-sector symbiosis in energy-intensive industries: synergy gaps, technology gaps, and sector classification gaps.

#### Synergy gaps

Table 3.3 helps to identify missing synergies across sectors at the level of stream categories while recognising the many symbiosis opportunities that are already explored. Still, it is observed that none of the process industry sectors has IS cases related to the use of by-products in urban districts. In terms of symbiosis with communities, most synergies refer to energy or waste streams (EWC code classified), but an apparent lack of urban reuse of industrial by-product streams is observed. This can be explained by the specificity of by-products from industry in the context of urban areas such as residential, commercial, and public facilities (roads, parks, etc.) (Kennedy et al., 2011; Lucertini & Musco, 2020), where a direct use may not be easy to find. Also, urban material streams, broadly categorised as urban waste, lack a valorisation step for potential reuse in industry. A promising option for further exploration is found in electronic waste from urban areas to be valorised in process industries such as chemicals and metal processing sectors (Wyns et al., 2018). Such urban-industrial symbiosis is considered to challenge the ability of cities and industries to join forces in driving the circular economy (European Commission, 2020b; A. SPIRE, 2018; EMF, 2015).

#### Technological gaps

The technology options presented in the results section show a representative list of existing options per category. However, innovation is challenging new technologies to emerge next to extending or improving the use of current technologies in order to tackle climate and resource neutrality. New tools and technologies to support IS cover energy grid optimisation and local clustering of renewable sources, as suggested in the EPOS project (EPOS project, 2019d). Grid optimisation refers to energy flexibility, buffering, and storage options, next to the implementation of digital energy signals. Local clustering refers to the generation and valorisation of renewable energy through joint investments. Typical examples are wind and solar energy to increase the availability of zero-carbon energy in a region, but hydrogen technologies and infrastructure also grow in importance and require local (public-)private partnerships to renovate and stimulate the hydrogen economy. Such options open the symbiosis scope to multiple sectors and invite service providers to facilitate joint action at industrial sites or even at a regional level. Synergies using such technologies are often not identified as IS cases due to issues to quantify the benefits for each party. To overcome this miss-out, a recent article on the technical viability of synergies proposes a three-step assessment method: compliance, characterisation, and feasibility (Dias et al., 2020). The methodology can be used to develop the technical aspects that characterise synergies and to evaluate the mutual sustainability gains resulting from the cases. Next to win-win allocation issues, other reasons for missing technologies as IS enablers are the critical time dependency and the complexity of many synergies. Here, however, the application of systems dynamics to IS cases is promising in its ability to open new opportunities for energy and waste technologies. Maqbool et al. (2019) investigated the dynamics and flexibility of wind energy integration using agent-based modelling to propose effective incentives at a policy level. Using a site-level approach, Norbert et al. (2020) developed systems dynamics frameworks for steel plants, enabling dynamic IS simulations for assessing environmental and economic benefits.

#### Classification gaps

Lastly, the use of NACE as a framework for IS classification shows advantages and disadvantages. Main advantages are the definition of the sectors in standard terms to connect with statistical databases such as EUROSTAT and get direct insights. The main disadvantage is the fixed layers of specificity that are not suitable for all cases or sectors. In the case of the steel sector, for example, the highest level of specificity includes the iron ore industry. Another observation is that the chemicals sector is difficult to categorise due to its diversity and the interconnectivity of many different sub-sectors. In this study, the base was taken from CEFIC (CEFIC, 2020a) added with oil refining since it is closely associated with petrochemical processing activities, processing of plastics, and others included in the four NACE codes chosen (C19, C20, C21, C22). Handling such issues requires developing a higher level of specificity for the industries in the cases collected, such that they can be easily adapted and grouped in sectors as required.

### 3.4.2 IS MANAGEMENT AND SUSTAINABILITY

The possibility to sustainably develop industrial symbiosis depends on internal and external factors that are often more complex than technology or engineering solutions. For such complexity, cluster management options gain priority. Before discussing the LESTS management approach for IS (Maqbool et al., 2017; Van Eetvelde, Delange, et al., 2005), the internal and external influences are described in this section.

Internal conditions for successful IS depend on many aspects such as a lead person in the company or a key entity in a cluster, available resources, existing infrastructure, economic incentives, technology pathways or breakthroughs, multi-party agreements, and many more. They need to be critically integrated into the sustainability assessment of the symbiosis in order to ensure that new synergies deliver socio-environmental performance next to mutual economic benefits.

External conditions refer to the potential to trigger rebound effects, for instance, due to the availability of competing materials for substitution or the abundance of traditional fossil fuel inputs (Sadik-Zada & Gatto, 2020). The rebound can be generated by the abundance or scarcity of alternative resources in terms of quantity or quality. This promotes or fails the full replacement of a primary resource and generates additional production/consumption along with an added environmental impact. A similar rebound effect can be triggered when secondary resources have lower or higher prices than the current market offers, which stimulates a higher level of consumption, again with a significant impact on the environmental gains (Figge & Thorpe, 2019; Zink & Geyer, 2017).

Both internal and external conditions need an evaluation per specific IS case to clarify the economic, environmental, and social benefits. Such a multi-level approach cannot be avoided in industrial symbiosis projects, but it faces the problem of fragmenting IS potential at specific levels, in casu the partnership, the entity/company involved, and the particular resource flow (Kerdlap et al., 2020; Maqbool et al., 2017).

A central challenge in addressing non-technological factors is their dependency on contextual elements, leading to a virtually unlimited range of drivers and pitfalls. At the level of sectors, it is useful to clarify specific domains or dimensions to map the motives and barriers for IS initiatives. A framework resulting from cluster management research is the LESTS approach (Maqbool et al., 2017; Van Eetvelde, Delange, et al., 2005) used to map legal, economic, spatial, technological, and social factors. Organised by resource category and sector profile, relevant factors can be registered to bring non-technical insights to the case in a systematic way. Any factor can drive or hamper a symbiosis option. A hampering legal factor for a specific under-used resource stream could be the complicated permit system for sending the resource to another legal entity. However, a legal driving factor could be the compliance with regional legislation to build a pilot for a carbon-neutral process or to receive carbon credits in cap and trade schemes such as EU-ETS (European Commission, 2015). A typical economic driver is a local or regional subsidy scheme but most often it is merely the profit gained from the IS optimisation. A spatial factor can be related to urban or regional planning but also to logistic availabilities of infrastructure such as storage facilities, which may stop or push synergies forward. Technological factors refer to the operational strategy and procedures in place in a company or city, e.g., towards recycling of critical materials. Finally, the social factors imply the interaction and trust among the parties within the industrial cluster but also include direct and indirect benefits to nearby communities. These can be measured in jobs or economic growth, in improved public health or general well-being. Communication and stakeholder engagement are fundamental social factors. The LESTS framework has proven to enable IS insights beyond technology or stream optimisation and allows us to build a more holistic database design in section 4.3. The LESTS information gathering can be organised in a matrix, as proposed in Table 3.12 illustrated with a simple example of single factors.

Table 3.12 LESTS factors enable the identification and management of non-technical factors. An example for a typical case is provided with case ID 1.

| Case ID | LESTS | Factor | Effect for the case (quantitative or qualitative) |
|---|---|---|---|
| 1 | Legal | Permit requirement | Time/effort spent to acquire permits for symbiosis |
| 1 | Economical | Rate of return | Enable negotiation among partners |
| 1 | Spatial | Space for new infrastructure | Enable initial feasibility of the project |
| 1 | Technology management | Expertise on-site | Time/effort spent to acquire permits for symbiosis |
| 1 | Social | Readiness to collaborate | Inclination to trust a partnership and enter the symbiosis clusters, including information flows and space for interaction |

The LESTS matrix can also be used as a tool for technology appropriation (Carroll, 2004), taking into account a panoramic assessment of the cluster and region to implement IS solutions. A critical factor for such solutions is the level of uncertainty associated with new technologies that may lead to unforeseen barriers. For such cases, the appropriation of technology may play a prominent role in clarifying the risks and opportunities involved in any IS project. Further research in this area can lead to the design and adoption of pilot technologies under the umbrella of the circular economy (A. SPIRE, 2019).

### 3.4.3 IS CASE-BASE FRAMEWORK

A further reflection on the methodology used in this chapter leads to a more general framework to develop IS databases, as shown in Figure 3.5. The IS case-base framework is envisioned as a continuous improvement cycle based on the Deming management cycle (Deming, 1982; Garza-Reyes et al., 2018), starting from setting the goals of the database to select IS schemes and running until all stakeholders obtain expected insights. The concept of an IS case-base refers thus to the product of such a cycle.

The cycle towards an IS case-base describes and summarises the learnings and recommendations obtained in working with most recent databases from successful EU projects focusing on main EIIs.

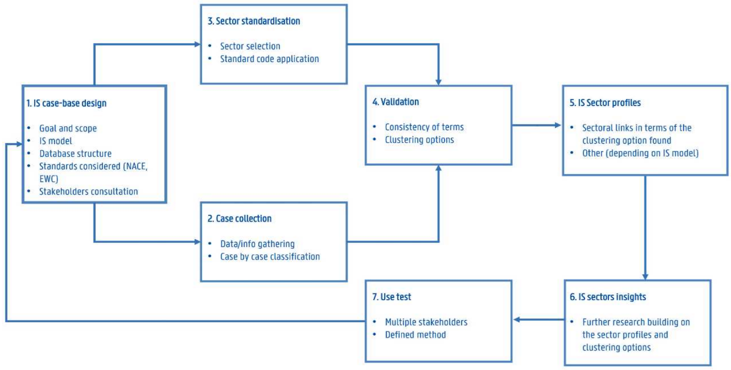



Figure 3.5 IS case-base framework: The improvement cycle reveals critical aspects for designing and collecting IS databases.

The first step is a structural IS case-base design. It has five elements. The *goal* & *scope* step is defined by the stakeholders expected to use the case collection. The next element is the IS *model* suitable to fulfil the expectations, including the selection criteria and case characterisation. The database *structure* is then defined by the IS model and clarifies the domains where *standards* play a role (sector, waste, LESTS aspects, etc.). The IS case-base design can be expanded to have additional elements depending on the goal & scope, the initial *consultation of stakeholders*, or the results of use tests in the final step of the cycle. As an illustration of this structural design, it is argued that the database in the MAESTRI project aimed to facilitate the identification of IS with a straightforward input/output approach. The objective was to promote IS solutions by mimicking existing cases to extend their replication potential (Benedetti et al., 2017). Comparing with MAESTRI, the EPOS collection was developed within the scope of specific industrial clusters and technologies in Europe but aimed at wider replication within the region. In a similar way, SCALER developed 'synergy types' or semi-generic synergies that aim for replication. Both projects provide a techno-economic assessment together with an environmental appraisal.

In the next step, the IS data collection and standardisation per sector are covered. In this step, the information is gathered systematically, guided by the IS model selected to cover all relevant aspects. When participants and other elements in a case are defined according to the standard codes or classification agreed upon, sector standardisation is done. In the present chapter, the NACE codes and the EWC were taken into account as a typical case.

The validation process starts when the collected data are revised in terms of input consistency and clustering options (resource category, region, etc.). This should enable different levels of analysis and insight. Application of data clustering techniques (Dunkelberg et al., 2019) and stream ontologies are part of this step (Nooij, 2014; Gruber, 1995). In the present study the categories were defined by inspection according to references in the literature; for more sophisticated techniques, a higher amount of data is required (Davis & Aid, 2022).

Then IS sectors profiles are defined aligned with the categories and clustering options in the case-base, focusing on links among sectors and the visualisation of results. In this research, the IS sector profiles referred to the overview of participants in synergy and the type of streams that they shared under standard classifications.

The IS insights refer to a further investigation of crucial factors defining the sector profiles. In this chapter, the IS insights consisted of further investigation on the cross-sector profiles, the technologies involved, and sustainability aspects based on the IS sector profiles obtained from the case-base.

The final step is testing the use of the database with the stakeholders. This step requires the design of a test method that guarantees valuable feedback from all the stakeholders. Such feedback is expected to re-start the cycle by improving some aspects of the IS case-base, for example, the standards considered or the expansion of the IS model.

The IS profiles that are drawn are directly based on reported IS cases per sector. Each case is a combination of two sectors connected through the valorisation of an under-used resource. The profiles reflect the number of cases per sector across multiple resource categories (energy, by-product, waste and waste), partnering with sectors in another NACE classification. Section 3.2.2 provides details on the databases used to report cases per NACE sector.

The input required from industry to perform an IS study depends on the goal of symbiosis. A starting point for each IS exploration is the energy-materials-services profile of each company in a cluster. To this purpose, sectoral blueprints are highly valuable. Such virtual profiles of typical processes per industry sector can facilitate the screening of high-potential symbiosis options by avoiding the ask for detailed industry data and information. A typical IS study will start by defining the general energy demand (or supply), ranging types and amounts of waste streams and by-products, and maybe also listing services such as waste or water management (Cervo et al., 2019). Once interest is triggered by demonstrating a mutually interesting case, non-disclosure agreements can be signed and detailed data exchange can take place.

### 3.4.4 CROSS-SECTOR MATCHMAKING

Industrial sectors can be represented by generic models (sector blueprints) that enable to define industrial profiles in terms of materials and energy needs added with relevant by-products (Cervo et al., 2020). Such profiles facilitate the study of IS cases. However, blueprints of industrial sectors for use by sector experts require support tools to facilitate the screening of potential IS cases. Industrial processes often have a myriad of resource streams, requiring sector expert knowledge to identify useful options for symbiosis. However, even with such knowledge, it is often not straightforward what resources can be exchanged as experts in one sector are often insufficiently aware of the processes in other sectors. IS case-bases and sector profiles are suggested to facilitate IS matchmaking to enable cross-sectoral clustering (Figure 3.6).

Strategies for IS matchmaking have advantages and disadvantages depending on the sophistication level (Davis & Aid, 2022). A first IS strategy is to match streams by names. It has the advantage of significant simplicity but often leads to not finding novel opportunities due to the lack of equivalence of terms. A second IS strategy is matchmaking based on classification of streams. It provides standardised names for streams and allows linking to statistical data but often uses too general category names. Finally, a more detailed IS strategy concerns matchmaking on explicit properties of streams; this generalises insights that can be extrapolated to other streams but requires intensive data collection, which can be prohibitively expensive (Davis & Aid, 2022).

The matchmaking process presented in this section combines the advantages of the various strategies to reduce the trade-offs. The process was applied in the EPOS project supporting the implementation of energy and material synergies among selected sectors (cement, chemicals, steel, added with urban districts).

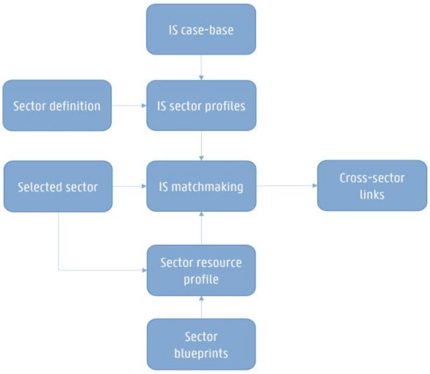



Figure 3.6 Application of the IS case base to the matchmaking of different industries, from databases to cross-sector collaboration (adapted from EPOS, 2019).

### 3.4.4.1 Matchmaking application in the EPOS project

In the EPOS project, the sector blueprints of the cement, chemicals, minerals and steel sectors contain more than 400 streams characterised at different levels. In order to find the streams that can be shared between sectors, a four-staged process was defined for each sector (Figure 3.7).

In a first step, all the streams of a sector blueprint were quantified and classified by the blueprint developer into a standard template for all blueprints. In the second step, the blueprint developer identified which streams are usable for symbiosis based on the blueprint design, regardless of the quality of the streams. In the third step, the developer scanned other blueprints to offer or request a stream for symbiosis for or from another sector. In the final stage, the input from other sectors was assessed to understand if the potential sharable streams could be connected between the different blueprints.

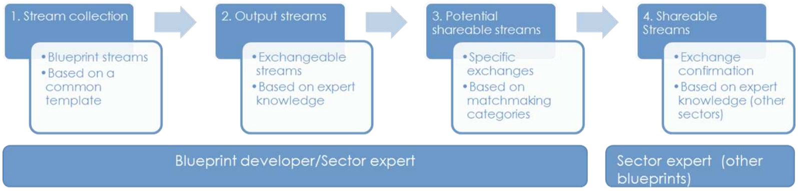



Figure 3.7 Matchmaking process in the EPOS projects.

The shareable streams were validated by the sector experts and included in the relevant blueprints. The agreement between the sector experts on the suitability of a stream for cross-sectoral exchange based on quality and process parameters was accepted as validation of the shareability of the stream. This resulted in a collection of streams related to heat, fuel and material exchanges among the different blueprints.

A generic classification was developed to enable the matchmaking at the level of categories to overcome the challenge of the unilateral sector knowledge.

### 3.4.4.2 Matchmaking profiles and categories

The main objective of matchmaking was to know which streams could be shared between sectors, in support of stage three of the matchmaking process (Figure 3.7). In the EPOS project, a first attempt to enable collaboration using IS sector profiles took place. The matchmaking categories were based on cases researched in the project, supplemented by the MAESTRI project IS case library (Evans et al., 2017). This resulted in a table that showed the kind of synergies that could be established between at least **two sectors (**

). In this way, the sector expert were provided with an initial set of potential streams for sharing with neighbouring industries from the same or different sectors.

For matchmaking, streams were selected if they fulfil two conditions:

1. They are a final output: no further use/value in the blueprint of origin.
2. They have a physical property enabling use as input in another sector.

The kind of (re)use in an accepting industry is divided over several categories. The matchmaking categories per sector, including critical properties, is presented in Table 3.13 Matchmaking categories per sector including guiding physical properties and potential partnering sectors indicated with X, ,meaning that the sector can supply or demand resources for IS in the corresponding category.

. The number of categories varies from 3 in the mineral sector to 8 in the steel sector. The partnering sectors per category are indicated with X.

| Steel | | | | | | |
|---|---|---|---|---|---|---|
| **#** | **Category** | **Property** | *Chemicals* | *Cement* | *Minerals* | *District* |
| 1 | Mineral substitution | Mineral concentration/Mixture | X | X | X | |
| 2 | Heat | Temperature/Pinch | X | | X | X |
| 3 | Alternative steel | Steel concentration | | X | | X |
| 4 | Fuel | Calorific value | X | X | | X |
| 5 | Wastewater | Concentration/no hazard | | X | | X |
| 6 | Flue gas | $CO_2$ concentration | X | X | X | |
| 7 | TAR valorisation | Calorific value/concentration | X | X | | |
| 8 | Other materials | concentration/amount | X | X | X | |
| Chemicals | | | | | | |
| **#** | **Category** | **Property** | *Steel* | *Cement* | *Minerals* | *District* |
| 1 | Fuel | Calorific value | X | X | | |
| 2 | Heat | Temperature+/Pinch | X | X | X | X |
| 3 | Wastewater | Water concentration/not hazard | - | X | X | X |
| 4 | Flue gas | $CO_2$ concentration in stream | X | X | X | |
| 5 | Gas residue | $H_2$ concentration in stream | X | | | |
| 7 | Other materials | High concentration in stream is trigger | X | X | | |
| Minerals | | | | | | |
| **#** | **Category** | **Property** | *Chemicals* | *Steel* | *Cement* | *District* |
| 1 | Mineral substitution | Concentration/composition/Mix | | X | X | |
| 2 | Heat | Temperature/Pinch | X | X | X | |
| 3 | Flue gas | High $CO_2$ concentration | X | X | | |
| Cement | | | | | | |
| **#** | **Category** | **Property** | Chemicals | Steel | Minerals | District |
| 1 | Fuel | Calorific value | X | X | | X |
| 2 | Mineral substitution | Concentration/composition/Mix | X | X | X | |
| 3 | Heat | Temperature/Pinch | X | X | X | X |
| 4 | Wastewater | Water concentration/non hazard | | X | | |
| 5 | CO2 | High $CO_2$ concentration | X | X | | |

An example is given for the chemical sector to illustrate the potential of the matchmaking process. To start, the chemical expert scans the list of output streams (from stage 2 in the matchmaking process Figure 3.7) to find streams that fit at least one of the seven categories from

for the chemical sector (fuels, heat, etc.). The expert proposes high-potential streams to neighbouring sectors based on the exchange potential in the chemicals blueprint. The expert(s) from the contacted sector(s) accept or reject the matchmaking opportunity based on their knowledge and experience of the process requirements in their own sector.

In case of interest, the matchmaking exercise is used as a starter for techno-economic discussions and, if positive, business propositions.

This type of matchmaking process is considered a strong enabler for discovering cross-sector opportunities for collaboration, and thus for implementing hubs for circularity.

The potential identification of additional categories will depend on the development of new technologies and new configurations per industrial sector. Davis and Aid propose a machine learning approach based on academic journals and patent databases related to waste valorisation, to enable word correlations to identify waste streams that could potentially be used as substitute feedstocks (Davis & Aid, 2022). The authors present a method to automatically generate word vectors representing waste and feedstocks to elicit similarity as a proxy for substitution potential. Such an approach, integrated into industrial systems, promises excellent facilitation towards IS and the development of sector profiles.

## *3.5 PERSPECTIVES AND FUTURE RESEARCH ON IS*

The research provides a documented analysis of current databases and sector profiles for IS, added with an unprecedented framework to develop a case-base for IS in the interface of the public and private domain. A method to describe sectoral profiles for industrial symbiosis is proposed, using existing open-source databases from IS innovation projects funded by the European Commission and considering the latest research on IS databases. By applying the method, IS profiles and insights were presented for key industrial sectors in the context of climate change and the circular economy. Moreover, the method was extended into a framework to build and improve IS databases, derived from the learnings gathered throughout the process, from the initial database compilation to final discussions regarding sectoral insights on technologies and sustainable improvement. The framework considers the need for common goals and stakeholder diversity in the initial design of the IS case-base. This approach is oriented towards sector associations and policymakers due to its relevance to various policy domains requiring joint efforts, going beyond a single industrial site and even sector boundaries.

Framed by today's changing policy landscape, EIIs seek to transition towards a circular economy in Europe. There are several pathways to explore, cross-sectorial symbiosis potential being one of them. An extensive analysis of 252 synergies in place has allowed to develop a methodology for building IS profiles for the chemicals, steel, and cement sector. Waste, energy, by-product, and water were defined as the most prevalent streams being exchanged.

