LIAISE
Cooperation, development
and cross-border transfer
of industrial symbiosis

D1.1. State-of-the-art report on Industrial Symbiosis topic and its different sub-areas (settling the basis for further improvements and their introduction in the industry).

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This report is part of LIAISE COST Action. Concretely, it is the D1.1. State of the art on Industrial Symbiosis topic and its different subareas. LIAISE COST Action (CA22110) is a project funded by the COST Action Programme in 2023, whose objective is to ensure an inclusive and holistic Industrial Symbiosis approach by generating relevant synergies among different actors from the q-helix stakeholder model and by setting the groundwork for increased and robust development of knowledge, apart from promoting future results-oriented R&D.

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Project Action Context

In the context of addressing climate change, industrial sectors play a significant role as major contributors to carbon dioxide emissions, energy consumption, and waste generation. To combat these challenges, adopting a Circular Economy strategy is imperative. The Circular Economy model diverges from the traditional linear approach by promoting sustainable production and consumption practices while considering societal, environmental, and economic factors in a balanced manner.

Industrial Symbiosis (IS) emerges as a practical solution within this framework. In IS, waste or by-products generated by one industry are repurposed as resources for another, presenting opportunities for environmental sustainability and economic efficiency. Despite its potential, many companies and industrial actors lack awareness of IS, and its development is hindered by various barriers, including environmental, economic, technical, regulatory, organizational, social, and cultural challenges.

To address these issues, the LIAISE COST Action seeks to foster an inclusive and holistic IS approach. By fostering synergies among stakeholders from diverse sectors and laying the groundwork for knowledge enhancement, LIAISE COST Action aims to bridge the gap between theory and practice. This initiative will involve developing a participatory approach to support cross-sector collaborations and establishing Key Performance Indicators (KPIs) for assessing the effectiveness of IS business models in industry.

The LIAISE COST Action represents a collective effort to make the Industrial Symbiosis a reality across Europe, fostering collaboration among researchers, practitioners, and policymakers. To achieve these objectives, LIAISE COST Action will leverage the expertise of four interdisciplinary Working Groups (WGs) and integrate their findings through a reference framework. This holistic approach aims to drive meaningful progress towards sustainable industrial practices and contribute to a more Circular Economy.

1. Introduction

This report focuses on Industrial Symbiosis (IS) and discusses it in relation to Circular Economy (CE) and Industrial Ecology (IE). The report aims to provide an overview of identifying, evaluating, establishing technical synergies, and selecting potential IS cases. The report also provides an overview of the IS cases identified by the LIAISE COST Action members.

1.1. Industrial ecology (IE)

Industrial Ecology (IE) is commonly referred to as the study of material and energy flows through industrial systems. Some definitions also consider these flows' effects on the environment and economic, political, regulatory, and social influences on resource flow, use, and transformation. The principle of closing material loops drives industrial ecology by avoiding pollution (Fet & Deshpande, 2023). From the IE perspective, natural systems should be used as inspiration to design sustainable industrial systems. This is because industry, as a human-made ecosystem, is similar to natural ecosystems, where the waste or by-product of one process can become input into another process (Nilsson 2016). IE is principally concerned with the flow of materials and energy through systems at different scales, from products to factories and up to national and global levels.

Industrial Ecology encompasses both Circular Economy (CE) and Industrial Symbiosis (IS), which, although closely related, are not interchangeable terms.

1.2. Circular Economy (CE) vs. Industrial Symbiosis (IS)

A Circular Economy (CE) is a production and consumption system where most of the products and the resources used in production processes can be used and recycled. It minimizes waste, maximizes resource efficiency, and promotes long-lasting product design. Instead of the traditional linear model of the economy (make, use, dispose), the CE encourages continuous use, repair, and recycling of materials when the latest act is viable. The CE seeks to restore our ecosystem and reduce the consumption rate of our natural resources. CE strategies can be applied at various scales, from individual products and services to entire industries and cities.

As a result, CE involves creating products and systems that minimize waste generation and their environmental impact. CE encompasses various materials and products, including consumer goods, electronics, textiles, and more (Elen MacArthur Foundation, N/A). CE encourages the continuous use, repair, and recycling of materials so that, if possible, any waste can be transformed into new feedstock. Five CE models can support the transition to a more resource-efficient society, and, as a result, the CE is 1) circular supply, 2) resource recovery, 3) product life extension, 4) sharing, and 5) product service system models.