In this study, each sector acts as a source and sink of resources. Chemicals as a resource sink primarily enables energy and waste synergies, while as a source, the sector enables primarily by-products and energy synergies. As expected, the chemical sector has the highest number of partnering sectors due to its wide range of applications. The steel sector mostly has a source role (72% of its cases) to build waste and energy synergies, and as a sink, the sector also primarily enables waste and energy synergies. In contrast, the cement sector tends to predominantly act as a sink (78% of its cases) developing waste synergies, while as a source, the sector mostly enables energy and waste synergies. Finally, the synergies with urban entities are integrated into an urban district profile for the EIIs. Districts tend to be a source for waste synergies (69% of the cases) with the main EIIs, while as a sink, they enable energy synergies with other sectors (mainly steel).

Building from the IS sector profiles, three focal insights were presented: typical synergies among sectors and urban districts, IS technologies common to all sectors, and sustainability insights drawn from IS cases. The technology insights cover a collection of technologies for energy, waste, by-product, and water synergies. The sustainability insights include an appraisal of the environmental gains for different resource categories and the need for assessing synergies at multiple levels due to the relevance of local non-technical factors. Additionally, the application of IS case-base and profiles as support tools for sectors exports was developed in the context of sectoral blueprints.

Further research is encouraged to design case-bases that consider geospatial aspects such as clusters and site locations involving urban districts. Such an approach could facilitate the identification and assessment of urban industrial symbiosis in specific regions.

Finally, the identification of new IS cases depends on the IS case-base design, particularly in the selected IS model. Further research on the extension of IS models (e.g., considering new shared services, equipment or technologies) can uncover unprecedented synergies to face current and future economic and socio-environmental challenges in the transition towards a net-zero, circular economy.

# CHAPTER 4 LESTS TOOLS: MANAGEMENT OF ORGANISATIONAL ASPECTS OF IS

Besides operational and engineering or so-called technical challenges in industrial symbiosis (IS) projects as described in the previous chapters, the organisational and management or so-called non-technical conditions have a significant impact on the potential to implement IS projects. This adds multiple layers of complexity to the identification and application of IS options. Chapter 4 presents an approach to deal with non-technical challenges by designing and applying the LESTS method to evaluate symbiosis potential in industrial clusters and urban-industrial hubs, taking into account legal, economic, spatial, technical, and social implications. The research and results are based on contributions to the H2020 EPOS project, in particular deliverables D5.4 and D4.3 and integrates findings of ongoing research.

The central topic of this chapter is the adaptation of the LESTS method for use in process industry clusters. To allow for IS screening in such hubs for circularity – whether cross-sector or urban-industrial. The tool considers the five LESTS dimensions at three different levels: strategic (policy), site readiness, and process level. The final LESTS score provides a generic orientation of the feasibility of the IS project analysed.

The methodology shows that the advanced LESTS approach can be tailored to diverse applications in order to reach multiple goals in IS projects (from IS identification to dealing with barriers to implementation) but IS case studies and demonstration projects confirm that non-technical factors remain a primary barrier to implementing symbiosis in industry.

The chapter outlines further application of the advanced LESTS method to assess stream exchange in hubs for circularity and energy infrastructure to interconnect high-potential IS hubs.

Finally, the scoring system is complemented with an assessment matrix. This is a decision support tool to screen the potential of IS activities, starting from the concept stage and running through the consecutive stages of project management.

## *4.1 FRAMEWORKS TO FOSTER COLLABORATION IN INDUSTRIAL CLUSTERS*

In ecology, symbiosis describes a pattern of interaction between two or more different biological species (Van Eetvelde, 2018). Symbiotic relationships occur naturally in an ecosystem (different communities of living organisms in association with inorganic environmental components) as evolving products of continuous interactions of multiple factors (M. E. Morales & Diemer, 2019).

Similarly, industrial symbiosis benefits from contextual factors, e.g., technical access in a region or spatial proximity for downstream or upstream business potential, creating an economic advantage in a common legal framework. Additionally, since the rise of corporate social responsibility, stakeholder management has grown importance in all IS activities (Van Eetvelde, 2018).

A central dichotomy in industrial symbiosis is found in economies of scale and scope to create a business web, involving feedstock, resources, waste streams, infrastructure, services, or purchasing (Pratten, 1988; Van Eetvelde, 2018). Such clusters have proven added value to more than one industry and the local community (Delgado et al., 2012; Van Eetvelde, 2018; Accenture, 2021).

Industrial symbiosis is rooted in the economy of the scope of cross-sectorial industrial activities, and it can be further improved by internal and external economies of scale (Van Eetvelde, 2018). **Economies of scope** refer to extending the (re-)use of resources in a wider range of business activities, making inputs common to various outputs, increasing efficiency, and often requiring a management entity (Troutman, 2021). The elements of scope economics are time (running business activities in parallel/common schedules), space (using a common infrastructure), and products/services (using common inputs to produce different outputs). Economies of scope aim to exploit the variety of potential in the system towards resource efficiency. For example, automotive manufacturers use similar engines and gear boxes across their entire product range so that the same devices can go into different models of cars. Significant cost savings are achieved by exploring and exploiting the use options of current resources (e.g., the engine and gear boxes) across several products (Troutman, 2021).

On the other hand, **economies of scale** refer to the reduction in the product unit cost upon increased production. The causes of such effect lie in indivisibilities (cost partially independent from the scale can be spread over a larger throughput), in the economics of increased dimensions (types of equipment where cost increases less rapidly than capacity, i.e. labour in process industry), and in learning curves (standardisation and benchmark improvement) that improves productivity over time (Junius, 1997; Mukhopadhyay & Dheeraj, 2018).

Economies of scale and scope find enhanced common ground in IS innovation. Reaching economies of scale increases innovation potential by providing a larger buffer in case of failure in small projects. In contrast, economies of scope allow the organic growth of innovation from existing resources (Troutman, 2021). Innovation is critical for industrial sectors as legislation constantly changes (J. Henriques et al., 2021). Also, the effect of economic cycles at multiples levels (regions, sectors, companies, products, feedstock) is a recurrent factor for innovation. Spatial constraints, especially in western Europe, require inventive spatial planning.

Furthermore, technology is quickly evolving, and industrial sectors and clusters must remain competitive by adapting their resources to the local constraints (Azevedo, Ferreira, et al., 2021; J. Henriques et al., 2021). Finally, stakeholder interactions and societal needs demand more attention, as they may cause project delays, such as permit appeals, or result in weakening the business case (Van Eetvelde, 2018; Walker et al., 2021). It is therefore of growing importance to evaluate innovation projects from a multiple-dimension and multiple-level perspective.

## *4.2 LESTS METHOD TO ASSESS NON-TECH DRIVERS AND PITFALLS FOR IS PROJECTS*

The pentagonal approach of LESTS was developed to assess the appreciation of existing resources and assets at a business park and provide a set of guidelines for better park management (Van Eetvelde et al., 2007). The LESTS book series (Van Eetvelde, Delange, et al., 2005) has served as a practical basis for building the LESTS methodology for IS facilitators active on eco-industrial parks, originally in Flanders-Belgium since the LESTS book series was published in Flemish. Later the LESTS method became widely used in projects at European union and country level , always consisting of five essential elements (Maqbool, 2020).

A **legal framework** is essential for industrial collaboration. Experience has taught that partnership in an industrial zone, although having benefits for the partners, often fails. Usually, this is due to the lack of a legal basis providing companies certainty and clarity about financial aspects, the allocation of tasks, decision power, and responsibilities that lead to the practical implementation of the intended partnership (Van Eetvelde, De Zutter, et al., 2005).

In addition, clarity on the **economic added value** is necessary for any business deal to be closed. Companies will only voluntarily join in symbiosis if there is a business case in place, in other words, potential win-win situations. Examples include shared gains and costs in the short term, a better competitive position in the medium term, and a long-lasting relationship with the stakeholders, including the government, in the longer-term (Van Eetvelde, Verstraeten, et al., 2005).

The **spatial preconditions** of potential clustering are another critical dimension through the efficient utilisation of the available space at a supralocal level. Such level includes the vitality, liveability, and quality of the area, e.g., via alternating built-up parts and green zones, supply chain management, and sustainable mobility (Van Eetvelde, Allaert, et al., 2005).

For any cluster activity the **technical feasibility** of the project is a prerequisite for implementation. The techno-economical basics of a cluster concept is considered fundamental to the execution, allowing for participating in joint projects or not (Van Eetvelde, 2005).

Finally, a contribution to a more sustainable **society** is essential. Since acceptance and commitment are indispensable, stakeholders at multiple levels are increasingly involved to advance collaboration (within the company, in the cluster or the surrounding community, at the regional level, and within and beyond the direct value chain) and generate successful IS.

### 4.2.1 LESTS SURVEYS

The LESTS method allows to collect information in the above five areas of importance to assess business park / industrial cluster management through a survey developed from a pool of predefined questions. These questions initially help clarify how a cluster is managed, the site is organised, and material and energy exchanges take place across the local companies and with their surroundings. A question can cover one or more LESTS dimensions, and each LESTS area is analysed using a long list of questions. The answers are ranked on a Likert scale, ranging from strongly disagree (0) to strongly agree (5). The weighted average of the answers provides the score for each LESTS aspect (Maqbool, 2020).

In the EPOS project, the LESTS approach was adapted for the role of an IS facilitator to identify symbiosis opportunities for the process industries in a (cross-)sectorial cluster (Maqbool et al., 2017). The proposed methodology incorporated the LESTS considerations into the IS identification and initiation process, considering top-down and bottom-up perspectives. The bottom-up approach was used to investigate the potential to start symbiosis activities for data collected at company level. When the information was received from higher authorities (government, park manager), it followed a top-down approach of implementing symbiosis in the industrial cluster. The methodology proposed progressive stages for the maturation of an industrial network, from its formation until full operation over time (Maqbool et al., 2017). When considering the *policy context* that the industries operate in, i.e., the relevance of the circular and low carbon economy was analysed. For the respective local context of industrial clusters, the *economic incentives* to engage in symbiosis were considered, while the plans of regional development clarified *infrastructure* change. An understanding of the relevant industrial processes defined the availability of *equipment and utility networks* that could support symbiotic activities. In addition, a focus on existing stakeholder networks took place, tackling *societal challenges*, such as job security and creation, as well as corporate responsibility (Maqbool et al., 2017).

### 4.2.2 LEVELS OF ADAPTATION

The LESTS framework has been proven resilient in applications to scan the collaboration intensity and sustainability progress in business parks (Van Eetvelde et al., 2007), but also to identify IS opportunities in industrial clusters (Cervo et al., 2019; Maqbool et al., 2017). A meta-framework can be defined for LESTS by grouping three levels of adaptability. The first level is conceptual, referring only to the goal and the means (LESTS dimensions) of collaboration; it has no immediate application due to the higher context but serves as the foundation of the next levels. The second level provides guidelines, defining the dimensions of the symbiosis in a specific context (business parks, industrial clusters, etc.) but not entering into the development tools (Van Eetvelde, Delange, et al., 2005). Finally, the third level is methodological, translating guidelines into tools (surveys, criteria, etc.) for application in specific cases, leading to IS-intensity scans and thus sustainability profiles of (urban-)industrial clusters.

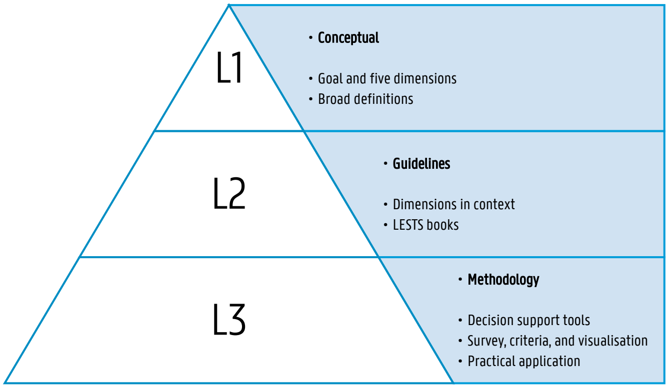



Figure 4.1 LEST level of adaptation (based on Van Eetvelde et al., 2005 and Maqbool, 2020).

Other authors have evaluated similar dimensions to map contextual factors for IS in a variety of settings. The PEST/PESTLE analysis is a first reference for assessing the macro (external) forces affecting a cluster organisation in broad scope (Newton, 2014). A number of authors favour adapted factors according to empirical findings in specific domains of application. In this direction, Labuschagne et al. defined a holistic framework for industrial sustainability (Labuschagne et al., 2005), Golev et al. used a generic classification to cluster barriers to industrial symbiosis (Golev et al., 2015b) and Mirata identified factors under similar categories as influencers of the development and operation of industrial symbiosis networks (Mirata, 2004).

More recently, in the SCALER project (SCALER project, 2020b), Henriques et al. proposed a systematic method to identify enablers and barriers to industrial symbiosis based on seven dimensions (social, economic, policy, management, technology, geographical, intermediaries) at three levels of implementation: local (companies, cities), regional (clusters, networks), and national (government, agencies). The authors recommended promoting industrial symbiosis specific to industrial sectors such as energy, cement, chemicals, and metals (J. Henriques et al., 2021). Branca et al. applied a survey to identify the key barriers to industrial symbiosis and energy efficiency in a comparative approach, finding that cost investments and regulations are the main barriers for IS. In contrast, for energy efficiency projects alone, it is mainly investment costs that are preventing IS from happening (Branca et al., 2021). Agudo et al. proposed a dual checklist for evaluating IS readiness based on exchangeable resources and the transfer capability (trust, information, accessibility, and infrastructure) (Agudo et al., 2022). From an organisational perspective, Fonseca et al. investigated contextual factors in the strategic management of corporate sustainability integration, finding that such factors have higher importance for small and medium-sized companies. They attribute the success of IS projects to adequate stakeholder engagement, effective planning, and strong social impact (A. Fonseca et al., 2021).

This chapter includes the LESTS methodology optimisation as part of two European projects. In the scope of the H2020 EPOS project, the LESTS framework was adapted to develop an LESTS scoring tool for cross-sectoral industrial symbiosis. The tool provides a screening procedure for identifying IS initiatives, yielding insight into potential barriers at multiple levels (EPOS project, 2019j). A comprehensive optimisation was developed in the form of an LESTS matrix including project management stages in the assessment. Finally, LESTS scores were adapted to discuss enablers and barriers in a workshop for an on-going research about energy infrastructure for the process industry (VITO et al., 2022).

## *4.3 LESTS SCORES TO CONSIDER NON-TECH FACTORS FOR IS*

A LESTS scoring pentagon supports the user in the decision-making process by considering five different dimensions that build up the readiness profile of a symbiosis activity at three levels (stream/process, site/cluster, and region/policy). From a management perspective, the final score provides a first generic orientation of the IS feasibility. The LESTS scores, as a validation criterion, depend on direct user interaction. This option was selected due to the level of variability in the non-technical, thus management conditions for an IS project. Based on LESTS, a 15 points checklist was designed to include IS success factors (Veolia R&I, 2017).

As mentioned above, the answers to the core LESTS questions are scored on a Likert scale (Rinker, 2014), as shown in Figure 4.2. The scale starts by detecting extreme barriers to a potential synergy case (value of 1) and runs towards recognising no barrier at all (value of 5). By making use of the scale, the user can screen the IS readiness level beyond technical aspects.

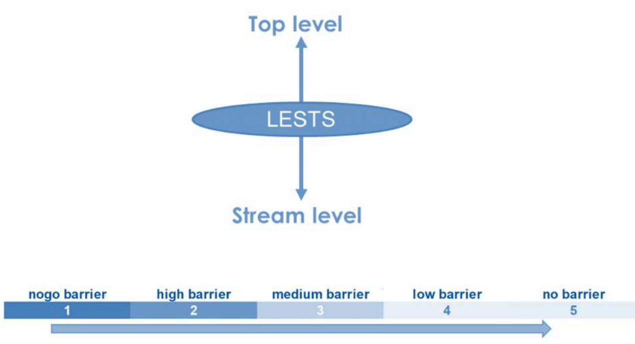
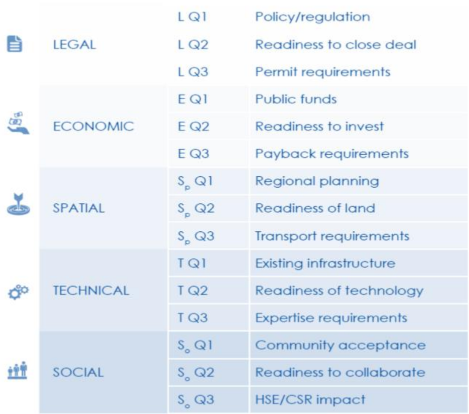



Figure 4.2 Multiple assessment levels enable a robust assessment, where the higher the aggregated score, the lower the barrier level, and the higher the implementation potential.

For a more consistent evaluation of the LESTS score, the 1 to 5 scale (Figure 4.2) was considered useful based on the feedback of a pilot group of LESTS scores users. The scale provides a consistent way to evaluate a symbiosis project.

The checklist includes three questions for each of the five LESTS dimensions. The three questions correspond to different levels. The first one tackles the strategy level (policy), the second one refers to the site readiness level (company/cluster), and the third one sits on the process level (shareable stream, technology, service). In this way, each LESTS aspect is summarised in 15 questions spread over three different levels. By graphically presenting the average scores in a pentagon (Figure 1.3) barriers and opportunities can be grasped quickly and many synergies can be represented in the same plot, enabling the IS profile of a cluster while considering various initiatives.



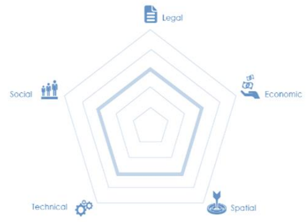




Figure 4.3 LESTS score check list and pentagon.

The LESTS score indicates the readiness to implement a potential symbiosis. If the average score is 3 or more, in the absence of low scores (readiness levels 1 or 2) in any of the dimensions, the symbiosis is declared to have the potential for implementation. A symbiosis is validated from a management perspective when the LESTS scores are above 3, as it represents the situation in which the synergy does not reveal any relevant barriers and thus can be considered viable from all 5 LESTS perspectives. When an average score of 3 is not met, the barriers to specific synergies are preventing direct implementation. The synergy is subject to critical mitigation plans if still considered optional by the stakeholders after identifying the barriers.

LESTS tags for each of the 15 interrogations are provided in Table 4.1. This guidance ensures an unambiguous understanding of the IS concept under scrutiny, as proven valid in the process industry pilot clusters in the H2020 EPOS project.

Table 4.1 LESTS score tags.

| | | |
|---|---|---|
| **LEGAL** | Policy/regulation | Transparency/applicability of regional strategies, rules, and boundaries for exchanging the stream |
| | Readiness to close a deal | Inclination to negotiate, sign a contract, and implement the symbiosis |
| | Permit requirements | Appreciation of time and effort spent to acquire permits for organising the symbiosis |
| **ECONOMIC** | Public funds | Availability/accessibility of regional funding (subsidies, incentives, …) to support or facilitate the symbiosis |
| | Readiness to invest | Inclination to invest capital and effort and implement the symbiosis |
| | Payback requirements | Appreciation of time and effort spent versus return on investment to realise the symbiosis |
| **SPATIAL** | Regional planning | Anticipation of industrial symbiosis and clustering in regional development plans |
| | Readiness of land | Availability/accessibility of space (plots) and connectivity of partners to realise the symbiosis |
| | Transport requirements | Appreciation of (multimodal) mobility amenities/services to support the exchange of the stream |
| **TECHNICAL** | Existing infrastructure | Usability/compatibility of available infrastructure to realise the symbiosis |
| | Readiness of technology | Maturity/market readiness of the technology (TRL) to implement the symbiosis |
| | Expertise requirements | Appreciation of knowledge and training required for implementing the symbiosis |
| **SOCIAL** | Community acceptance | Appreciation of the symbiosis by the local/regional communities and public |
| | Readiness to collaborate | Inclination to trust a partnership and enter the symbiosis cluster |
| | HSE/CSR impact | Appreciation of the socio-environmental gains of the symbiosis (energy, waste, water, health & safety, responsibility, …) |

### 4.3.1 INTEGRATION OF NON-TECH FACTORS IN THE EPOS TOOLBOX

The EPOS methodology was built from existing theoretical concepts and tools originating from different academic and industrial fields. The resulted EPOS toolbox facilitates the identification of IS added with a preliminary assessment following up to support the engagement of stakeholders (Cervo et al., 2019). The methodology was systematically tested by the industrial partners in the five EPOS clusters and was refined based on the feedback from the process industries to make it generic and operable by a variety of actors. These actors include companies as well as IS facilitators (e.g., cluster managers, consulting companies, academics, local public authorities, associations, etc.).

The EPOS toolbox is organised at three levels in seven interconnected steps (Figure 4.4). At the cluster level, the steps enable the identification of collaboration opportunities between the existing cluster's actors and the examination of the background information that might be of importance for the rest of the analysis. At the symbiosis level, the scope is adjusted to the symbiosis that emerges from the list of previously identified opportunities. An IS business model follows the symbiosis, taking into account the whole set of stakeholders. At the actors' level, the methodology provides decision-makers with a specific business case that aims to trigger their interest. The last step (feasibility study) guides the firms that have decided to proceed with the symbiosis, explores the technical feasibility of the exchange, and can even help to improve the organisational aspects of the symbiosis. The application of the methodology led to published study cases of industrial symbiosis (Cervo et al., 2019).

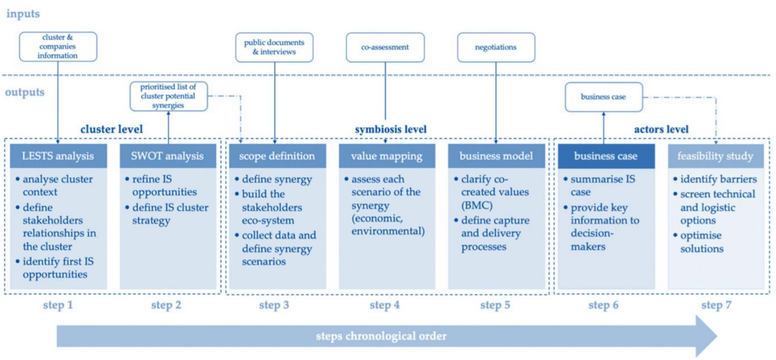



Figure 4.4 IS guide, integrated EPOS methodology (Cervo et al, 2020).

The LESTS tool supports the start and the end stage in the chronological sequence of the IS. By using the LESTS surveys to screen for collaboration potential in a given cluster, IS options are systematically assessed from the five different angles. The initial LESTS scores added with the matrix supplement allow to assess any barriers throughout the process, and lead in step 7 to a re-evaluation. The final scores and matrix support the next step in developing the IS, which usually is the feasibility study.

The LESTS scores and the matchmaking process were integrated in the EPOS engineering toolbox (EPOS project, 2019j; EPOS project, 2018). The first step of symbiosis identification is the user's selection and definition of the site/sector. This is followed by selecting (a) partner sector(s). The matchmaking engine generates and displays shareable streams for the specific case that is defined (validated shareable streams). For each shareable stream, the user completes the LESTS score checklist. After optimisation, a pentagon displays the potential for symbiosis, highlighting the synergies resulting from an optimisation run based on user-defined parameters (related to the optimisation objective(s)).

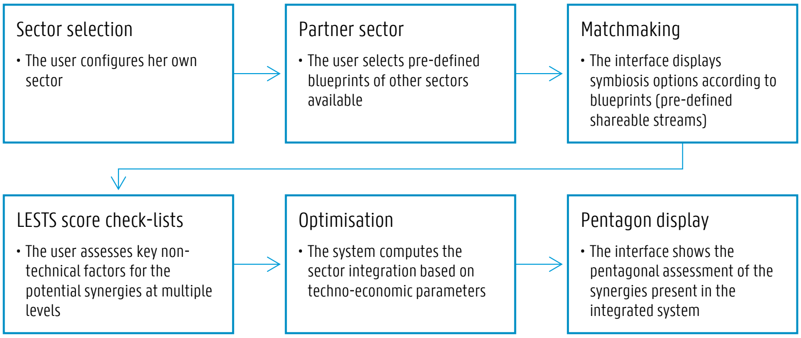



Figure 4.5 LESTS scores and the matchmaking process integrated in the EPOS engineering toolbox.

### 4.3.2 APPLICATION IN ENERGY INFRASTRUCTURE OPTIMISATION FOR THE PROCESS INDUSTRY

In order to produce a picture of potential pathways towards 2050 for industry in Europe, at site as well as industrial cluster level (VITO, 2021), it is required to also consider non-technical factors that are relevant for future production processes. As part of this research, the LESTS scores were adapted to allow for this assessment. A virtual workshop was organised with European sector associations and industries from various sectors: cement, chemicals, fertilisers, glass, refineries, and steel.

Consistently, all sector associations reported that the process industry considers carbon capture, utilisation, and storage (CCUS) as a critical pathway toward carbon neutrality in Europe in 2050 (Accenture, 2021; A.SPIRE aisbl, 2022; Wyns et al., 2018). Therefore, CCUS was selected as the key pilot case to apply the upgraded LESTS scores in the workshop, added with a second case focusing on renewable energy infrastructure (alternative case included in appendix 4-B).

**CCUS IS case: $CO_2$ capture and treatment for usage or storage (workshop case)**

The idea of generic IS cases originates from the applied research and results obtained in the EPOS project. Based on similarities of industrial partners and sectors, the type or size of resource streams, local conditions, and incentives, some high-potential IS solutions in the EPOS clusters were selected for broader application and/or replication across Europe (EPOS project, 2019h).

The aim of the CCUS case was to trigger barriers and enablers for collaboration across the European process industry sectors from a holistic perspective. The developed CCUS case was based on EPOS generic cases #2, #14, #16, and #21 on www.spire2030.eu/epos and aligned with the sector associations' roadmaps.

The CCUS case consisted of two stages. In the first stage, $CO_2$ streams from industrial emissions were captured and purified, while the second stage covered the usage or storage of the captured $CO_2$. The latter implied permanent geological storage of $CO_2$ in deep-sea or underground formations. The former involved the valorisation of $CO_2$ (whether intra- or cross-sectorial) either for direct use (such as cooling, bottling, boosting growth in horticulture) or as a building block in the process industry (for instance, chemical or cement manufacturing). The direct applications of $CO_2$ were not considered as abatement measures but nonetheless resulted in a reduction of on-purpose produced $CO_2$, for instance, for fizzy drinks. Mineralisation was considered as an in-between example, as it led to both utilisation and sequestration, bringing economic value while lowering the environmental impact. Several scenarios apply to the CCUS case, as shown in Figure 4.6.

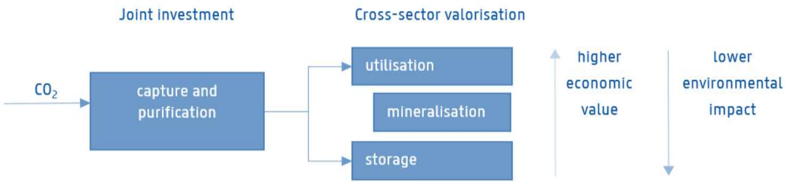



Figure 4.6 $CO_2$ as a case for collaboration across industries.

**Capture and purification scenario**

Industries can decide to jointly invest in a central hub for the shared purification of captured $CO_2$. Process industry clusters have a high potential to share the costs of such pre-treatment facilities. This IS has a growing demand since it directly and effectively contributes to the low-carbon economy (EPOS project, 2019g).

**Utilisation scenario**

The chemical industry can transform $CO_2$-rich streams into raw materials for reuse as chemical building blocks (EPOS project, 2019e). Process industry clusters have a high potential to supply $CO_2$ to the chemicals industry and there is a growing demand for valorising carbon emissions (EPOS project, 2019e).

**Storage**

Storing $CO_2$ streams from process industries can be organised via piping or shipping into empty gas fields. Such permanent storage actively reduces $CO_2$ emissions, hence again there is a growing demand from the process industry in order to contribute to the low-carbon economy (EPOS project, 2019f).

By performing a LESTS assessment, single sectors or sector groups can identify obstacles and/or incentives for any IS case. Table 4.2 illustrates an example of such assessment for the CCUS case.

Table 4.2 LESTS output example for the CCUS case.

| LESTS | Barriers | Enablers |
|---|---|---|
| **Legal** | diverse international policy | long-term supporting policy |
| **Economic** | high CAPEX | public-private partnership |
| **Spatial** | lack of space for installation | transport infrastructure |
| **Tech** | high expertise | pilot projects in the industry |
| **Social** | local opposition | educational schemes |

In the example, the technical barrier of lack of expertise can be overcome not only by developing pilot projects but also by developing educational schemes embedded in the project. Any barrier in one of the LESTS dimensions may find an indirect enabler in another dimension, bringing a more integral approach to the collaboration challenges. The analysis provides a first generic orientation of the feasibility of an IS project from a managerial point of view. It is used to identify both barriers and enablers for potential collaboration projects (EPOS project, 2019j).

The workshop focused on carbon capture, utilisation, and storage as a generic case, achieving a dynamic discussion on non-technological barriers for collaboration towards carbon neutrality (workshop material included in Appendix 4-A).

Based on 15 questions from the LESTS methodology (Figure 4.3), the workshop collected input through real-time surveys with immediate follow-up discussions. Overall, the main barriers for the CCUS case tended to be economical and spatial:

- Legal: Integrated policies on 'waste streams' (energy, waste, emissions, etc.) would boost collaboration; **fragmented policies are considered clear barriers**.
- Economic: (1) The most cost-effective solutions toward carbon neutrality for Europe still need to be revealed; however, even apparent minimum cost pathways for neutrality can only be seen as indicative for long term

planning; a single strategy is not preferred, and **a variety of pathways should be outlined.** (2) Economic indicators differ between long-term and short-term collaborations based on the level of interaction (region, site, company). **Uncertainty on long-term economic strategies** prevents collaboration.

- Spatial: (1) **Cross-border agreements on infrastructure could boost collaboration** tailored for projects towards climate neutrality. (2) **Regional planning is key for collaboration**; new projects can influence planning and spatial design decisions (for example, a recently built car factory near Berlin in Germany).
- Technological: (1) Substitution of current technology and infrastructure towards carbon neutrality can be seen as a barrier (phasing out of profitable assets, inadequate technologies) or enabler (retrofit of existing piping infrastructure for connecting industry and energy players in clusters. (2) **Technology readiness varies across options**, e.g., CCS options in use for decades have limited scalability or replicability across regions and sectors; emerging technologies have low readiness levels and do not yet provide generic or local solutions.
- Social: (1) Community acceptance of the carbon neutrality concept is good among younger generations but shows more **resistance with older generations**. Different communication strategies may be needed. (2) The safety aspect is key for social acceptance; like any engineering project, there is an associated safety risk with CCUS; high visibility of such projects prompts for additional attention to **SHE aspects.**

## *4.4 LESTS MATRIX TO GO BEYOND EARLY STAGE IS*

Following the amendment of the LESTS scores for initial scanning and for project identification, the LESTS matrix is envisioned as a management support tool to assess the risks throughout an IS project's life cycle. The LESTS scores were upgraded to assess the main barriers to IS initiatives at different stages of a project's life, leading to a user guide.

A prerequisite to applying the matrix was to identify a business case and bring insights about the value of a specific synergy (typical sustainability impact on people, planet, and profit, the so-called PPP triangle). In different phases of an IS project, there are varying kinds of uncertainties, and therefore the aim of the LESTS score was adapted to each phase (Table 4.3). As such, in the first steps the matrix could bring design insights for the project and in the last steps, the matrix could trigger action plans for a successful implementation of the project.

Table 4.3 IS Assessment Matrix .

| Project life phase | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Stage name | Identify | Appraisal | Selection | Definition | Execution | Operation |
| LESTS score aim | NA | Framing | Avoid dead ends | Establish action plans | Prevent delays | Sustainability |
| Cost of change | Low | Low | Low | Medium | High | High |

### 4.4.1 PROJECT LIFE CYCLE STAGES

The application of the LESTS scores is based on the stages of projects as defined in the **ASDEO framework**, consisting of 5 stages. In each ASDEO stage, the score has a similar structure but a different aim. The baseline is to have insight on potential benefits related to a IS case. This implies first notions of environmental, social, and economic benefits (PPP) and costs that trigger further investigation and implementation.

**The appraise phase** is the first step. Here, a potential synergy project is examined on a high level. At this stage, the big frame is set, and a value proposition is in place (a specific under-used resource is identified as having potential benefits in terms of profit, planet, or people domains). Questions focus on identifying the appropriateness and rough outlines of potential projects, which include relevant regulations, stakeholders, company policy (willing to invest), standard solutions and potential providers, required land area/real estate, etc.

In the appraise phase, the first score sets the initial frame in terms of all 5 LESTS dimensions. At the earliest phase of a project, the LESTS scores are expected to be the lowest due to the high uncertainty levels. The contribution of the LESTS score is to anchor the framework holistically, considering insights from the different dimensions. It can be considered as a design support tool.

The **select** phase is started once a decision is taken to go on with the project. In this step, the project frame is drafted.

During the selection phase, the LESTS score aims to detect project options that present substantial barriers and exclude those leading to dead ends. The options with the highest score are preferential, while LESTS scores lower than 2 in any dimension indicate the need to reconsider the feasibility of an option.

The **define** phase then prepares the outline and master plan for execution; therefore, it is the last phase where significant alterations can be made. This means that stakeholder involvement is crucial at this point in time, as responding to complaints during later phases often results in much higher costs.

During the definition phase, the LESTS score aims to establish the necessary plans to overcome detected barriers. After this stage, the cost of changes in the project increases significantly as execution and investments start. The approach of the project becomes highly convergent, and the significance of the LESTS scores moves from design support to operations support.

In the **execute** phase, the implementation, application, and collaboration take place. Significant changes in this stage are known to stall the project and probably result in budget exceedance. To avoid deviations which might highly impact the project, major attention is given to following up on decisions taken in the earlier stages and making sure that everything stays on target.

During the execution phase, the LESTS score helps to identify aspects of the action plan that may lead to delays. It aims to trigger preventive action plans.

Once the IS is set up, the process is not over: the **operation** phase covers the entire operational lifespan of the symbiosis project. As with the Deming circle, continuous improvement is essential to ensure performance of the symbiosis to meet the challenging changing demands of an IS project over time.

In this last phase, the LESTS score assesses the sustainability profile of the operations. The LESTS dimensions with the lowest scores help prioritise the actions needed to maintain and improve the synergy.

### 4.4.2 USER GUIDE FOR TEAMS

Based on a wide variety of experience and expertise in using the LESTS scores and the generic IS assessment matrix, in particular in the EPOS Dunkerque cluster in France, a step-by-step guide was developed to ensure adequate in- and outputs of IS cases.

The LESTS score is best used when a team is making the assessment rather than an individual. The outcome of the tool depends on the skills of the user, in terms of using the tool as well as analysing the IS case. In order to provide insights into the different LESTS dimensions, it is therefore recommended to work in teams of qualified colleagues in multidisciplinary areas, such as engineering, management, finances, communications, etc. In a team, the individual appreciations must pass through discussion with the others to agree on a common appreciation. Thus, it is a prerequisite to using the tools to have a team of two or more users that consolidate different levels of perspective in the analyses.

The team is encouraged to follow a step-by-step checklist:

1. **Define** the case (what is the value of the case, why to do it).
2. State the current project phase and define the objective of the LESTS score accordingly.
3. Read the **question** corresponding to the LESTS dimension and level (starting with LQ1).
4. **Agree** with your team on a score according to the score scale (1-5).
5. Write down a **statement** for the agreed score using the corresponding dimension, the level, and the score scale resulting from the discussions.
6. If the score is below 4, make a specific statement about the **barrier found related to the objective** defined in step 2. If the score is four or above, go to step 7.
7. Go to step 3 for a **new iteration** in the next line/question of the LESTS score. If all lines are done, go to 8.
8. Discuss the **global assessment** of each dimension (average of the three scores for each LESTS dimension).
9. Write down a statement about the critical assessment of the case, relating the objective (step 2) and all the barriers found to consider the phase of the project (0-5, Table 4.3).
10. Establish plans, accountable people, and deadlines to overcome the barriers found.

It is also essential to be aware of the potential biases associated with using the Likert scale to avoid them (Rinker, 2014). The central tendency bias is identified when users choose the neutral response in an odd point scale, termed forced choice, to avoid items that they are not comfortable or confident in answering. A second potential bias is the acquiescence bias, where the users tend to give positive responses to the survey questions. It is sometimes approached by reversing the polarity of the item. A third important bias is related to the role/position of the user, and this bias can be mitigated by involving experts with roles at different levels and with different expertise.

## 4.5 SUMMARY AND FUTURE RESEARCH DIRECTIONS

Chapter 4 presented the application of the LESTS methods to identify and analyse non-technical factors for industrial symbiosis projects. Based on the methodology, tools focused on the early assessment of non-technical barriers for industrial symbiosis projects. The LESTS score tool consisted of 15 questions to identify barriers in IS initiatives, complemented with the LESTS matrix, approaching further stages in the life cycle of a project and providing guidelines for the users of the tools. Furthermore, the above-described workshop application used the tool to identify barriers to collaboration for CCUS across industrial sectors. The use of the LESTS tool showed the relevance of non-technical aspects to identify and further implement IS.

The LESTS method could be used to study hubs for circularity as a further research line. H4Cs envision specific clusters in Europe that require to be characterised in terms of technical needs and multiple non-technical aspects to enable collaboration and avoid barriers in the identification and implementation of CE and IS projects. Such hubs would have a geographic spread leading to a diversity that can be captured systematically through LESTS analysis, developing practical approaches for the circular solutions in the hubs. Also, due to the multiple actors (industry, government, civil society, etc.) participating in H4Cs, the relevance of non-technical factors would become even more critical. The multiple applications of the LESTS tool in EPOS may be an excellent starting point to deal with non-technical factors, as the tools were developed to be applied to the five industrial clusters across Europe (EPOS project, 2019a).

The application of LESTS in the context of regional energy transitions is a relevant research line. One learning was that the higher the regional specificity required (from EU level to NUTS3 regions), the more relevant the non-technical factors become, making assessing such factors a critical need for local cases. Regional variations on energy legislation, the availability of levies for renewable energy infrastructure, the spatial availability for new infrastructure in the region, the access to mature technology, and the support of the regional community require evaluation. Examples such as the electrolysis infrastructure for hydrogen production and its symbiosis opportunities (power flexibility, oxygen as a by-product) would be a typical case to apply LESTS in the energy transition context. The development of LESTS tools specific for local infrastructure projects promised fascinating insights to model more realistic cases and design more effective regional roadmaps for a sustainable energy transition.

The focus of most LESTS tools has been either on analysing industrial clusters to identify options for collaboration or on analysing synergies (IS precursors) to identify barriers and enablers. A different approach could relate LESTS factors to specific modes of symbiosis (Figure 4.7). In the case of identification of a significant amount of waste heat in a cluster or region (IS precursor or synergy), the comparison between the creation of centralised infrastructure to generate electricity versus the direct heat exchange network in the cluster may be highly influenced by non-technical factors, such as the energy policy in the region, the clarification of economics of scope scale, the space required for the centralised infrastructure, and the willingness of the companies to negotiate contracts for resource exchanges. Most of these factors needed to define effective collaboration strategies in industrial parks remain unexplored.

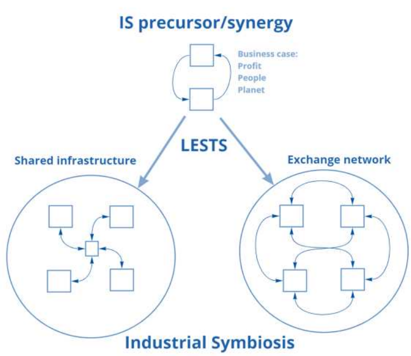



Figure 4.7 LESTS factors leading to specific types of symbiosis.

# CHAPTER 5 IS GENERIC CASES: SCHEMES FOR INDUSTRIAL REGIONS

Following the discussion on organisational and managerial aspects of industrial symbiosis, Chapter 5 presents a methodology to select potential symbiosis cases that facilitates collaboration in and between industries. The cases are selected to promote replicability in the process industry and trigger the use of game theory tools for potential contracts and strategic agreements.

Starting from an IS inventory, the IS generic case selection was based on critical factors for collaboration, such as policy relevance, the potential for the market, cluster reality, and technology maturity. The method was developed, focussing on cases for different process sectors in Europe (cement, chemicals, minerals, and steel). The cases were added with urban districts as partners when suitable. Furthermore, various modes of symbiosis were analysed with fitting game theory tools to identify situations that prevent optimal collaboration or collaboration overall.

The results show a collection of 21 generic cases that forms the IS case base. In most cases, the chemicals sector is present, followed by the steel industry, leading to similar results as presented in the quantitative approach in chapter 3. A cross-case analysis supported the identification of eight main impact categories of symbiosis grouped per sustainability driver (profit, planet and people). The use of payoff matrices (game theory) for analysis of resource exchanges synergies and Shapley values for profit-cost allocation of mutualised infrastructure deliver insights towards strategic agreements. Applying game theory tools to IS generic cases suggests that spatial proximity in clusters and the capacity to generate contracts are critical factors in advancing cooperation across industries, inviting for further applications besides the prescriptive options explored in this research.

## *5.1 A TOOL TOWARDS IS IDENTIFICATION AND REPLICATION*

The initial intention to elaborate cases as tools for IS replicability was based on the idea of identifying IS opportunities by mimicking successful relationships in similar organisations. Such a process is considered a primary means for identifying synergic opportunities (Grant et al., 2010). A significant development in this direction was achieved in the H2020 European projects EPOS, exploring more than 150 potential cross-sectoral IS cases, and Maestri, where a database of bi-sectoral cases of industrial symbiosis showed options for symbiosis for industry based on sector or specific resource exchanges (Evans et al., 2017). However, the database is not widely accessible, and the cases require more insight to improve the visibility of their potential.

The work in this chapter focuses on the IS generic case elaboration method and results in the EPOS project. In the EPOS project, the study of specific clusters and sectors leads to cases with potential for replication designed to reach broader audiences and visibility (IS generic cases). However, the cases are limited to the sectors involved in the project (EPOS project, 2019h). In the H2020 European Project Scaler, the idea of generic cases was further valorised, refining the assessment and expanding the number of sectors and cases, reaching 100 cases and performing a thorough assessment of about a third of them (SCALER project, 2020c; SCALER Project, 2020).

The starting point of IS cases as tool is that industrial clusters and regions can find initial IS solutions based on documented cases considering the similarity of partners and sectors, the type or size of resource streams, and local conditions or incentives. When appropriate, IS cases can be virtualised as generic cases and summarised in one-pagers to trigger business engagement.

The IS generic cases have four different sections:

A first section describes the concept behind the symbiosis in terms of resources, challenges and means to overcome them. An eye-catcher image is designed to quickly grasp the concept. An under-used resource (energy, material, service) is often presented, and the potential for synergy is clarified.

The second section focuses on key insights drawn from the case. A schematic represents the synergy between the involved sectors.

The third section elaborates on the symbiosis potential by giving quantitative information on the synergy.

The last section summarises the sustainability impact in terms of profit, planet and people. The references of the figures and numbers used are listed on the backside of the one-pager. Figure 5.1 shows the four sections integrated as one-pager.

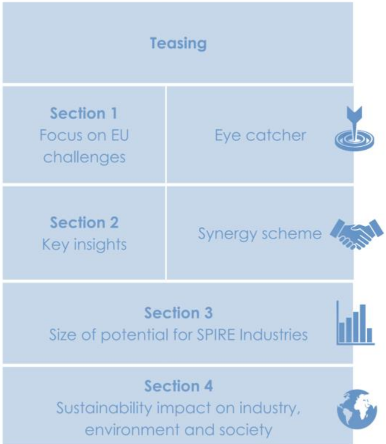



Figure 5.1 Generic case sections (EPOS project, 2019).

### 5.1.1 METHOD TO IDENTIFY CASES FOR REPLICATION

The elaboration of the generic cases was based on specific progress steps. It followed the industrial ASDEO approach: appraise, select, define, execute and operate.

The process starts when an IS case is appraised and a case is selected from a list of options. Such list is based on IS expertise and lessons learnt from the use of LESTS and SWOT tools (EPOS project, 2018; Ogé et al., 2019) and feedback from sector associations or companies.

Overall, the most promising IS cases were selected using a criterion based on four factors: policy relevance, market potential, cluster reality and simulation potential. Each selected case was considered relevant to each of the categories (Table 5.1).

Table 5.1 Generic case selection factors.

| Factor | Description |
|---|---|
| **Policy relevance** | Fits into a policy agenda towards sustainability |
| **Market potential** | Initial appreciation to establish a virtual marketplace |
| **Cluster reality** | interest in a cluster within EPOS to be further investigated |
| **Simulation potential** | Modelling capacity in the toolbox, as streams and technology are in there already |

Once the selection was made, the generic case was defined based on the IS generic template, leading to research EU challenges, synergy schemes and impact (Figure 5.1).

The execution of the research took two stages:

- A prime research focus was on the case topic itself, its type, size, importance, recurrence, etc. The benefits of the case were condensed in a clear statement in order to conceptualise the case and identify the industrial and policy challenges. The EU sources of information used peer-reviewed journal articles, project reports from the European Commission (Cordis), and related European news items.
- The second research step consisted of a literature review to estimate benefits/incentives for the integrated case across-sectors i.e., the impacts in terms of economics (costs estimations, savings, ROI), environmental (estimation of resource-saving, emissions reduction and mitigation), and social benefits (qualitative implications such as stakeholder relations, sustainability image, etc.).

Finally, by sharing the generic cases via the online platform from the European process industry sector association (SPIRE), the project reaches out to clusters across Europe (operation phase).

### 5.1.2 OVERVIEW OF SELECTED IS GENERIC CASES

The method led to a collection of 21 IS generic cases involving cement, chemicals, minerals, steel, engineering, and urban districts. *Table 5.2* presents a matrix with the overview of cases and the sectors involved in each case. Such an overview promotes an initial trigger for companies or sector associations to replicate high potential cases of symbiosis, highlighting topics and other partnering sectors. The full description of cases can be consulted in Annex section (Appendix 5).

Table 5.2 IS generic case matrix (adapted from EPOS project, 2019).

| # | Title | Description | Cement | Chemicals | Minerals | Steel | Engineering | District |
|---|---|---|---|---|---|---|---|---|
| 1 | **Waste fuel valorisation** | Transform waste streams with high-calorific value into alternative fuels for process industry | x | x | | x | x | x |
| 2 | **$CO_2$ mineralisation** | Capture and purify $CO_2$ emissions for reuse as raw material in process industry | x | x | x | x | x | |
| 3 | **District heating** | Reuse low-temperature waste heat from process industry to supply district heating networks | x | x | | x | x | x |
| 4 | **Energy optimisation** | Optimise energy use in process industry and seek synergies with other process industries | x | x | x | x | x | x |
| 5 | **Wind power collaboration** | Jointly invest in wind power generation for shared use of renewable electricity in industry and communities | x | x | x | | x | |
| 6 | **Coke valorisation** | Transform industrial steam cracker coke into raw materials for steel and cement industries | x | x | | x | x | |
| 7 | **Solar power collaboration** | Jointly invest in solar power generation for shared use of renewable electricity in industry and communities | x | x | x | x | x | |
| 8 | **Industrial heat networks** | Optimise heat use in process industry via heating networks in industrial clusters | | x | | x | x | |
| 9 | **Industrial water networks** | Optimise water use in process industry via water networks in industrial clusters | x | x | x | x | x | x |
| 10 | **Co-product valorisation (minerals)** | Use inorganic residues as raw materials in minerals industry | x | | x | x | x | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 11 | **Co-product valorisation (cement)** | Transform industrial co-products into raw materials for the cement and construction sector | x | x | | x | x | x |
| 12 | **Demand Side Response** | Optimise electricity sourcing and use via demand-response flexibility in industry clusters | x | x | x | x | x | |
| 13 | **CO valorisation from steel** | Transform rich CO off-gases into raw materials for the chemical industry | | x | | x | x | |
| 14 | **Industrial $CO_2$ capture and utilisation** | Transform rich $CO_2$ streams into raw materials for the chemical industry | x | x | | x | x | |
| 15 | **Wastewater treatment** | Optimise water treatment in process industry and seek synergies with other industries | | x | | x | x | x |
| 16 | **Industrial $CO_2$ capture and storage** | Store $CO_2$ streams from process industry via piping or shipping in empty gas fields | x | x | | x | x | |
| 17 | **Waste plastic valorisation in steel** | Use plastic waste as raw material in steel industry | x | x | | x | x | x |
| 18 | **Solar heat** | Jointly invest in solar heat plants for shared use of renewable heat in industry | x | x | x | | x | |
| 19 | **Steel slag valorisation** | Transform steel slag into raw materials for the chemical and cement industries | x | x | | x | x | |
| 20 | **Waste plastic valorisation in cement** | Use plastic waste as raw material in cement industry | x | x | | x | x | x |
| 21 | **Hub for $CO_2$ upgrading** | Jointly invest in hub central for share upgrading of captured $CO_2$ | x | x | | x | x | |

The sustainability impact analysis of generic cases allowed to identify eight main categories of high relevance for Europe (Table 5.3), spread over all three sustainability pillars: profit, planet and people:

As economic drivers, two categories are distinguished: the first is creating virtual marketplaces that generate relevant cost reductions in the process industry; and the second collects competitiveness impacts due to the other costs avoided.

There are four key environmental drivers: $CO_2$ emissions reduction indicates the reduced carbon footprint due to the symbiosis due to decreasing, avoiding or mitigating GHG emissions; energy efficiency refers to the savings in primary energy use and energy generation; material efficiency points to the savings in (virgin) resources; and renewable energy relates to joint investments or flexible use of resources and infrastructures.

Finally, as social drivers, all cases considered the preservation and generation of work positions and the potential to create, improve or diversify business networks.

Table 5.3 EU impact categories of IS.

| EU impact category | Generic case # |
|---|---|
| PROFIT | |
| **Virtual market** | 1, 2, 3, 8, 9, 10, 13, 14, 16, 17, 19, 20 |
| **Other cost reduction** | 1, 6, 15, 16, 17, 19, 20, 21 |
| PLANET | |
| **$CO_2$ reduction** | 2, 5, 7, 11, 13, 14, 16, 18, 19 |
| **Energy efficiency** | 1, 3, 4, 6, 8, 20 |
| **Material efficiency** | 6, 9, 10, 11, 15, 17 |
| **Renewable energy** | 5, 7, 12, 18 |
| PEOPLE | |
| **Job preservation and creation** | 1, 2, 3, 8, 9, 10, 13, 14, 16, 17, 19, 20, 21 |
| **New business relations** | 1-21 |

From Table 5.2, it can be observed that the Engineering sector is present in all cases, as expertise outside of the typical domain of a single sector is required. This is an expected outcome due to the need for logistics, transport, treatment or other technological implications outside of the scope or core competencies of the process industry sectors (A.SPIRE aisbl, 2022).

Likewise, chemicals and steel are present in most synergies (~90%). In the chemicals sector, the transformation of a broad range of materials in a wide diversity of processes takes place, resulting in a high potential for industrial symbiosis. This is evidenced in the long history of industrial clustering within the sector itself (Ketels, 2007). On the other hand, the steel sector has a strong tradition of recycling and a straightforward quest for optimising its processes (high energy-intensive, high material input).

Also, the cement sector has a long tradition of waste valorisation and continues its search for alternative raw materials. These aspects offer possibilities to explore collaborations with other sectors given, based on the high energy requirement in process industries.

Finally, the minerals sector and districts are present in less than half the list of generic cases. The minerals sector is characterised by a relatively low process diversity and a significant energy intensity (more electro-intensive). However, the sector has a high potential for carbon capture and utilisation via mineralisation processes, opening opportunities in the low to net-zero carbon economy (EPOS project, 2019a).

Urban districts, as significant sinks for energy and source of by-product materials, share some options for material exchange (secondary inputs such as plastics, glass, steel, etc.) and infrastructure development (e.g., district heating) towards hubs for circularity. However, the interaction with urban districts may increase the complexity of collaboration thanks to an increased diversity of interests. Thus, it is essential to identify supporting tools to facilitate such interactions.

## *5.2 STRATEGIC ANALYSIS OF INTERACTIONS FOR INDUSTRIAL SYMBIOSIS*

When moving from generic cases towards implementation, the next step is to screen contracts (Figure 5.2) when game theory applications are proven beneficial. Game theory starts from the economics of single industries and enables the systematic analysis of interactions between industries (Desideri-Perea, 2021).

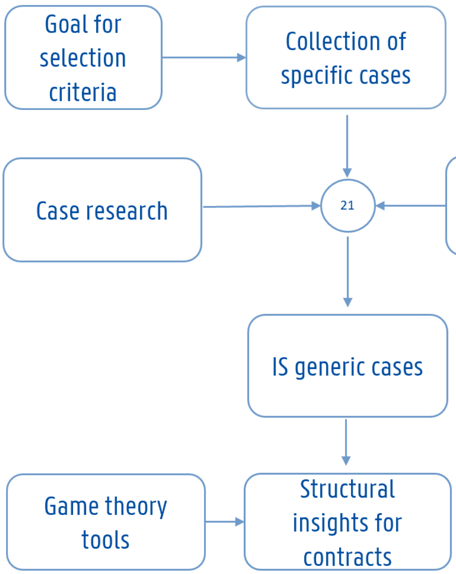



Figure 5.2 Use of game theory tools as a further step for IS generic cases.

Game theory (GT) is broadly defined as a systematic analysis of strategic interactions. Therefore, it can be applied as fundamental theory to turn insights into pathways that prevent or enable cooperation in industrial symbiosis. This section reviews the game theory and its application to industrial symbiosis. It starts with describing the fundamental concepts, followed by challenges for optimal collaboration, and including options to overcome such challenges.

Game theory is a renowned research field with major applications in the standard economic area. Most, if not all business deals are closed based on opportunistic decisions, which are the principle drivers of GT. Similar but less extensive GT research touches on wider domains such as institutional collaboration and even behavioural biology, but in each domain the focus is forthright on maximising payoff for rational players.

Industrial symbiosis, however, is not only based on market economic principles; it needs additional enablers – beyond techno-economic drivers – to facilitate the sharing of resources or joining forces to reach a common goal. IS resorts under 'incentivised economics', combining engineering, business and managerial skills to make a deal happen.

With this complexity and multidisciplinarity in mind, the practitioner-oriented IS field requires simple tools and telling (generic) cases to convince industries and communities to explore IS opportunities. Hence two straightforward tools are introduced to analyse IS in a prescriptive way: payoff matrices for exchange symbiosis and the Shapley value for mutualisation symbiosis. In this work, the tools only provide an initiation to strategic IS analysis; in particular in the field of GT, the deployment of more sophisticated tools is recommended for further research, specifically with regard to industrial organisations. Such tools can *i.a.* support pricing mechanisms to deal with asymmetries in the sharable resources between actors, making use of existing models and equations for oligopoly markets and supplementing the research with additional tools. Two typical examples are ABM, agent base modelling as researched in the H2020 projects EPOS and SHAREBOX (Maqbool, Baetens, et al., 2019; Yazan et al.,

2020) or system dynamics, making use of hybrid models to study the behaviour of firms in oligopoly markets (Mohammadi et al., 2016; Guzzo et al., 2022).

In this chapter, no specific databases are used. The input required from industry to perform an IS potential study depends on the symbiosis mode (exchange or mutualisation). Per mode, simple models are proposed and discussed in sections 5.2.3.1 and 5.2.3.2.

### 5.2.1 THE CONCEPTS OF GAME THEORY

Several studies have shown that one of the main bottlenecks of establishing successful symbiosis projects is the lack of cooperation between potential network participants (Rodin & Moser, 2021) related to conflicting interests and lack of trust between the network proponents (Jato-Espino & Ruiz-Puente, 2021; Van Eetvelde, Delange, et al., 2005). Therefore, it is crucial to articulate cooperation mechanisms, explicating systematic ways of arriving at conditions for negotiations among parties. For industrial symbiosis, the closing of deals between industries marks its implementation (Mortensen & Kørnøv, 2019). Such contracting mechanisms have been analysed using game theory in non-cooperative and cooperative environments (Aviso et al., 2022).

Before presenting the documented claims and insights of game theory applied to IS situations, it is fundamental to present basic concepts (Aviso et al., 2022):

- Games are strategic situations where individual outcomes depend on individual actions upon actions from others, such that logical decisions are based on maximising individual payoff or utility functions.
    - Players are entities in the game that can make decisions rationally and independently, affecting the outcome of the game.
    - Strategies are courses of action or choices taken by the players to reach a specific payoff, profit, or utility (the higher the payoff, the better the strategy).
    - Utility/payoff functions: integrated appreciations of cost-benefits of a player's strategy.
- The Nash Equilibrium (NE) is the state in a game where no player benefits from changing the current strategy regardless of all other possible strategies (Holt & Roth, 2004).
    - The NE is reached when all players display their best response to each other.
    - A player's strategy is strictly dominated by another strategy (of the same player) when the first strategy has lower payoffs than another one for all possible responses of the other players. Thus, dominated strategies should be avoided.
- A cooperative game is a game where coalitions can be formed and establish agreements/contracts to sustain the group, given that it maximises the participants' payoffs.
    - Profit and cost distribution mechanisms are key.

In summary, game theory conceptualises multi-actor decision-making in terms of three components: interacting players, individual strategies, and payoffs under certain conditions of rationality and personal self-interest. Within game theory, there are typical cases to analyse collaboration and competition.

Study cases that compare outcomes of competition and collaboration are called "social dilemmas", where the socially desirable outcome can only be achieved by direct collaboration among players. One of the best-known problems belonging to this family is the prisoner's dilemma (PD) (Tucker, 1950). This is a situation in which two rational players fail to achieve the optimal collaborative outcome because they have no means to build trust that creates certainty about the other player's choice. They opt for a "best response strategy" to protect themselves against the risk deriving from the other player's choice. However, when players are able to exchange information, build trust and join forces, they can gain a higher payoff. In light of the above, the PD allows to distinguish between "non-cooperative" and "cooperative" outcomes (Radner, 1986). The non-cooperative outcome results from the best (individual) response strategies of the players, in which all players maximise their individual payoff, anticipating that the other players will do likewise. In this setting, Nash Equilibria can be identified. These are equilibria because given the possible strategies of the rivals, each player has no incentive to deviate from the current strategy, or else it would lower his/her payoff. As a result, no external means of enforcement are needed to maintain this equilibrium since it is in the self-interest of each player to maintain their positions (Holt & Roth, 2004). On the other hand, a cooperative outcome that yields higher payoffs is defined as "Pareto optimal". Although also this strategy is regarded as rational (as it leads to the mathematical optimum for the system) (Radner, 1986), it cannot occur without the correct enforcement mechanisms in place (Desideri-Perea, 2021).

The basic concepts of game theory can be illustrated by the PD in a payoff matrix (*Figure 5.3*) (Tucker, 1950). In the classic example, there are two players / convicts, each player with two mutually exclusive strategies (to confess or not) and without the possibility to communicate or interact with the other. If both convicts confess/blame each other, both get a sentence of three years in prison (-3 in the payoff matrix). If convict 1 confesses and convict 2 does not, convict 1 goes free, and convict 2 gets five years. When no convict confesses, there is less evidence, and they both get one year. The best response for convict 1 is to confess, no matter what convict 2 chooses (if convict 2 chooses to confess too, convict 1 goes three years to prison, which is better than five if not confessing. If convict 2 chooses not to confess, convict 1 goes free, which is better than spending one year in prison when not confessing). In this setting, cooperation is rationally impossible for each convict since they both have an incentive not to cooperate, although the cooperative solutions (both not confessing) lead to a minimum of total years spent in prison (considering the sum of both convicts). The rational outcome of the game is that both convicts spend three years in prison, which is worse than spending one. However, to get out of the trap, they need to interact to ensure that there would be no betrayal, as confessing would lead to higher individual outcomes.

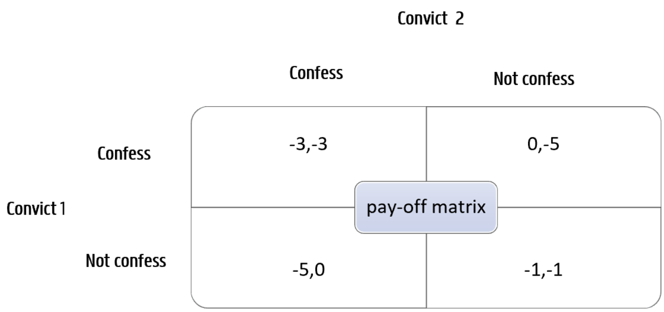



Figure 5.3 Prisoner dilemma payoff matrix.

Moreover, the complexity of games can increase depending on payoff combinations. In *Figure 5.4* 1A strategy does not dominate 1B strategy (1B is better for player 1 if player 2 chooses 2B). However, 1A is always chosen because strategy 2A dominates strategy 2B. Player 1 chose 1A as a strategic response to the best response of the other player, having a clear option between two non-dominated strategies. This example illustrates how the complexity of games builds up with different variations of payoffs that clarify choices between non-dominated strategies.

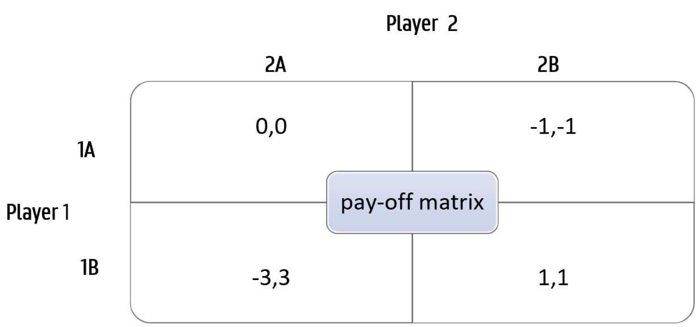



Figure 5.4 Payoff matrix where strategy 2A dominates strategy 2B defining a fixed response for player 1.

Finally, cooperation in games can be fostered by the frequency of interaction, the structure of the game, and the establishment of enforceable contracts (Polak, 2007). The frequency of interaction refers to the potential for subsequent repetition of the game favoured by contextual factors, e.g., geographical proximity in industrial clusters and already ongoing commercial and non-commercial interactions. The game's structure refers to the existence of multiple Nash Equilibrium situations with different payoffs, requiring leadership and communication to reach a specific equilibrium with no need for formal contracts (as equilibrium self-regulates once reached). Changing the game's structure requires macroeconomic interventions that shift how payoffs are defined. Lastly, contracts refer to enforceable agreements to reach a fair level of payoff for all the players involved, which requires a significant and clear benefit added with the negotiation willingness of the parties.

## 5.2.2 GAME THEORY TOOLS IN IS RESEARCH

This section explores the state of the art of game theory application to industrial symbiosis. In this context, the synergy is the result of cooperation strategies based on resource exchange and (infrastructure) mutualisation among two or more parties. The section starts with a review of game theory application to non-cooperative situations, then focuses on cooperative games, clarifying the formation of coalitions in games.

The fundamental difference between non-cooperative and cooperative game theory is that non-cooperative games focus on what individuals can do acting alone. In contrast, cooperative games focus on what groups can achieve working together. Collaboration must be self-enforcing in non-cooperative games (internal agreements), whereas players can make enforceable contracts in cooperative games requiring external support for enforcement (Corley, 2017).

### 5.2.2.1 IS in non-cooperative games

One of the earliest works in game theory for IS is found written by Lou et al. (2004). They used non-cooperative games and energy analysis to determine the best strategy for integration in an eco-industrial park. They also considered how uncertainty could influence the benefits gained by the stakeholders (Lou et al., 2004). Van Eetvelde et al. (2005) proposed to analyse economic management options in business parks and industrial clusters using game theory (Van Eetvelde, Delange, et al., 2005). Chew et al. (2009) examined the use of non-cooperative games for inter-plant water integration, considering environmental (e.g., reduction in water use and wastewater generation) and economical (e.g., associated costs for establishing network) payoffs for the participants (Chew et al., 2009). Chew et al. examined all possible network schemes between the participants and identified the final solution obtaining the Nash Equilibrium. As expected, the solutions through the Nash Equilibrium did not coincide with the global optimum, which maximises the network's collective benefit. Xiao-Ping et al. (2009) identified the Nash Equilibrium using linear programming to initially define the individual payoffs for the network participants (Xiao-Ping et al., 2009).

In applying non-cooperative game theory to study IS practices, most approaches rely on purely single-time games where firms have only one chance to play or multiple-times games with a handful of rounds (Chew et al., 2009; Grimes-Casey et al., 2007). Such a perspective would be appropriate to see the emergence of IS but limits the chance of studying how a potential IS relation can evolve in the long run regarding companies' behaviour and adopted strategies. In order to fill this gap, game theory models integrated with agent-based modelling showed that the evolution of cooperation towards symbiosis takes place in consecutive rounds of games (Yazan et al., 2020). The findings suggest that clusters, where industries are in proximity, can benefit from cooperation towards symbiosis, as industries cannot relocate easily. Once they start collaborations, consecutive interactions will likely take place.

### 5.2.2.2 IS in cooperative games

Albino et al. (2015) suggest that contracts facilitate industrial symbiosis. They considered two contractual options, the first one being firms that pay to supply waste to other companies (profiting from savings in waste disposals costs), and the other where firms pay to purchase by-products (profiting from savings in raw materials). A reference option was added to indicate the absence of contracts. Contracting options were integrated as a non-linear programming problem to minimise the probability of failure of the relationship. The work of Chew et al. (2009) also explored the use of cooperative games in designing inter-plant water integrated networks. In contrast with non-cooperative games, cooperative games assume that the participants can reach binding agreements regarding the strategy to be played. Unlike the non-cooperative game solution, the cooperative solution coincided with the global optimum when a proper allocation of cost and benefits was done.

A key factor for IS collaboration is that each player benefits more from the exchange than from individual responses. Such mutual benefits lead to the formation of coalitions. However, there has been limited work on companies as players forming clusters to get the most of industrial symbiosis. Work in this context has focused on the allocation of benefits using various bargaining strategies such as the Shapley value (Shapley, 1953), nucleolus method (Schmeidler, 1969), or the Utopia payoff (Tijs & Driessen, 1986). Hiete et al. (2012) examined the use of different allocation schemes to identify the fair allocation of added value for participants in an energy network (Hiete et al., 2012). The overall benefits were determined using the principles of heat integration, where the allocation was based on the contribution by a company into the network or the loss in savings if a company decided not to join the network.

Overall, games for symbiosis can be characterised by their degree of coordination, referring to the actions of internal or external agents enabling the development of the game in a specific direction (Figure 5.5). Coordination applies to non-cooperative (often when multiple Nash Equilibria are possible) and cooperative (when forming coalitions is possible) games.

Coalitions take place when the formation favours individual payoffs to a relevant degree. Growing collective benefits or controlling the options of players may increase the potential for cooperation. More collective benefits (due to incentives or synergies) increase the total size of the payoff e.g., availability of subsidies to access to technology. On the other hand, raising the level of control (rules, order) can also lead to the formation of coalitions as the transaction cost would be relatively lower in a group approach (economies of scale) i.e., increasing standards for environmental protection that apply to multiple sectors may stimulate sector coalitions to develop effective solutions at lower costs. Overall, push or pull options for IS are present from a game theory perspective.

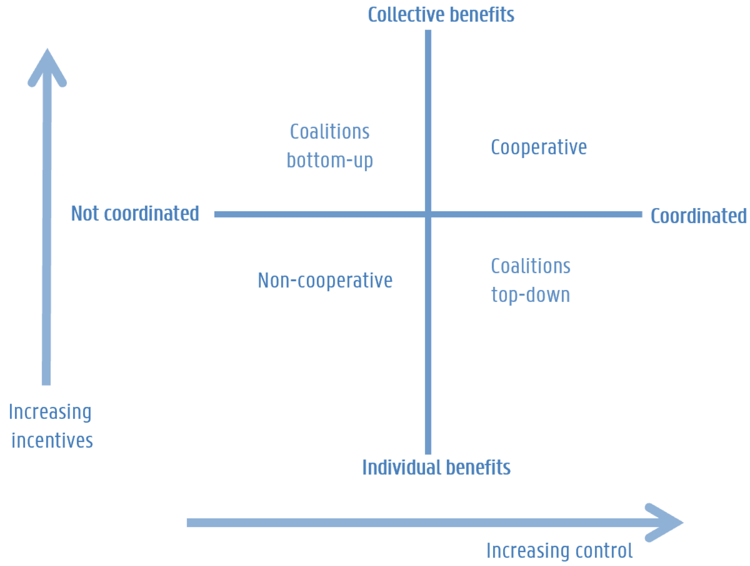



Figure 5.5 Game orientation towards cooperation.

### 5.2.2.3 IS coalitions

Industrial symbiosis can be conceptualised as the formation of coalitions with a physical base (resources and infrastructure) where synergies take place. Coalitions are possible in different types of games, from competition in zero-sum games to cooperation in non-zero-sum games (von Neumann & Morgenstern, 1944).

In zero-sum games, the total size of payoffs remains constant: increasing the payoffs of one player necessarily means reducing the payoffs of another. Zero-sum games are characterised by individual competition. However, the formation of coalitions competing with one another is also possible. In competitive games, there is a possibility of reaching sub-optimal equilibrium points (Pareto inefficiency). Thus, cooperation is encouraged to avoid such situations, fostering negotiations and contracts (Petrosyan & Zenkevich, 2016). In an industrial context, chemical cluster economics are most likely a non-zero-sum game, given the complex interrelations of activities and exchanges among stakeholders (Lozano, 2007). On the other hand, applying a zero-sum game to chemical clusters would mean solely optimising investment decisions for one actor. Thus, alternatives that would benefit the whole industrial configuration would be ignored (Desideri-Perea, 2021).

In non-zero-sum games, the total payoffs can increase or decrease due to the actions of the players. Non-zero-sum games are best suited to deal with diverse and complex environments (Lozano, 2007) as they allow to search for the cluster's common interest, exploiting the system's various complementarities to achieve the optimal sustainable strategy for all actors (Desideri-Perea, 2021). Cooperation in symbiosis implies a non-zero-sum game due to the establishment of synergies, providing benefits that emerge from interactions in a system compared with the situation without the interaction of its components (M. Morales et al., 2021). Cooperation and coalition formation can be encouraged in this kind of game, either to reach a higher payoff level or to reduce the risk of diminishing the current payoffs of the game.

Coalitions can be formed in both zero-sum and non-zero-sum games to different degrees. In cooperative environments, where partners can negotiate and establish contracts, coalition formation can be partial (competitive coalitions) or towards total integration (single coalition) in non-zero-sum games. In a non-cooperative environment for non-zero-sum games, the coalition may be formed without needing contracts as self-regulated interactions, and an exchange platform may still be needed to initiate the interactions (Figure 5.6).

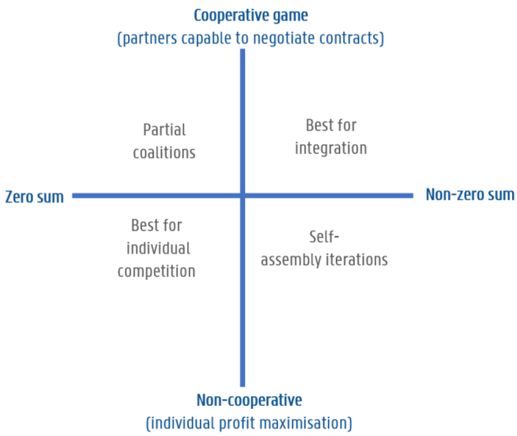



Figure 5.6 Coalitions can emerge in different types of games.

### 5.2.2.4 Contractual networks

A common issue in cooperative situations is the potential to unevenly shared benefits (Albino et al., 2016; Van Eetvelde et al., 2005). Here, contracts as external enforcement mechanisms specify how the involved actors share pains and gains of the cooperative strategy as a result of a joint investment decision. The optimal outcome is obtained when all the industries choose their moves collectively, such that the resulting strategy generates the highest total payoff (i.e., the sum of the payoffs for the individual players). However, this does not imply that every industry will be better off: the payoffs of some players might be so high that they can compensate for the negative payoffs of some other industries. Thus, a Pareto-optimal outcome can only materialise when the companies are willing to negotiate and reach an agreement both on their strategies and on how to redistribute the obtained payoff (Van Eetvelde, Delange, et al., 2005). Such contracts enable modifying the incentives of individual firms and pushing each other to behave in a way that is desirable for all parties.

The IS generic cases aim to increase the visibility of a coalition's potential and synergies to enable cooperation. The cooperative outcome is often unstable in ways that can make cooperation difficult to maintain (Holt & Roth, 2004). Thus, instruments are needed to transform games from prisoner's dilemmas into games in which cooperation delivers a sustainable balance (Holt & Roth, 2004). The transition of energy-intensive industrial clusters can be seen as an example of the prisoner's dilemma. Players are represented by industries in a cluster, making investment decisions in cleaner technologies. When choosing their strategies, industries can either jointly invest in a project and cooperate or they can make investment decisions individually, obtaining different payoffs. Different states of equilibrium can be achieved in the cluster when each industry chooses its strategy to balance its investments' gains and costs with its environmental performance to maximise its payoff, constrained by the other players' strategies.

From a legal perspective, most coalitions require contracts to sustain themselves as networks in industrial clusters (Van Eetvelde, De Zutter, et al., 2005). Contractual networks are hybrid forms of organisation between markets and hierarchies (Cafaggi, 2008). Networks differ from market contracts because the participants are well-identified players chosen based on resource complementarities (instead of being anonymous agents). They differ from hierarchies because agents in the network are autonomous and legally independent, even if they may be economically dependent. The main characteristics of contractual networks are (Cafaggi, 2008):

- Interdependence: common goal or set of objectives to be achieved among all participants.
- Stability: focus on the overall network more than on current partners.
- Duration: a tendency towards long term.
- Multiplicity: a tendency towards multiple relationships.
- Cooperation and competition: partners cooperate on some projects and compete in other dimensions.

Contractual networks may emerge in different ways. Some arise as a form of collaboration among independent and autonomous enterprises that decide to increase levels of coordination and interdependence. This frequently happens when enterprises own complementary critical resources and capabilities, but merging is not a feasible or desirable alternative. In particular, interdependence leading to contractual networks may be generated by knowledge systems characterised by fragmentation and difficulty to allocate properties (Cafaggi, 2008), which is often the case with industrial symbiosis.

Contractual networks can take two primary legal forms (Cafaggi, 2008):

- Bilateral contracts: A set of linked pairs of players with contractual duties related to specific activities (*Figure 5.7*).

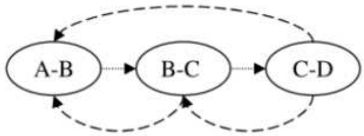



Figure 5.7 Network with bilateral contracts (Cafaggi, 2008).

- Multilateral contracts: A set of a linked group of players with contractual duties related to specific activities. Typically results in joint ventures (creating a new legal entity) or consortia (not a new legal entity) involving multiple actors cooperating towards a common objective by combining their resources (Swensson, 2012) as illustrated in *Figure 5.8*.

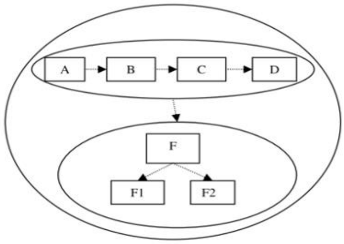



Figure 5.8 Network with multilateral contracts (Cafaggi, 2008).

Bilateral contracts are related to resource exchange in industrial symbiosis, enabling the creation of exchange networks. On the other hand, multilateral contracts are related to the mutualisation of infrastructure, as the network's identity is more related to the group of actors sharing infrastructure towards a common objective by combining resources Cluster site managers and facilitators can enable both types of contracts. Research and data available in this respect are limited, as contracts tend to be confidential due to commercial sensitivity.

### 5.2.3 TOOL APPLICATIONS FOR IS GENERIC CASES

In order to explore further the contracts for IS, generic cases provide the context to apply game theory tools. The two legal forms for contractual networks correspond with the two basic modes of industrial symbiosis: exchange and mutualisation. To analyse the exchange mode, the payoff matrix model is proposed. On the other hand, a Shapley value model is proposed to analyse the mutualisation mode.

Figure 5.9 schematises the use of IS generic cases to develop insights for contracts based on game theory tools. The IS generic case can lead to a specific type of symbiosis. In the case of a (bilateral) exchange of resources, developing a payoff matrix from revenue-cost models can bring significant insights to negotiate and elaborate agreements enabling collaboration. In the case of (multilateral) mutualisation of infrastructure, the application of the Shapley value to allocate revenues and/or costs can support business cases towards a more specific contract. In the following sections, the methodology is further explained and exemplified.

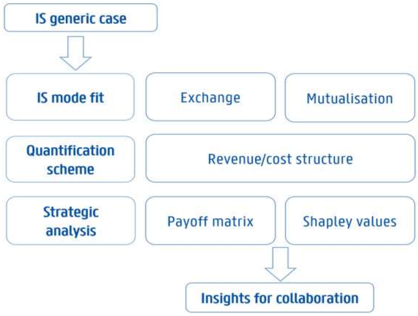



Figure 5.9 Application method for IS games based on generic cases.

The modelling approaches for IS games can be divided into two types: static and dynamic. The static approach focuses on optimising payoffs towards the design of an integrated system, requiring top-down coordination. The dynamic approach focuses on the interaction of the players (i.e., agent-based modelling), exploring bottom-up symbiosis options that do not require coordination (*Figure 5.10*). In between the two approaches, hybrid models can be established by taking advantage of each approach, e.g., by including an optimisation step in the dynamic interaction of the agents.

In this chapter tools for both, dynamic and static approaches are covered. The payoff matrix for the IS exchange mode is related to the dynamic approach. On the other hand, the Shapley value approach is related to the static focus, as this leads to the optimal value under static circumstances.

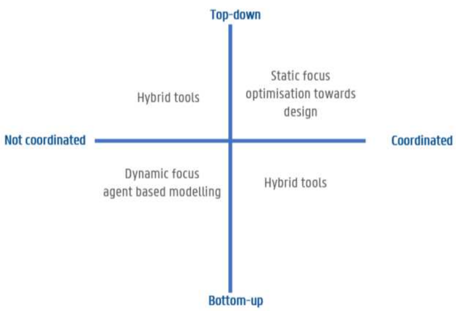



Figure 5.10 Modelling approaches for IS as non-zero-sum game (adapted from (Aviso et al., 2022).

#### 5.2.3.1 Bilateral exchange model (payoff matrix for two players)

The bilateral resource exchange model is the most frequently reported model for symbiosis. It refers to the exchange of solid or liquid waste that can reach distances across industrial clusters (Jensen et al., 2011). From the generic cases collection, eight cases are oriented towards bilateral resource exchange (*Table 5.4*), including waste fuel valorisation, coke valorisation, and the exchange of other by-products in the process industry.

Table 5.4 List of cases oriented towards resource exchange in bilateral schemes.

| # | Title | Description | Cement | Chemicals | Minerals | Steel | Engineering | District |
|---|---|---|---|---|---|---|---|---|
| 1 | **Waste fuel valorisation** | Transform waste streams with high-calorific value into alternative fuels for process industry | x | x | | x | x | x |
| 6 | **Coke valorisation** | Transform industrial steam cracker coke into raw materials for steel and cement industries | x | x | | x | x | |
| 9 | **Industrial water networks** | Optimise water use in process industry via water networks in industrial clusters | x | x | x | x | x | x |
| 10 | **Co-product valorisation (minerals)** | Use inorganic residues as raw materials in minerals industry | x | | x | x | x | |
| 11 | **Co-product valorisation (cement)** | Transform industrial co-products into raw materials for the cement and construction sector | x | x | | x | x | x |
| 17 | **Waste plastic valorisation in steel** | Use plastic waste as raw material in steel industry | x | x | | x | x | x |
| 19 | **Steel slag valorisation** | Transform steel slag into raw materials for the chemical and cement industries | x | x | | x | x | |
| 20 | **Waste plastic valorisation in cement** | Use plastic waste as raw material in cement industry | x | x | | x | x | x |

The typical costs to consider for bilateral exchanges are:

- Raw material cost.
- Alternative material cost.
- Disposal cost of alternative material.
- Logistics cost.
- Engineering cost (if needed).

Key gains are identified as cost savings in terms of raw materials and disposals. Additionally, associated costs related to environmental (raw material savings) and social impacts (increased business relations) may influence the payoff values, requiring a significant inclination to communicate and negotiate among the interested parties. Thus, game theory tools and especially the IS payoff matrix can support the communication by helping the agents think from the perspective of others.

A simple framework to explore further the IS payoff matrix proposes a pair of industries with two extreme strategies: fairness and opportunism (Yazan et al., 2020). If both industrial players run a fair game, the highest system gains are reached, given the total system optimisation. However, as an often-dominated strategy, it requires contracts to enforce compliance, given the possibility of increasing individual benefits with alternative strategies. If both players move in an opportunistic way, there is no option for symbiosis (figure 5.11). The opportunistic player will have a maximum profit (defined as sum of the maximum profit of each player by establishing symbiosis) minus a minimal contribution to the other parties. In this way, games with mixed strategies (fairness and opportunism) enable exploring options to define the minimal contribution for the fair player, which may involve the analysis of technical (process modification) and non-technical factors (company policy, resource control, negotiation skills, etc.).

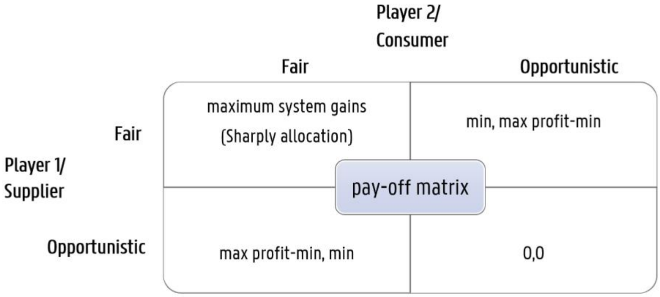



Figure 5.11 IS payoff matrix (adapted from Yazan et al., 2020).

For figure 5.11, agent-based modelling can show that opportunistic strategies turn into fair strategies in the long term due to the game's repetition and the players' learning (Yazan et al., 2020). Similarly, it can be argued that industrial clusters enable game repetition for process industries, as the site cannot be easily relocated.

Another fundamental approach, more specific for the resource exchange type of symbiosis, suggest two strategies: sending waste vs. non-sending actions. Such approach enables to explore further IS possibilities based on the specific action of the players.

In a startling example of application, each partner has two options with their respective payoffs (

Figure 5.12). The initial logic is that if they send their under-used resources to each other, they will have a profit that is not necessarily the same for each player (1,10 profit units as an example) due to the difference in waste disposal costs and raw material costs. If no player sends the resources, there will be no profit, or there may even be a penalty associated with keeping the resource (as waste).

For the mixed strategies (only one partner sending waste to the other), it can be assumed that the situation follows the same logic. I.e., if partner 1 is not sending waste, he gets zero profit. If partner 2 chooses the sending strategy, he gets unilateral profits (due to avoiding high waste disposal costs). Such a game setting encourages both partners to send on materials as best mutually benefitting response (sending dominates, not sending in the payoff matrix). However, the situation is not exactly the same for both partners: for partner 1 the difference between sending and not sending is minimal, while for partner 2 it is dramatic. In this situation, partner 2 may need to negotiate sharing profits with partner 1 to increase the incentive for partner 1 to set the exchange in a bilateral contract.

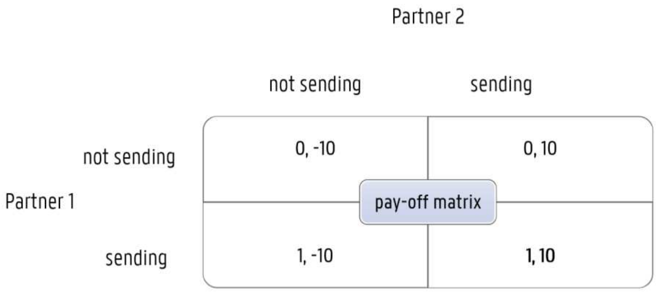



Figure 5.12 IS payoff applied to a typical bilateral exchange.

The study case of IS in the Humber region exemplifies the situation above (Cervo et al., 2019). In this case, a chemical company identified a synergy case with a cement company to valorise waste, first with internal material reuse of the stream (resulting in over 95% of total profit), and then use the residues as a low-cost fuel in the cement factory, avoiding the disposal cost. Such a case is primarily a recycling case in the advantage of the chemical company, the involvement of the cement company would require a degree of profit sharing/adjusting the payoffs for the players, as the incentive for the cement company may be insufficient to compensate for process adaptations derived from using such a new fuel, on top of additional logistics for both companies. Setting the cost-benefits analysis in a payoff matrix may support the collaboration by putting the players 'in each other's shoes', which is subject to changes in regional conditions.

Once the parties enable communication, potential responses (considering synergies and other externalities) can be clarified, in addition to the sharing of profits. To elaborate further, an acceptable pay-off may be 4, 12 (instead of 1, 10 in

*Figure* 5.12), which is a more balanced option to involve both partners.

Another learning from payoff matrices for symbiosis is that having the option of sharing optimal profits does not necessarily change the outcome of the game.

Figure 5.13 shows the case where profits are shared when both partners are sending. For the mixed cases, conflicting negotiations can lead to a proposal that benefits partner 1. In this case, the sending strategy dominates the not-sending one for partner 1. Therefore, partner 1 will send. For partner 2 there is no dominant strategy, but as partner 2 is choosing to send, it is best for partner 1 not to send (payoffs 4>3 in

Figure 5.13). However, such contract would lead to a suboptimal solution, as profit-sharing was insufficient to make non-sending a dominant solution. Thus, when establishing contracts, the magnitude of profit sharing should be considered, and also any penalties resulting from deviating from the agreed strategy. The systematic use of the payoff matrix may prevent the failure of an incentive or penalty strategy by taking into account all possible strategies in the game, going beyond the single player perspective.

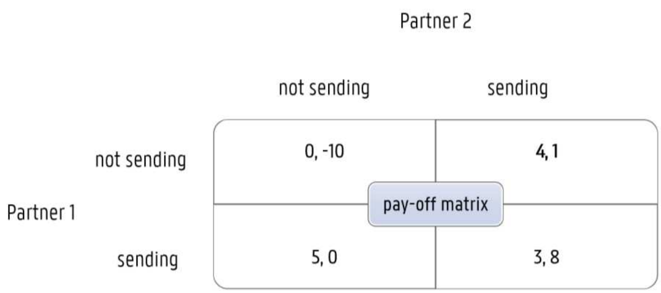



Figure 5.13 IS payoff applied to a typical bilateral exchange with conflicting negotiations.

#### 5.2.3.2 Multilateral mutualisation model (Shapley value)

The multilateral mutualisation model of symbiosis focuses on shared infrastructure including the processing of gas streams that show disadvantages when they are transported long distances (Bütün et al., 2019b; Hu et al., 2020). From the generic cases collection, 13 cases are oriented towards mutualisation symbiosis (Table 5.5). They include valorisation of $CO_2$ through shared infrastructure for upgrading, utilisation, and storage. Also, cases such as heat exchange networks and renewable energy productions are included, as all these cases have critical infrastructure needs.

Table 5.5 List of IS generic cases oriented towards infrastructure mutualisation.

| # | Title | Description | Cement | Chemicals | Minerals | Steel | Engineering | District |
|---|---|---|---|---|---|---|---|---|
| 2 | **$CO_2$ mineralisation** | Capture and purify $CO_2$ emissions for reuse as raw material in process industry | x | x | x | x | x | |
| 3 | **District heating** | Reuse low-temperature waste heat from process industry to supply district heating networks | x | x | | x | x | x |
| 4 | **Energy optimisation** | Optimise energy use in process industry and seek synergies with other process industries | x | x | x | x | x | x |
| 5 | **Wind power collaboration** | Jointly invest in wind power generation for shared use of renewable electricity in industry and communities | x | x | x | | x | |
| 7 | **Solar power collaboration** | Jointly invest in solar power generation for shared use of renewable electricity in industry and communities | x | x | x | x | x | |
| 8 | **Industrial heat networks** | Optimise heat use in process industry via heating networks in industrial clusters | | x | | x | x | |
| 12 | **Demand Side Response** | Optimise electricity sourcing and use via demand-response flexibility in industry clusters | x | x | x | x | x | |
| 13 | **CO valorisation from steel** | Transform rich CO off-gases into raw materials for the chemical industry | | x | | x | x | |
| 14 | **Industrial $CO_2$ capture and utilisation** | Transform rich $CO_2$ streams into raw materials for the chemical industry | x | x | | x | x | |
| 15 | **Wastewater treatment** | Optimise water treatment in process industry and seek synergies with other industries | | x | | x | x | x |
| 16 | **Industrial $CO_2$ capture and storage** | Store $CO_2$ streams from process industry via piping or shipping in empty gas fields | x | x | | x | x | |
| 18 | **Solar heat** | Jointly invest in solar heat plants for shared use of renewable heat in industry | x | x | x | | x | |
| 21 | **Hub for $CO_2$ upgrading** | Jointly invest in hub central for share upgrading of captured $CO_2$ | x | x | | x | x | |

IS mutualisation models focus on the revenue and cost allocation of multiple players, often related to shared infrastructure or services. A widely used allocation algorithm in game theory is the Shapley value. It is a fair allocation strategy considering the marginal contribution of all players, including all possible coalitions (Kenton, 2021).

Four conditions for application of Shapley value in games can be identified (Kenton, 2021):

1. All the gains from cooperation are distributed among the players: none are wasted.
2. Players that make equal contributions receive equal payoffs.
3. The game cannot be divided into a set of smaller games that together achieve greater total gains.
4. A player that makes no contribution to the gains from cooperation receives zero payoff.

In set N of n players (Equation 2), function *v* gives the value (or payoff) for any subset of those players. Let S be a subset of N, then v(S) gives the value of that subset (characteristic function). So, for a coalitional game (N, v) the equations calculate the payoff for player *i*, i.e., the Shapley value $\Phi_i(v)$. The equation calculates the *marginal value* of adding player *i* to each subset S. The equation is divided into two main factors, one for the permutations given by the number of players N, and the other for calculating the marginal contribution for each coalition. The average (1/n) product of such terms correspond to the Shapley value.

Equation 2 Shapley value formula (Shapley, 1953).

$$\varphi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(n - |S| - 1)!}{n!} (v(S \cup \{i\}) - v(S))$$

The Shapley value is one way of distributing the total costs/ gains over the players, assuming that they all collaborate (Ichiishi, 1983). Equation 3 can be calculated in a spreadsheet format, where each raw corresponds to a specific coalition.

Equation 3 Shapley value as a summation of marginal contributions for player i.

$$\varphi_i(v) = \frac{1}{\text{number of players}} \sum_{\text{coalitions excluding } i} \frac{\text{marginal contribution of } i \text{ to coalition}}{\text{number of coalitions excluding } i \text{ of this size}}$$

The Shapley value can also be interpreted in terms of synergy. The total value of the coalition comes from summing up the synergies of each possible subset of players in the coalition. In the Shapley value allocation, the synergy of each coalition is divided equally between all members (Grabisch, 1997; Wikipedia, 2022).

Equation 4 Shapley value as distribution of synergy gains for player i.

$$\varphi_i(v) = \sum_{\text{coalitions including i}} \frac{\text{synergy of the coalition}}{\text{members in the coalition}}$$

To apply Shapley value distribution, it is necessary to define a cost function that allows to know the value for each coalition. The typical case is the IS mutualisation of infrastructure (electricity, water, $CO_2$, $H_2$, heat, IT, etc.). It is mainly driven by economies of scale. Therefore, a cost-scaling function enables to know the value for each coalition, as it only depends on the volume processed in the infrastructure.

The model for IS mutualisation based on the Shapley value requires two functions. The first function is to define the individual gains/costs based on the technology for a given production volume (*Equation 5*). A second function (*Equation 6*) is to define the change in volume or scale (Tribe & Alpine, 1986). With these two functions, the inputs for the Shapley value can be defined.

Equation 5 Base cost as a function of the production volume and the technology model used.

$$C1 = f(V1, technology)$$

*Simplest case:* $C1 = k \times V1$, *where k is a cost factor based the technology suitable for the case.*

Equation 6 Power sizing function adapted for coalitions

$$C_{coalition} = C_0 \left(\frac{V_{coalition}}{V_0}\right)^x$$

$C_{coalition}$=Scaled cost for the coalition.

x=Cost capacity factor ranging from 0.5 to 0.9 (sector and scale dependent).

$C_0$=Weighted average cost of sized units at the individual capacities (1 to n) corresponding to the coalition (Equation 7)

Equation 7 Weighted average cost

$$C_0 = \sum_{1}^{n} \frac{C_i V_i}{\sum_1^n V_i}$$

$V_0$=Weighted Average production volume at the individual capacities corresponding to the coalition (Equation 8).

Equation 8 Weighted Average production volume

$$V_{0=} \sum_{1}^{n} \frac{V_i^2}{\sum_1^n V_i}$$

$V_{coalition}$=Total production volume at the individual capacities corresponding to the cluster (Equation 9).

Equation 9 Total production volume

$$V_{coalition} = \sum_{1}^{n} V_i$$

An example can illustrate the insights provided by this model. The example consists of three players willing to fairly mutualise the cost of a carbon capture facility in an industrial cluster. Player A alone would pay 15 cost units to process their emissions. Similarly, players B and C would pay 20 and 30 units, respectively. In this case, the cost of the unit could be a direct function of the emission volume that each capture unit needs to process (in this case, k=1 in *Equation 5*). A common scaling factor (x=0.7) in *Equation 6* can be used to scale the plants, serving as the base for the calculation of the marginal benefits of increasing the size of the units due to multiple coalitions. Applying the scaling function to the maximum capacity of 65 units (V2=A+B+C) leads to a cost of 47.9 units, generating a total cost of 26% lower, significant for the business case of mutualised infrastructure. The Shapley values obtained for this configuration for each player are A=9.0 B=14.3 C=24.6, leading to cost reductions of 40%, 29%, and 18%, respectively. The partner with the smallest infrastructure gets the highest cost reduction fraction, but in absolute numbers, the cost benefits are much lower than for the partner with the highest capacity need (C), leading to a fair distribution.

The allocation model based on Shapley values enables the initial outline of a fair contract for mutualisation of infrastructure based on a cost function that can be tailored per sector adapted for major precision (Junius, 1997; Tribe & Alpine, 1986).

## 5.3 DISCUSSION AND FURTHER RESEARCH

A total collection of 21 generic cases has been introduced covering five industrial sectors. To take the next step in the exploration of IS generic cases, promising tools were investigated according to the main types of symbiosis: mutualisation and exchange. Payoff matrices provided a starting tool of analysis, while Shapley values provided allocation options of cost and benefits for multiple parties. In this section, further research possibilities are discussed.

### 5.3.1 GENERIC CASES GAPS AND OPPORTUNITIES

Generic cases are not mutually exclusive; they are rather inclusive. Combining symbiosis cases can be encouraged, e.g., for a company to size its IS opportunities in a local industry cluster or hub, or in the wider surroundings. An example is a mineral industry company jointly developing water network infrastructure with other companies (case #9) while simultaneously capturing and utilising $CO_2$ emissions in their mineralisation processes (case #2). Hence the list of generic IS cases can present a building block for multiple IS solutions according to the sector diversity in various industrial clusters.

An important remark is that generic cases exploited as business engagements have a tendency towards promoting further collaboration, while paying less attention to the typical challenges associated with the case. For the latter, other tools are developed such as the LESTS survey and scores as detailed in chapter 4. It is expected that after raising motivation to engage with other companies in a specific case, the involved parties define associated challenges in more detail so as to evaluate the IS feasibility in a specific cluster or region. Therefore, the cost and environmental impact reduction requires further evaluation.

Many generic cases contribute to $CO_2$ emission reduction; however, the emission accounting in industrial symbiosis implies several challenges. A first challenge is that emission reduction resulting from IS frequently occurs beyond scope 1 and scope 2 emissions (WRI & WBCSD, 2004), thus beyond the reach of standard emission reporting and trading systems such as the ETS in the EU. They growingly include product footprints, thus emissions across the entire value chain, i.e., scope 3 emissions (WRI & WBCSD, 2004). Here, reductions frequently depend on substitution assumptions (replacing one material with another, assuming that there is no additional production) with limited traceability and wide variability of suppliers and client's conditions, leading to complex reporting. Automated environmental foot printing in integrated (circular) supply chains in Europe promises effective solutions (Belhadi et al., 2021) towards transparent scope 3 emissions accounting. However, there is still a long way to go to develop a policy framework that recognises the above-mentioned challenges and provides answers to general value chain analytics as well as for specific industrial symbiosis cases.

Strategic analysis based on generic IS cases can give more certainty on the relation of the energy/material resources substitution in symbiosis and its environmental impact reduction. Such substitution leads to an increased material or energy efficiency relative to primary materials, regardless of collateral increases on other material or energy resources, leaving open the possibility of higher production, i.e., if a significantly low-cost secondary resource is available to substitute primary resources in a product, and there is demand in the market for such a product; the synergies will lead to an increase in production and their associated environmental impacts. As a pathway to reduce environmental impacts, IS should aim for strategic substitution cases when no player produces more, and the others produce the same or less to take advantage of the resource efficiencies as environmental reduction measures. Such strategic substitutions often require a market analysis and the identification of the local conditions of companies. Symbiosis studies that consider strategic effects and options promise further insights into the energy/material substitution assumption in IS.

Finally, the generic cases can be analysed at three consecutive levels (Figure 5.14). The first level is the initial quantification, using blueprints and simulation models to define the case more concretely. Economics is the following level, identifying the specific offer-demand situation between a perfect competition (low prices due to diversification options) and a perfect monopoly situation (high prices due to a narrow set of offer/supply options). Lastly, the third level considers the strategic effect, i.e., the position and reaction of other players when assuming symbiosis as a strategy. The integration of different levels of analysis, including a strategic one (where players interact), is a promising research line, leading to compressive simulation exercises and potentially more effective IS matchmaking, given that more opportunities can be identified, and more risks can be mitigated in advance.

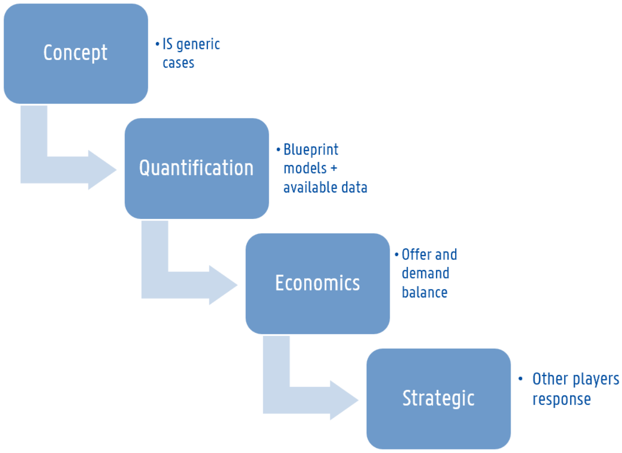



Figure 5.14 Levels of analysis for generic cases.

### 5.3.2 FURTHER APPLICATION OF GAME THEORY TO IS RESEARCH

From the generic cases, it can be learned that combinations of technical options bring synergies and externalities that can be optimised. Such optimisation often requires contracts among different parties (Van Eetvelde, Delange, et al., 2005). Without contracts, the distribution of benefits and costs leads to unacceptable options for some of the partners in a network, making such options unfeasible.

Starting an analysis with an exchange/bilateral perspective is recommended. Bilateral contracts enable the highest flexibility at the smaller partnership size with expansion possibilities. Such contracts are also suitable for a dynamic assessment (Desideri-Perea, 2021; Yazan et al., 2020). On the other hand, multilateral contracts for infrastructure are beneficial in tick/stable markets, requiring solid political and macroeconomic certainty to be sustainable. The study of contracts with multiple degrees of flexibility is necessary to study further IS generic cases.

In bilateral and multilateral contract schemes, a key challenge is defining utility functions that output the payoff of partners and coalitions (Jato-Espino & Ruiz-Puente, 2021). It is challenging due to the need to evaluate significant aspects (in both risks and opportunities) that may not be the same for all the parties involved. Also, decision-makers tend to be either risk avoiders who tend to emphasise costs or gain seekers who emphasise benefits, making the cost-benefit analysis difficult to perform and agree upon. Participatory methods (Santos Coelho et al., 2022) are recommended in the definition of the utility functions for coalitions.

The application of game theory to substantiate further the use of the generic cases lies in the exploration of the payoff matrix with a wide range of domains for utility functions. The IS generic case suggests 3 clusters of categories to define the utility function:
Profit

1. Virtual market. Consider the supply and demand relations for the resources to define the costs and revenues of the opportunity.
2. Other costs. Consider economies of scale and scope related to resource exchange or mutualisation to define costs and revenues.

Planet

1. $CO_2$ reduction. Consider the current incentives and penalties derived from emissions reductions.
2. Energy efficiency. Consider the direct (energy savings) and indirect (resource preservation, public incentives) gains to define cost and revenues.

3. Material efficiency. Consider the direct (material savings) and indirect (resource preservation, public incentives) gains to define cost and revenues.
4. Renewable use. Consider the direct (material savings) and indirect (resource preservation, public incentives) gained to define cost and revenues.

People

1. Jobs. Consider the preservation and generation of work positions.
2. New business relations. Consider the potential to diversify your business network.

The eight benefits categories listed above can be used as a checklist to explore the benefits that a generic case may provide to a company in a cluster. There are already methodologies to define the cost-saving functions of symbiosis (Fraccascia et al., 2019; Yazan et al., 2020). Additionally, environmental and social benefits calculation methods are available to define integral payoff matrices for strategic analysis (Jato-Espino & Ruiz-Puente, 2021). Such cost-benefit models can substantiate the payoff matrix or the Shapley value allocation model. However, documented cases are necessary to define the effectiveness of an integrated utility function for multiple stakeholders in an IS network.

The two modes of symbiosis in this chapter are associated with specific cost types (Figure 5.15). The IS resource exchange mode is related to a reduction in direct variable costs (depending on the amount exchanged with minimal need to allocate costs), while the IS infrastructure mutualisation mode is related to indirect fixed costs (requiring allocation). Analysis of cost structures in symbiosis projects may bring valuable insights for research on effective contracts.


Figure 5.15 General cost scheme for a four-sector cluster illustrates the IS modes (ABCD indicates a different sector in the cluster).

In the multilateral scheme for mutualising infrastructure for IS, economies of scale cannot always be taken for granted. Increasing the size of infrastructure may lead to diseconomies of scale. It refers to increasing unit costs upon increasing scale due to limitations on different resources than at lower scales were not a limit. Such resources could be insufficient labour; also, additional management required, added infrastructure (energy), and others. Thus, further evaluation of the mutualisation of infrastructure is recommended to determine if economies of scale apply.

The concept of evolutionary stable games (Cowden, 2012) is a promising area of study for industrial symbiosis at a strategic level. In evolutionary games, strictly dominant strategies will be successful mutations. Such studies can bring detailed insights into stability and replicability for industrial symbiosis. There is already an ongoing project in the Netherlands with this evolutionary approach focused on Dutch industrial clusters (NWO, 2019), where alternative feedstock options are evaluated from an evolutionary perspective. Strong interdependences in multi-process/multi-firm industrial systems are a barrier for the implementation of alternative feedstocks as interventions in any single process can affect other processes (possibly operated by other firms), both at the local scale of an industrial cluster and in the supply chains involved (which are geographically dispersed) (NWO, 2019). A high level of iterative joint-work between engineering modelling (current and future industrial processes), and innovative economic approaches are recommended to explore industrial symbiosis projects.

# CHAPTER 6 GENERAL CONCLUSIONS

The accelerated development of industry has reached a global scale of environmental and societal impact with an unprecedented level of international interdependency. Such development has affected global and local aspects beyond natural restoration capacity (i.e. biodiversity loss, exhausted abiotic resources, among others) (Rockström et al., 2009; Steffen et al., 2015), including pollution of water, air, and soil (e.g. plastic waste) (Chen, 2018; Rhodes, 2018). This adds to the increasing social awareness of environmental impacts influencing both the demand and the supply sides of economies (EMF, 2015; European Environment Agency, 2019). Recognising the need for adaptation and increased consideration for natural and social patterns are crucial aspects that require firm and explicit action. In the European Union, policies are developed to face local and global challenges (European Commission, 2016b, 2019c, 2022), shaping a legal framework where all agents of society can take action. Such ambitions are enormous and require intense research as well as industry collaboration to provide compelling insights, user-friendly tools and practicable solutions.

The central topic of the present work is industrial symbiosis (IS) as a strategic enabler for process industries towards Europe's carbon neutrality and circular economy goals. Process industries (cement, chemicals, steel, etc.) are the foundation of the European economy, transforming raw materials into building blocks for strategic products and applications in today's society. Specifically, process industries are energy-intensive, requiring a high level of transformation to align with the regional ambitions in Europe. Although each sector has specific needs, cross-sectoral collaborations (by-product exchange, joint infrastructure, etc.) offer efficient opportunities to enable the required transformations.

The present work addressed two main research questions.

First it was studied how to systematise the exploration of cross-sectoral collaborations (IS) in the process industries. A regional approach to systematically identify clusters and locations with specific potential to establish industrial symbiosis was developed. The research has proven that DBSCAN clustering is highly suitable to locate hubs and regions with high levels of industrialisation when using a combination of publicly available industrial and urban databases. The method also provided sufficient adaptability to explore IS sensibilities related to the distance between sites and the minimum number of sites in clusters.

It was observed that clustering for IS can be optimised in several ways. A first topic of research was dedicated to improving the quality of the databases used to close existing gaps e.g., with regard to multiple sectors including cities. The use of EU databases brought significant information to ground clustering. A second step to improve clustering was taken by including additional parameters or focal areas, such as thematic frameworks (e.g., hubs around $CO_2$). This way supplementary indicators of relevance for clustering could be found across databases. An orientation framework was presented to direct researchers in process industries to specific topics and databases with a higher level of detail in the context of the circular economy and thus facilitate the prospection of IS potential. Finally, the research highlighted the importance of integrating non-technical factors (LESTS) in cluster analysis. This area of research is further elaborated by the ECM group in the TRILATE project (VITO & UGent, 2022). This project brings the current research to the next level by exploring the above-mentioned improvement options to investigate the energy infrastructure needs in Belgium and nearby regions in answer to the nexus of electrons and molecules to flexibilise the current energy system.

A sectoral instead of a regional approach was found useful to systematically explore IS. The research to develop IS profiles for energy-intensive sectors combined with IS databases (IS case-base), has facilitated the top-down identification of potential IS initiatives. The profiles included four layers of sharable resources: energy, by-product, water, and waste resources, and enabled three focal insights: typical synergies among sectors and urban districts emerged, IS technologies common to all sectors could be identified, and sustainability insights were drawn from IS cases. Together they were found to advance replication of IS across clusters and regions with higher industry densities.

The research also pointed to optimisation potential of the IS profiles. A direct improvement of symbiotic activity was introduced by widening the method to new sectors. Although cement, chemicals and steel have an intense energy demand and emissions footprint, the process industry is under-represented with only three sectors. Paper, glass and power plants were recommended for inclusion, along with other energy and carbon-intensive process industries. It was also suggested to expand the IS model by considering collective services, sharing equipment, infrastructure or technologies to uncover unprecedented resource categories and create new synergies. Finally, widening the scope of technologies towards new solutions with a direct and positive impact on the climate and circular economy goals, was suggested. This enters the IS profiles into energy and materials transition tools and allows to include links between sectors. Recent projects (PBL & TNO, 2018; VITO et al., 2022) are modelling future technologies into process and database libraries. They can be the base of new IS profiles and thus enable more detailed studies of IS potential and advance the climate and circular ambitions of industries and regions.

The second research question investigated the challenges and opportunities beyond technological aspects.

The more one wants to study the implication of technological innovation; the more one needs to look at the local conditions of implementation (mostly non-technological factors). In IS cases, the involved industries are the focus level for analysis. This requires tools to explore technical (product/process) aspects significant for any potential collaboration, next to organisational or managerial aspects. The LESTS guidelines published by ECM group (Van Eetvelde, Delange, et al., 2005) provide a framework to study non-technical aspects that are critical to implementing industrial clusters. The LESTS tools have proven adaptable and valuable for identifying barriers to industrial symbiosis based on surveys dedicated to potential partners. The tools were either simplified to provide a quick risk assessment of IS initiatives or expanded to discuss the full project life cycle implications of a symbiosis project.

The work evidenced the need for further research on LESTS tools in multiple directions. An initial direction is adapting the tools to specific frameworks, such as circularity or the energy transition in selected sectors. A bottom-up approach is presented by inviting industries or regional actors to define a topic of interest. This allows the selection of specific cases or projects for applying the LESTS surveys and building a database of non-technical factors for specific hubs. It is understood that challenges common to IS cases are best addressed together; this enables efficient organisational strategies. Another improvement aspect was suggested by linking LESTS factors to specific modes of symbiosis organisations (exchange or mutualisation). Providing a non-technical factor profile for each type of symbiosis is perceived to facilitate the adoption of symbiosis projects by solving non-technical barriers. Such integration is proven beneficial for a region or sector to promote specific symbiosis.

Another way to investigate the challenges of non-technological aspects was studied by focusing on generic collaboration schemes. The IS generic cases that were analysed showed a broad range of opportunities to join symbiosis projects across process industries. The 21 generic cases indicated initial collaboration directions of involved sectors with high potential for deeper analysis and specific evaluation. Furthermore, by applying game theory tools adapted to industrial symbiosis in generic cases, challenges could be identified based on the structure of interaction among sectors. Game theory tools proved helpful in providing insight into how to reach optimal collaboration by fairly distributing revenues and costs among partners.

It was observed that IS generic cases can be enhanced in several ways. Firstly, the scope can be expanded to include more process sectors. It is understood, though, that such an increase also impacts the complexity of the cases and the analysis, thus requiring further research on present and future IS cases. A second improvement aspect is related to impact assessment. Ideally, statistical data would show the impact of projects in different dimensions, but since mostly not available, impact models were suggested to fill the gaps. Finally, the research showed that applying game theory could be developed further by utilising such tools in existing industrial clusters. They could generate the data required for strategic evaluation of potential IS projects, thus advancing collaboration in clusters.

As with any tool or framework, an IS approach can serve multiple purposes, but not necessarily all at the same time. For example, industrial symbiosis can increase resource circularity as well as climate neutrality when both objectives are set as goal to find synergies. The chemical sector provides an excellent case to illustrate this, due to its long tradition of energy and material optimisation in typical chemical clusters such as the Port of Antwerp-Bruges. Chemical process integration is mostly driven by efficiency but growingly also includes climate and resource neutrality as well as wider societal goals (Accenture, 2021; Ketels, 2007). To this purpose, the sector crosses boundaries and enhances the integration with other sectors, such as energy, waste, recycling, agriculture, or even urban communities.

The research in this thesis focuses on the process industry with a special emphasis on large industrial $CO_2$ emitters (explained in section 1.2.4). Such emphasis may hide the potential for IS with other sectors, within and outside the process industry. This is the case for recycling and waste management sectors, which are becoming essential to deal with asymmetries in the supply and demand of resources in clusters and regions. Another example is the bio-based sector, which growingly contributes to the transition of the process industry towards a greener and cleaner economy (Tanzer et al., 2021).

By restricting the work to three key process industries (chemicals, steel and cement), by choosing distance and number of sites as key clustering parameters and by applying Sharply values, it was possible to develop methods and select tools to explore IS potential and generate replicable IS cases within the frame of this PhD. While the limitations of these choices are recognised, it is also acknowledged that the work has paved the way to widening and deepening the methods and tools, thus advancing the research on industrial hubs and clusters in Europe. In particular the symbiosis potential at local, regional, and national scale is encouraged (Domenech et al., 2019). This depends on case-specific parameters, such as enlarging cluster sizes in distance, number of sites, even in shape and variety of partners (e.g. including SMEs). To expand the research beyond static scenarios using the Sharply value, it is suggested to experiment with a Monte-Carlo approach which can introduce flexibility by accounting for negative as well as favourable variations (Schoubroeck et al., 2021). Likewise, further research is encouraged to evaluate the socio-environmental impact of selected generic IS cases, applied in existing clusters. This will enable to integrate life-cycle thinking in empirical cases (Kerdlap et al., 2022) and incorporate a systems perspective in the evaluation of the impact in all three pillars of sustainability.

It can be concluded that technical and non-technical factors are essential in assessing industrial symbiosis. A technical base provides the starting point for contextual (clustering) and specific (cross-sectoral synergies) industrial symbiosis potential. However, the technical base alone has critical shortcomings due to the demanding collaborative nature of symbiosis projects. An industrial cluster or regional synergy with a high technical potential for collaboration may never result in more than an academic exercise if the organisation's capabilities for symbiosis are not triggered. Financial (economic), local (spatial, social), contractual (legal), and similar non-technical aspects (Van Eetvelde, Delange, et al., 2005) provide a necessary organisational base to implement symbiosis. They include additional dimensions relating to IS management that enable or prevent symbiosis. Considering such factors on top of a solid technical base supports strategic navigation of the challenges involved in industrial symbiosis.

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# ANNEXES

# APPENDIX 1 AUTHOR BIBLIOGRAPHY

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Publication X. Mendez Alva, F., & Van Eetvelde, G. (2021). Enhancing circularity in the process industry through industrial symbiosis. Presented at the 2nd Online Symposium on Circular Economy and Sustainability, Alexandroupolis, Greece.

**Contribution report:**

Publication I. Workshop participant. Main contribution to discussion on concepts and definitions for industrial symbiosis, final version revision.

Publication II. Second author. Main contribution to data collection, support on content discussion and anlysis.

Publication III. Second author. Main contribution to data collection, support on content discussion and anlysis, and conference presentation.

Publication III-VII. Main author. Main contribution to data collection, conceptualisation, methdology development, discussion and final manuscrip revision.

Publication VII. Contributing author. Main contribution on methodology development, result discussion and review.

Publication IX-X. Main author. Preseting author in international conference (extended abstracts).

# APPENDIX 2-A DATABASE OF INDUSTRIAL FACILITIES PER CLUSTER

Database of industrial facilities per cluster. Supplementary data to this chapter can be found online at https://www.mdpi.com/article/10.3390/su132413906/s1.

# APPENDIX 2-B DATABASE OF CITIES PER CLUSTER

Database of cities per cluster. Supplementary data to this chapter can be found online at https://www.mdpi.com/article/10.3390/su132413906/s1.

# APPENDIX 3 IS CASE COLLECTION

Table A31 shows the first 10 cases of the collection. Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128031

Table A3.1 IS case collection.

| # | Stream class | NACE (source) | NACE name (source) | NACE (sink) | NACE name (sink) | Stream description | Final use | References |
|---|---|---|---|---|---|---|---|---|
| 1 | energy | C2442 | Aluminium production | C2011 | Manufacture of industrial gases | electricity | electricity | Golev et al., 2014 |
| 2 | waste | C2442 | Aluminium production | C2410 | Manufacture of basic iron and steel and of ferro-alloys | red mud | raw material | Dong et al., 2014 |
| 3 | waste | C2442 | Aluminium production | C2351 | Manufacture of cement | red mud | raw material | Beers et al., 2007 |
| 4 | by-product | C2442 | Aluminium production | C2351 | Manufacture of cement | silica fume | raw material | Golev et al., 2014 |
| 5 | waste | C2442 | Aluminium production | C2351 | Manufacture of cement | slag | raw material | Li et al., 2015 |
| 6 | by-product | C2370 | Cutting, shaping, and finishing of stone | C2013 | Manufacture of other inorganic basic chemicals | ammonium chloride solution | raw material | Dong et al., 2014 |
| 7 | by-product | C2370 | Cutting, shaping, and finishing of stone | C2012 | Manufacture of dyes and pigments | ammonium chloride solution | raw material | Dong et al., 2014 |
| 8 | waste | C1101 | Distilling, rectifying, and blending of spirits | C2015 | Manufacture of fertilisers and nitrogen compounds | vinasse | raw material | Yu et al., 2015 |
| 9 | waste | C1101 | Distilling, rectifying, and blending of spirits | C2015 | Manufacture of fertilisers and nitrogen compounds | alcohol residue | raw material | Zhu et al. 2007 |
| 10 | energy | D35 | Electricity, gas, steam, and air conditioning supply | C19 | Manufacture of coke and refined petroleum products | steam and demineralised water | heating / cooling | Notarnicola et al., 2016 |

# APPENDIX 4-A LESTS SCORES DESIGNED FOR A WORKSHOP SESSION

The appendix includes the instruction to use the LESTS scores, the interface with user, and the description of the scale (1-5).

| | |
|---|---|
| ***Goal:*** | *Scan IS readiness level per LESTS angle* |
| ***Method:*** | *Score key questions on Likert readiness scale* |
| | *key Qs at 3 levels; 5-point semantic scale with explicit end-points* |
| *Q1:* | *IS strategy question (policy/region line)* |
| *Q2:* | *IS readiness question (company/cluster line)* |
| *Q3:* | *IS condition question (stream/project line)* |

Figure 4-A1 LESTS scores instructions.

| | | *nogo barrier* 1 2 3 4 5 *no barrier* | *ex: waste fuel* | |
|---|---|---|---|---|
| LEGAL | L Q1 Policy/regulation | | 3 | 3.0 |
| | L Q2 Readiness to close deal | | 3 | |
| | L Q3 Permit requirements | | 3 | |
| ECONOMIC | E Q1 Public funds | | 3 | 3.0 |
| | E Q2 Readiness to invest | | 3 | |
| | E Q3 Payback requirements | | 3 | |
| SPATIAL | $S_p$ Q1 Regional planning | | 3 | 3.0 |
| | $S_p$ Q2 Readiness of land | | 3 | |
| | $S_p$ Q3 Transport requirements | | 3 | |
| TECHNICAL | T Q1 Existing infrastructure | | 3 | 3.0 |
| | T Q2 Readiness of technology | | 3 | |
| | T Q3 Expertise requirements | | 3 | |
| SOCIAL | $S_o$ Q1 Community acceptance | | 3 | 3.0 |
| | $S_o$ Q2 Readiness to collaborate | | 3 | |
| | $S_o$ Q3 HSE/CSR impact | | 3 | |

Figure 4-A2 LEST scores interface.

Table 4-A1 LESTS scores scale description.

| extreme barrier | high barrier | medium barrier | low barrier | No barrier |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| Stop point | Focus point | Action plan | Feasibility | No issue |
| The item represents a barrier to the synergy that prevents further development at this early stage. | The item represents a barrier to the synergy that needs a plan with a high priority level/high degree of changes/high level of effort | The item represents a barrier to the synergy that needs an action plan with a not outstanding effort level | The item represents a barrier to the synergy, but it is foreseen to be easy to solve | The item does not represent a barrier to the synergy foreseen |

# APPENDIX 4-B RENEWABLE ENERGY INGRATION IN THE PROCESS INDUSTRY

The idea of generic industrial symbiosis (IS) cases is conceived from the wider potential of some specific cases explored and researched in the H2020 SPIRE project 'EPOS'. Based on similarities of industrial partners and sectors, on the type or size of resource streams, local conditions and incentives, some high-potential IS solutions in the EPOS clusters are selected for wider application and/or replication across Europe (EPOS project, 2019h).

The aim of the renewable energy case is to trigger barriers and enablers for collaboration across process industry sectors from a holistic perspective. The RES case is based on EPOS generic cases #5, #7 and #12 on www.spire2030.eu/epos and is aligned with the sector associations' roadmaps.

Depending on the regional availability of wind or solar power, different collaboration strategies can be implemented. A first option is to participate in power purchase agreements (PPA) to supply industry sites or clusters with renewable energy. The next option is participating in a virtual power plant (VPP) that requires electrical flexibility. Another option is to develop joint renewable energy generation facilities, such as wind and solar power, in an industrial cluster. The PPA offers a lower level of operational complexity, while the cluster installation offers a high level of involvement and influence for energy production and cluster integration. An in-between option in terms of complexity and influence capacity is the participation in a VPP (figure A4-B1.

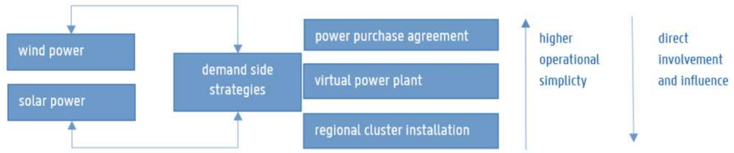


Figure A0-B1 Renewable energy: A case for collaboration across industries.

### Wind power collaboration

Industries can jointly invest in wind power generation for the shared use of renewable electricity in industry and communities. They increase renewable electricity use by jointly investing in wind turbines (EPOS project, 2019b).

### Solar power collaboration

Industries can jointly invest in solar power generation for the shared use of renewable electricity in industry and communities. They increase renewable electricity use by jointly investing in solar panels (EPOS project, 2019c).

### Demand-side response

Industrial collaboration optimises electricity sourcing and uses via demand-response (flexibility) in industry clusters. It reduces and balances industrial power demand by joining a virtual power plant. Process industries have a realistic potential to provide flexibility to the grid and improve the security of the power supply (EPOS project, 2019d).

# APPENDIX 5 IS GENERIC CASE COLLECTION

Case 1-21 available in the EPOS in the SPIRE depository

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case01.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case02.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case03.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case04.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case05.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case06.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case07.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case08.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case09.pdf

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https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case12.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case13.pdf

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https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case15.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case16.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case17.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case18.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case19.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case20.pdf

https://www.aspire2050.eu/sites/default/files/users/user222/Epos-docs/CaseWatch/epos_case21.pdf

*H2020 project EPOS - Enhanced energy and resource Efficiency and Performance in process industry Operations via onsite and cross-sectorial Symbiosis*

EPOS Industrial Symbiosis

# CASE WATCH 01 : WASTE FUEL VALORISATION

Transform waste streams with high-calorific value into alternative fuels for process industry.

Reduce primary resources and costs by reusing waste fuels.


## RECYCLING OUR WASTE FUELS

### KEY INSIGHTS

- value waste streams
- optimise plant operations
- reduce primary fuel use
- reduce $CO_2$ emissions

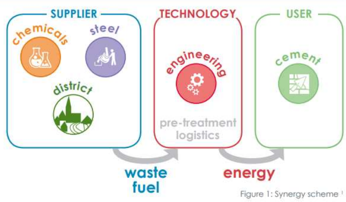


Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Process industries have a high potential to better valorise their waste fuels.

Cement kilns and process industry burners/furnaces often have a top-up demand for high-calorific waste fuels.

- 200-220 KWh of alternative fuel/1000 barrels of oil processed
- 150-200 KWh of alternative fuel/ton steel produced
- 100-200 KWh of alternative fuel produced/person in 1 year
- ---- Minimal calorific value to process fuels in cement kilns (ca. 5 kWh/kg)

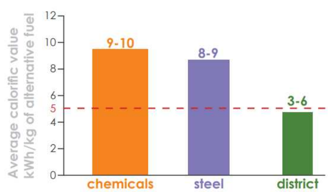


Figure 2: Fuel potential per sector [1,2,3,4,5,8]

## SUSTAINABILITY IMPACT

**Wins for industry**
〉for suppliers: 10-15 €/ton waste fuel[1]
〉for cement: 10-20% reduction of total OPEX[6]

**Environmental gains**
〉primary resource savings:
20-22 GJ saved per ton of waste fuel used[7]

**Wins for society**
〉municipal waste management avoidence[1]
〉improved business relations in regional clusters
〉job creation and new skills development


Figure 3: Sustainability [1]

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*This work was supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 15.0217*

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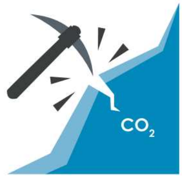
# CASE WATCH 02 : $CO_2$ MINERALISATION

Capture and purify $CO_2$ emissions for reuse as raw material in process industry.

Mine $CO_2$ emissions by converting carbon costs into revenues (credits, resources).




## MINING OUR EMISSIONS

### KEY INSIGHTS

- value $CO_2$ streams
- keep license to operate
- reduce $CO_2$ emissions
- improve sustainability profile

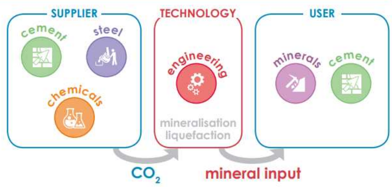



Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Carbon-intensive process industries have a high potential to capture part of their $CO_2$ emissions.

Minerals and cement sectors have a demand for $CO_2$ as feedstock.


Figure 2: $CO_2$ potential per sector [3,4,5,6,7]

## SUSTAINABILITY IMPACT

**Wins for industry**
〉for suppliers: 15-35 €/ton $CO_2$ emissions reduction[10]
〉for minerals: 60-200 €/ton of mineral[7,8]

**Environmental gains**
〉$CO_2$ emissions reduction:
20-70% $CO_2$ mitigation potential[7,9]

**Wins for society**
〉public health benefits due to emissions reduction[1]
〉improved business relations in regional clusters
〉job creation and new skills development


Figure 3: Sustainability [1]

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# CASE WATCH 03 : DISTRICT HEATING

Reuse low-temperature waste heat from process industry to supply district heating networks.

Reduce primary resources by valorising waste heat in communities.

## HEATING OUR CITIES

**KEY INSIGHTS**

- value waste energy
- reduce $CO_2$ emissions
- invest in district heating
- collaborate with society

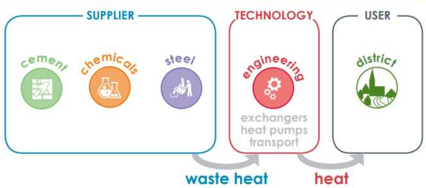

Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Energy-intensive industries have a high potential to share waste heat with surrounding communities.

Communities have a growing demand for waste heat to feed district heating networks.

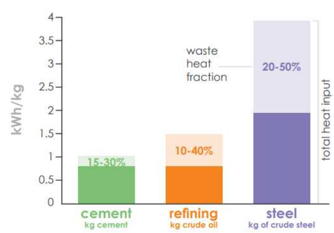

Figure 2: Waste heat potential per sector [1,2,3,4]

## SUSTAINABILITY IMPACT

**Wins for industry**
- for suppliers: 17-20 €/MWh waste heat[1]
- for districts: increase heating network efficiency[5,6]

**Environmental gains**
- primary resource savings:
  10-20 kWh saved/ton crude steel produced[5,6]

**Wins for society**
- waste heat supply to communities[6,7]
- improved community relations in regional clusters
- job creation and new skills development[6,7]

Figure 3: Sustainability [1]

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SPIRE Sustainable Process Industry through Resource and Energy Efficiency

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# CASE WATCH 04 : ENERGY OPTIMISATION

Optimise energy use in process industry and seek synergies with other process industries.

Reduce primary resources by increasing energy efficiency onsite and in industrial clusters.


## GROWING OUR EFFICIENCY

**KEY INSIGHTS**

- reduce energy intensity
- optimise energy use
- reduce $CO_2$ emissions
- integrate sites & clusters

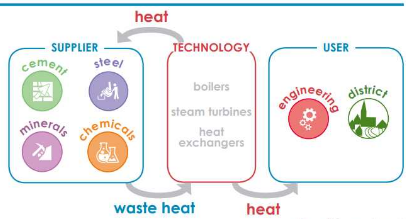


Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Energy-intensive industries have a high potential to recover and reuse waste energy in regional clusters.

Energy-intensive industries can valorise waste energy in regional clusters, esp. in chemical and steel sectors.

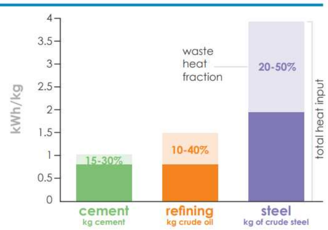


Figure 2: Waste heat potential per sector [1,2,3,4]

## SUSTAINABILITY IMPACT

**Wins for industry**
› for suppliers: 40-80% heat recovery potential[1]
› for industry: 5-10% heat input reduction[1]

**Environmental gains**
› primary energy savings:
80-150 kWh electricity produced/ton steel produced[1,5]

**Wins for society**
› public health benefits due to energy reuse
› improved business relations in regional clusters
› job creation and new skills development[5]


Figure 3: Sustainability [1]

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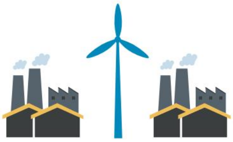
# CASE WATCH 05 : WIND POWER COGENERATION

Jointly invest in wind power generation for shared use of renewable electricity in industry and communities.

Increase renewable electricity use by jointly investing in wind turbines.



## TAPPING INTO RENEWABLES

**KEY INSIGHTS**

- use renewable electricity
- reduce $CO_2$ emissions
- integrate sites and clusters

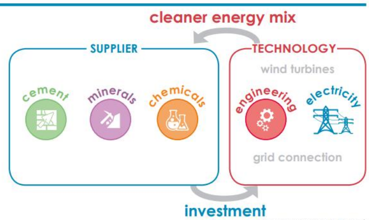



Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Process industries in certain regions have a high interest in sourcing renewable electricity.

Electricity-intensive industries have a growing demand for renewable power.

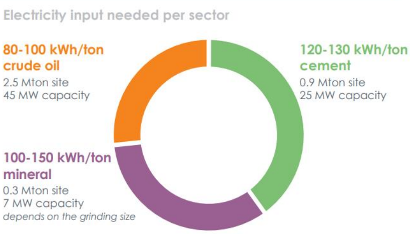



Figure 2: Cross-sector potential [1,2,3]

## SUSTAINABILITY IMPACT

**Wins for industry**

〉for industry: 20-50% ROI and lower OPEX[6]

**Environmental gains**

〉$CO_2$ emission reduction:
10-20 kton $CO_2$/y (10 MW wind farm)[2,4]

**Wins for society**

〉public health benefits due to renewable energies[5]
〉community integration through PPP investment
〉job creation and new skills development[1]


Figure 3: Sustainability [1]

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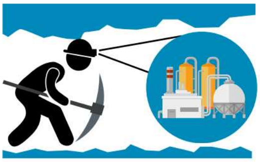
EPOS Industrial Symbiosis

# CASE WATCH 06 : COKE VALORISATION

Transform the coke from industrial steam crackers into raw materials for steel and cement industries.

Reduce the use of primary resources by valorising secondary materials in another sector.



## VALORISING COKE

### KEY INSIGHTS

- value waste streams
- reduce primary resources
- reduce $CO_2$ emissions
- create new markets

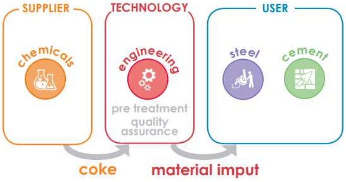



Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Refineries have a high potential to better valorise coke co-products.

Steel and cement industries have a growing demand for innovative (secondary) materials.

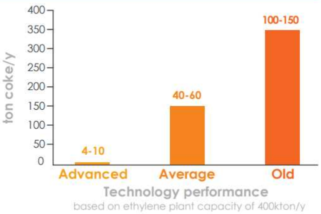



Figure 2: Coke production potential [1,2]

## SUSTAINABILITY IMPACT

**Wins for industry**
› for suppliers: reduction in waste[1]
› for industry: 10-30% energy gains/ton coke (vs coal)[3]

**Environmental gains**
› virgin resource savings:
% carbon in coke defines coal substitution rate[1]

**Wins for society**
› public health benefits due to emissions reduction
› improved business relations in regional clusters[1]
› job creation and new skills development

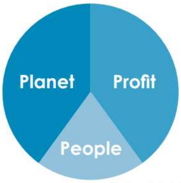



Figure 3: Sustainability [1]

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# CASE WATCH 07 : SOLAR POWER COGENERATION

Jointly invest in solar power generation for shared use of renewable electricity in industry and communities.

Increase renewable electricity use by jointly investing in solar panels.

## TAPPING INTO RENEWABLES

**KEY INSIGHTS**

- use renewable electricity
- reduce $CO_2$ emissions
- integrate sites and clusters

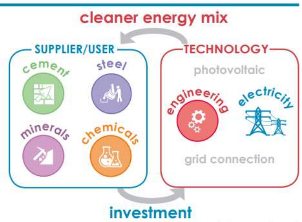


Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Process industries in certain regions have a high interest in sourcing renewable electricity.

Electricity-intensive industries have a growing demand for renewable power.

Electricity input needed per sector


Figure 2: Sector potential per sector [1,2,3,4,5]

## SUSTAINABILITY IMPACT

**Wins for industry**
› for industry: 6-16% ROI and lower OPEX[6,7]

**Environmental gains**
› $CO_2$ emissions reduction: 12-24 g $CO_2$/kWh used[7]

**Wins for society**
› public health benefits due to renewable energies
› community integration through PPP investment
› job creation[1]

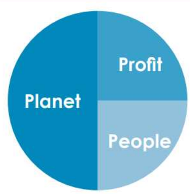


Figure 3: Sustainability [1]

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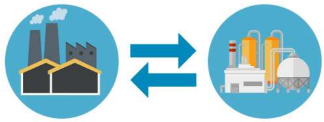
# CASE WATCH 08 : INDUSTRIAL HEAT NETWORKS

Optimise heat use in process industry via heat networks in industrial clusters.

Increase energy efficiency by cross-sector collaboration in industrial heat networks.



## CASCADING OUR HEAT

### KEY INSIGHTS

- reduce energy intensity
- reduce $CO_2$ emissions
- reduce primary heat sources
- integrate sites & clusters

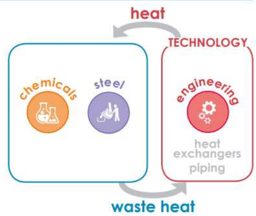



Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Energy-intensive industries have a high potential to exchange waste heat in industrial clusters.

Industrial clusters have a growing demand for heat exchange with regional networks.

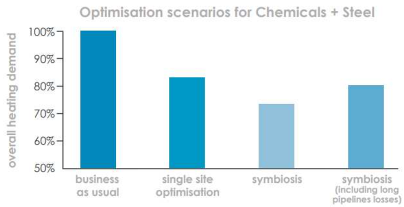



Figure 2: Cross-sector potential [1]

## SUSTAINABILITY IMPACT

**Wins for industry**
〉overall gains: 0-15 €/MWh exchanged (depending on distance)[1]

**Environmental gains**
〉primary energy savings:
10-30 MW/typical steel or chemicals plant[1]

**Wins for society**
〉public health benefits due to energy reuse
〉improved community relations in regional clusters
〉job creation and new skills development[1]


Figure 3: Sustainability [1]

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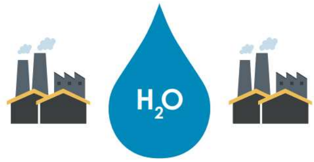
# CASE WATCH 09 : INDUSTRIAL WATER NETWORKS

Optimise water use in process industry via water networks in industrial clusters.

Increase water efficiency by cross-sector collaboration in industrial water networks.




## CASCADING OUR WATER

**KEY INSIGHTS**

- optimise water use
- reduce fresh water demand
- integrate sites & clusters

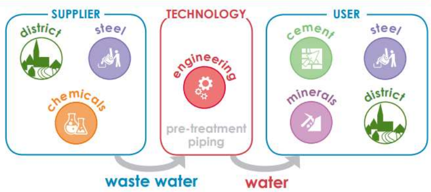



Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Energy-intensive industries have a high potential to exchange water in industrial clusters.

Industrial clusters have a growing demand for regional water networks.

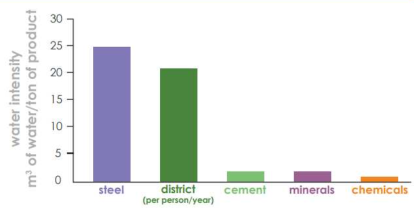



Figure 2: Cross-sector potential [1,2,3,4,5,6,7]

## SUSTAINABILITY IMPACT

**Wins for industry**
› overall gains: 1-1.5 €/m³ exchanged[8]
› high relevance in water scarce regions[4,8]

**Environmental gains**
› fresh water savings:10-40% potential[9]

**Wins for society**
› security of supply due to water reduction
› improved community relations in regional clusters
› job creation and new skills development


Figure 3: Sustainability [1]

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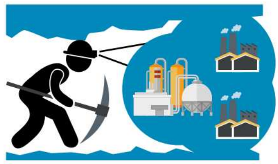
# CASE WATCH 10 : CO-PRODUCT VALORISATION (MINERALS)

Use industrial inorganic residues as raw materials in minerals and cement industry.

Reduce primary resources by valorising secondary materials in another sector.



## REUSING OUR MINERALS

**KEY INSIGHTS**

- value waste streams
- reduce mineral extraction
- reduce $CO_2$ emissions
- create new markets

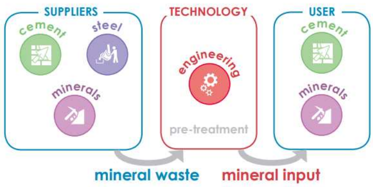



Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Process industries have a high potential to better valorise mineral co-products.

Minerals and cement industries have a growing demand for innovative (secondary) materials.


Figure 2: Cross-sector potential [1,2,3,4]

## SUSTAINABILITY IMPACT

**Wins for industry**
› for suppliers: 1-40 €/ton exchanged[5] depending on the pre-treatment level

**Environmental gains**
› primary mineral savings: 15-100% substitution[6,7]

**Wins for society**
› public health benefits due to emissions reduction
› improved business relations in regional clusters
› job creation and new skills development[1]


Figure 3: Sustainability [1]

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EPOS Industrial Symbiosis

# CASE WATCH 11 : CO-PRODUCT VALORISATION (CEMENT)

Transform industrial co-products into raw materials for the cement and construction sector.

Reduce use of primary resources by valorising secondary materials in another sector.

## REUSING OUR WASTE

**KEY INSIGHTS**

- value waste streams
- reduce primary resources
- reduce $CO_2$ emissions
- create new markets

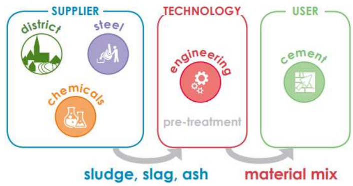


Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Process industries have a high potential to better valorise co-products such as ash, slag and sludge.

Cement industries have a growing demand for (secondary) raw materials.

- Steel sludge, Fly ash
- Sludge, Fly ash
- Urban sludge

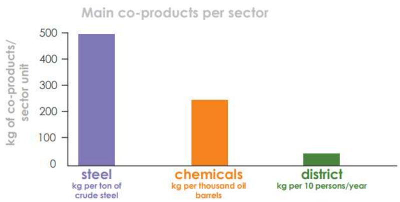


Figure 2: Cross-sector potential [2,3,4,5,6,7,8,9]

## SUSTAINABILITY IMPACT

**Wins for industry**

〉for suppliers: reduction in waste
〉for construction industry: reduction in raw materials[6,8]

**Environmental gains**

〉$CO_2$ emissions reduction in cement:
0.4 - 0.7 ton $CO_2$ saved/ton steel co-product use[8]

**Wins for society**

〉public health benefits due to emissions reduction
〉improved business relations in regional clusters
〉job creation and new skills development[1,8]


Figure 3: Sustainability [1]

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Industrial Symbiosis

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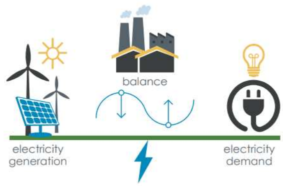
# CASE WATCH 12 : DEMAND SIDE RESPONSE

Optimise electricity sourcing and use via demand-response (flexibility) in industry clusters.

Reduce and balance industrial power demand by joining a virtual power plant.




## BALANCING THE GRID

**KEY INSIGHTS**

- optimise power use
- secure power supply
- integrate sites & clusters
- enable renewable energy

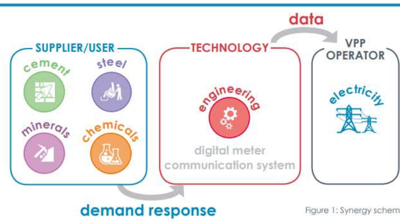



Figure 1: Synergy scheme[1]

## CROSS-SECTOR COLLABORATION

Process industries have a realistic potential to provide flexibility to the grid.

Electricity-intensive industries have a growing demand for security of power supply.

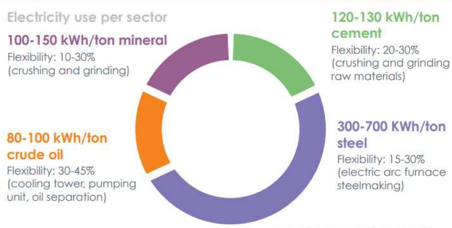



Figure 2: Cross-sector potential[1,2,3,4,5,6,7,8]

## SUSTAINABILITY IMPACT

**Wins for industry**
- for suppliers: reduction of power instability[9,11]
- for industry: 5-10% electricity cost savings[1,10]

**Environmental gains**
- renewable energy enabled: 10-45% lower peak power demand[1,9,10]

**Wins for society**
- security of power supply (blackout avoidance)[9]
- improved business relations in regional clusters
- job creation and new skills development[1]

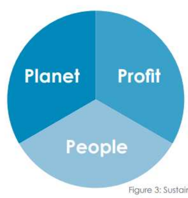



Figure 3: Sustainability[1]

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Industrial Symbiosis

# CASE WATCH 13 : CO VALORISATION FROM STEEL

Transform CO rich off-gases into raw materials for the chemical industry.

Reduce fossil dependency by valorising CO emissions in the chemical industry.


## CLOSING CO LOOPS

**KEY INSIGHTS**

- value CO streams
- reduce primary resources
- reduce $CO_2$ emissions
- integrate sites & clusters

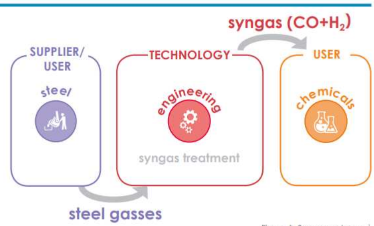


Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Steel industry has a high potential to supply CO to the chemicals industry. Industries have a growing demand for valorising carbon emissions.

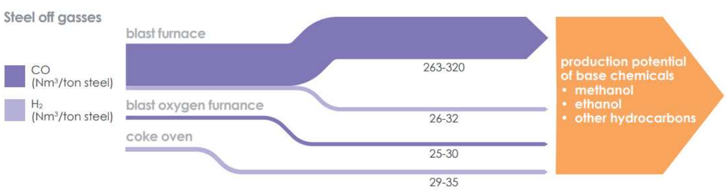


Figure 2: Cross-sector potential [1,2,3,4]

## SUSTAINABILITY IMPACT

**Wins for industry**

› for suppliers: 50-150 €/1000 Nm³ CO[4]
› for industry: 150-300 €/ton product[3]

**Environmental gains**

› $CO_2$ emissions reduction:
20-40% $CO_2$ saved/ton crude steel produced[2,3]

**Wins for society**

› public health benefits due to emissions reduction
› job creation and new skills development[1]

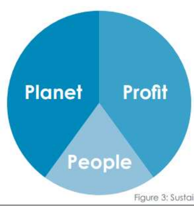


Figure 3: Sustainability [1]

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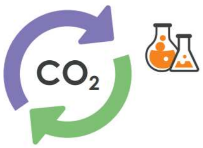
# CASE WATCH 14 : INDUSTRIAL $CO_2$ CAPTURE AND UTILISATION

Transform $CO_2$ rich streams into raw materials for the chemical industry.

Reduce $CO_2$ emissions by capturing and utilising them as chemical building blocks.




## CLOSING $CO_2$ LOOPS

**KEY INSIGHTS**

- value $CO_2$ streams
- reduce primary resources
- reduce $CO_2$ emissions
- turn cost into business opportunites

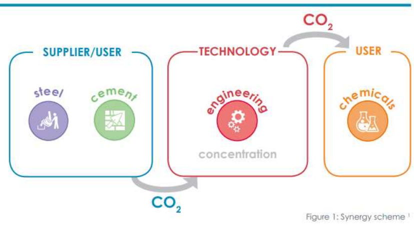



Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Process industries have a high potential to supply $CO_2$ to the chemicals industry.

Industries have a growing demand for valorising carbon emissions.

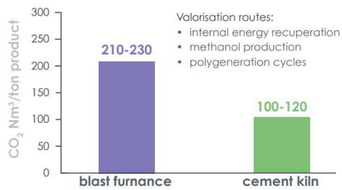



Figure 2: Cross-sector potential [1,2,3]

## SUSTAINABILITY IMPACT

**Wins for industry**
〉for suppliers: 15-35 €/ton $CO_2$ emissions reduction[4,5]
〉for chemicals: 50-300 €/ton product (virtual market place)[3]

**Environmental gains**
〉$CO_2$ emissions reduction:
20-70% $CO_2$ mitigated[2]

**Wins for society**
〉public health benefits due to emissions reduction
〉new skills development[1]

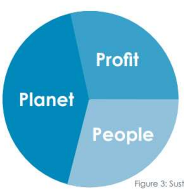



Figure 3: Sustainability [1]

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EPOS Industrial Symbiosis

# CASE WATCH 15 : WASTE WATER TREATMENT

Optimise water treatment in process industry and seek synergies with other industries.

Reduce water pollution and fresh water use by joint investment in treatment plants.

## CARING FOR WATER

**KEY INSIGHTS**

- optimise water management
- reduce fresh water demand
- integrate sites & clusters
- collaborate with society

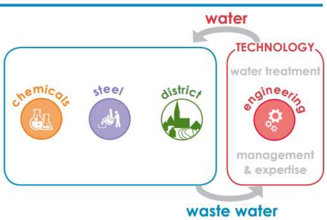


Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Process industries have a high potential to jointly invest in waste water infrastructure.

Industries have a growing demand for valorising co-products.

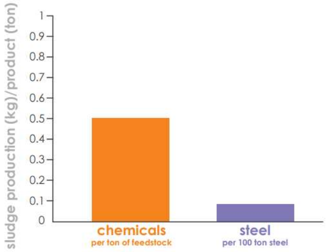


Figure 2: Cross-sector effluent potential [2,3,4,5]

## SUSTAINABILITY IMPACT

**Wins for industry**
〉for industry: economy of scale for waste water treatment[6,7]

**Environmental gains**
〉water management: avoided pollution and increased reuse of water[6,7,8,9]

**Wins for society**
〉public health benefits due to pollution reduction[1,10]
〉improved business relations in regional clusters


Figure 3: Sustainability [1]

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# CASE WATCH 16 : INDUSTRIAL $CO_2$ CAPTURE AND STORAGE

Store $CO_2$ streams from process industry via piping and shipping in empty gas fields.

Reduce $CO_2$ emissions by capturing and transporting for permanent storage.


## CLOSING $CO_2$ LOOPS

**KEY INSIGHTS**

- reduce $CO_2$ emissions
- value existing logistics
- integrate sites & clusters

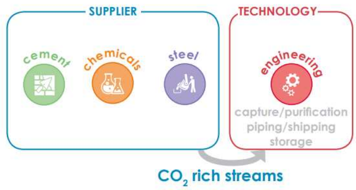


Figure 1: Synergy scheme [1,2]

## CROSS-SECTOR COLLABORATION

Process industries have a certain potential to capture and jointly store $CO_2$.

Industries have a growing demand for strategies towards the low-carbon economy.

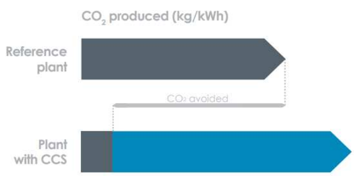


Figure 2: Carbon Capture and Storage (CCS) potential [1,2,3,4]

## SUSTAINABILITY IMPACT

**Wins for industry**
- for suppliers: 15-35 €/ton $CO_2$ emissions reduction[3,4]
- for clusters: low-carbon profile[2,3]

**Environmental gains**
- $CO_2$ emissions reduction: 10-90% $CO_2$ captured (depending on situation)[2,3,5]

**Wins for society**
- public health benefits due to emissions reduction[1]
- improved business relations in regional clusters
- job creation and new skills development


Figure 3: Sustainability [1]

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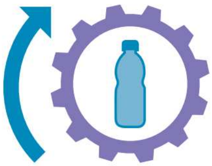
# CASE WATCH 17 : WASTE PLASTIC VALORISATION IN STEEL

Use plastic waste as raw material in steel industry.

Reduce primary resources by valorising secondary waste in another sector.



## CLOSING PLASTIC LOOPS

**KEY INSIGHTS**

- value waste streams
- reduce primary resources
- reduce $CO_2$ emissions
- create new markets

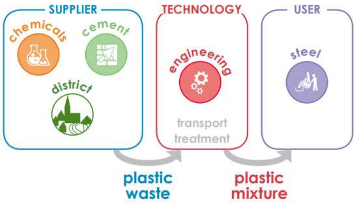



Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Process industries (and districts) have a high potential to better valorise plastic waste.
Steel industries have a growing incentive for contributing to the circular plastics economy.

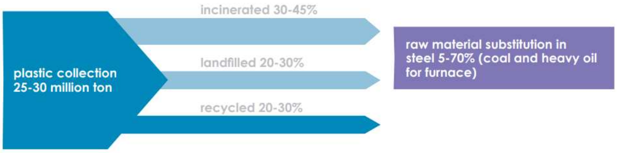



Figure 2: Plastic waste potential [1,2,3,4,5]

## SUSTAINABILITY IMPACT

**Wins for industry**

› for suppliers: diposal cost reduction (0-50%)[6,7]
› for steel: 0-200 €/ton plastic waste[6,7,8,9]

**Environmental gains**

› primary resource savings:
0.4-0.8 ton heavy oil saved/ton waste plastic[3]

**Wins for society**

› social benefits due to plastic waste disposal reduction[1]
› improved business relations in regional clusters
› job creation and new skills development


Figure 3: Sustainability [1]

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# CASE WATCH 18 : SOLAR HEAT IN PROCESS INDUSTRY

Jointly invest in solar heat plants for shared use of renewable heat in industry.

Support renewable electricity in process industry by joining renewable heat incentives.

## TAPPING INTO RENEWABLES

**KEY INSIGHTS**

- use renewable heat
- reduce $CO_2$ emissions
- reduce primary heat sources

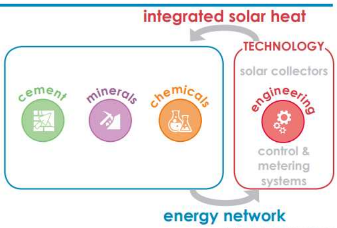


Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Process industries in certain regions have a high interest in sourcing renewable heat.

Energy-intensive industries have a growing demand for renewable heat.

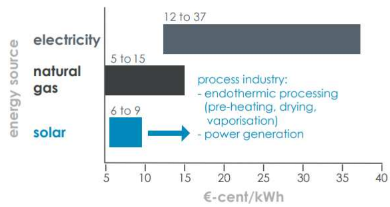


Figure 2: Thermic solar panels potential [1,2,3,4]

## SUSTAINABILITY IMPACT

**Wins for industry**

› for industry: 5-20% ROI and lower opex[2,3,5]

**Environmental gains**

› $CO_2$ emissions reduction: 100-300 g $CO_2$/kWh used[6]

**Wins for society**

› public health benefits due to renewable energy[1]
› community integration through PPP investment
› job creation and new skill development

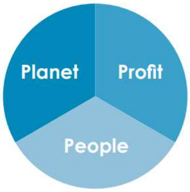


Figure 3: Sustainability [1]

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Industrial Symbiosis

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# CASE WATCH 19 : STEEL SLAG VALORISATION

Transform steel slag into raw materials for the chemical and cement industries.

Reduce primary resources by valorising secondary materials in another sector.

## VALORISING SLAG

**KEY INSIGHTS**

- value waste streams
- reduce primary resources
- reduce $CO_2$ emissions
- create new markets

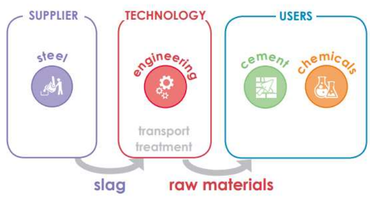


Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Steel industries have a high potential to valorise slag in chemical and cement industries. Chemical and cement industries have a growing demand for (secondary) raw materials.

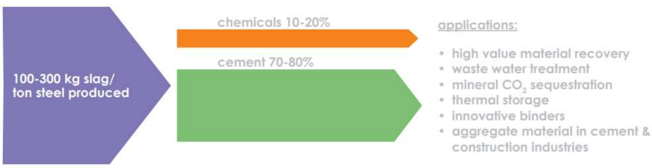


Figure 2: Cross-sector potential [1,2,3,4,5,6]

## SUSTAINABILITY IMPACT

**Wins for industry**
- for suppliers: 20-50% disposal cost reduction[1,4]
- for industry: 20-60 €/ton slag as raw material cost[1]

**Environmental gains**
- $CO_2$ emissions reduction: 0.5-0.6 ton $CO_2$ saved/ton slag[7]

**Wins for society**
- public health benefits due to emissions reduction[1]
- improved business relations in regional clusters
- job creation and new skills development


Figure 3: Sustainability [1]

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*H2020 project EPOS - Enhanced energy and resource Efficiency and Performance in process industry Operations via onsite and cross-sectorial Symbiosis*

# CASE WATCH 20 : WASTE PLASTIC VALORISATION IN CEMENT

Use plastic waste as raw material in cement industry.

Reduce primary resources by valorising secondary waste in another sector.

## BUILDING PLASTIC SOLUTIONS

**KEY INSIGHTS**

- value waste streams
- reduce primary resources
- reduce $CO_2$ emissions
- create new markets

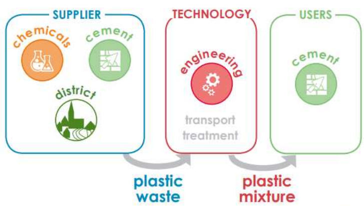


Figure 1: Synergy scheme [1]

## CROSS-SECTOR COLLABORATION

Process industries (and districts) have a high potential to better valorise plastic waste.
Cement industries have a growing demand for contributing to the circular plastics economy.

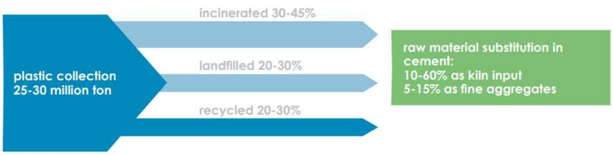


Figure 2: Cross-sector potential [1,2,3,4,5,6,7]

## SUSTAINABILITY IMPACT

**Wins for industry**
› for suppliers: disposal cost reduction (0-50%)[7,8]
› for cement: 0-200 €/ton plastic waste[7,8,9,10]

**Environmental gains**
› primary resource savings:
20-22 GJ saved/ton waste plastic[10]

**Wins for society**
› social benefits due to plastic waste disposal reduction[1]
› improved business relations in regional clusters
› job creation and new skills development


Figure 3: Sustainability [1]

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EPOS Industrial Symbiosis

# CASE WATCH 21 : HUB FOR $CO_2$ UPGRADING

Jointly invest in a central hub for shared upgrading of captured $CO_2$ in process industry cluster.

Increase $CO_2$ capture for storage or utilisation by jointly investing in pretreatment facilities.


## BUILDING $CO_2$ SOLUTIONS

**KEY INSIGHTS**

- value waste streams
- reduce $CO_2$ emissions
- create new markets
- integrate sites & clusters

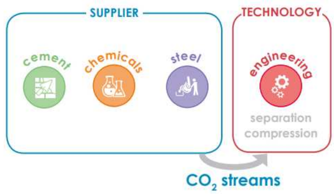


Figure 1: Synergy scheme [1,2]

## CROSS-SECTOR COLLABORATION

Process industries have a high potential to jointly upgrade captured $CO_2$.

Industries have a growing demand for contributing to the low-carbon economy.

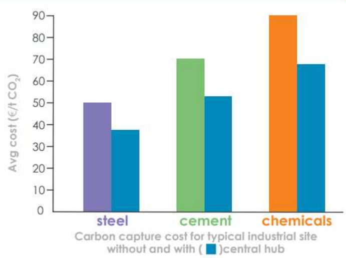


Figure 2: Cross-sector potential [1,3,4,5,6]

## SUSTAINABILITY IMPACT

**Wins for industry**
› for suppliers: 20-40% reduction on $CO_2$ upgrading cost[1,6,7]
› for clusters: low-carbon profile[5,6]

**Environmental gains**
› Emissions management:
increased carbon capture potential[1,4]

**Wins for society**
› public health benefits due to emissions reduction[1]
› improved business relations in regional clusters
› job creation and new skills development


Figure 3: Sustainability [1]

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SPIRE Sustainable Process Industry through Resource and Energy Efficiency

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Resource circularity through collaboration in the process industry.