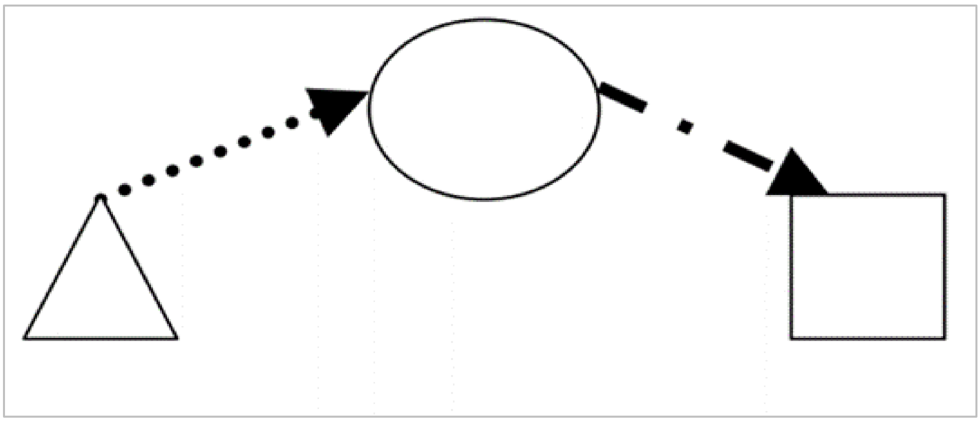
On the other hand, Industrial Symbiosis (IS) is a subset of Industrial Ecology (IE). It involves using waste or by-products from one actor as resources for another actor, aiming to achieve environmental and economic benefits. In other words, IS is the association between industrial facilities or companies in which the waste or by-products of one become raw materials for another.

IS can be described as a collaboration between several different, often geographically proximate entities, i.e., companies and factories closely co-located in clusters or industrial parks exchanging resources (e.g., materials, energy, water and by-products) that can well be used as substitutes for the much needed, and often scarce and expensive, raw materials or products, which would otherwise be imported from elsewhere or treated as waste. Therefore, Industrial Symbiosis is pivotal in terms of resource reuse and prevention of waste, driven by collaborative opportunities and synergies facilitated by geographic proximity (Chertow, 2000). IS enables the waste from one company's or secondary materials to become valuable resources for another, very often without any preparation and pretreatment, resulting in mutual financial benefits (savings) and, as a result, reduced dependence on fresh raw materials and then unpopular landfill disposal. Therefore, an Industrial Symbiosis (IS) should:

- Involve actors, entities, and organizations that consider symbiosis a business opportunity.
- Highlight the beneficial economic aspects that empowerment entails.
- It should be considered a business strategy that encourages the creation of synergies between companies.
- Frame the concept in a systemic vision of the industry to achieve a better result than that achieved by entities/organizations/activities operating individually.
- Introduce the concept of underused (residual) resources.
- Improve efficiency in the use of natural resources.
- Reduce the costs of raw materials, goods, services and waste treatment.
- Allow resources to be kept in the economic cycle for longer, reducing the exploitation of raw materials.
- Improve competitiveness.

To distinguish the IS from other types of exchanges, a "3–2 heuristic" as a minimum criterion is often adopted (Chertow, 2007). Thus, at least three (3) different entities must be involved in exchanging at least two (2) other resources to be counted as a primary type of IS (Figure 1). The 3–2 heuristic begins recognizing the complex relationships compared to the linear one-way exchanges by involving three entities, none primarily engaged in a recycling-oriented business. A simple version of this is the example of a Waste Water Treatment Plant (WWTP) providing cooling water to a power station (producing energy via steam turbines), and the power station, in turn, supplying steam to an industrial user in need. However, most IS definitions do not imply the criterion of a minimum of three actors.

Figure 1. Example of 3-2 symbiosis



Source: Chertow, 2007: 13

1.3. Industrial Symbiosis definition

Traditionally, the most frequently used definition of Industrial Symbiosis (IS) is the one used by Chertow (2000): "*The part of industrial ecology known as Industrial Symbiosis engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to Industrial Symbiosis are collaboration and the synergistic possibilities [often] offered by geographic proximity*". Laybourn and Lombardi (2012) presented a renewed definition of Industrial Symbiosis, which the Journal of Industrial Ecology accepted. This definition was summarized by Domenech et al. (2019) as follows: "*Industrial Symbiosis (IS) is a systems approach to a more sustainable and integrated industrial system, which identifies business opportunities that leverage underutilized resources (such as materials, energy, water, capacity, expertise, assets etc.)*". Explaining this definition further, Domenech et al. (2019) state that *"Industrial Symbiosis involves organizations operating in different sectors of activity that engage in mutually beneficial transactions to reuse waste and by-products, finding innovative ways to source inputs and optimize the value of the residues of their processes, for instance by using waste or by-products from one activity as an input for another activity".*

However, different EU research and innovation projects and EU policy departments, known as Directorates-General (DGs), define IS differently. Only recently, in 2018, the European Committee for Standardisation (CEN, 2018) initiated the process to address the need to define Industrial Symbiosis. During the 2018 workshop, an agreement on Industrial Symbiosis was reached, defining Industrial Symbiosis as *the use by one company or sector of underutilized resources broadly defined (including wastes, by-products, residues, energy, water, logistics, capacity, expertise, equipment and materials) from another, with the result of keeping resources in productive use for longer*. However, this process is still ongoing, and CEN plans a series of consultations and standardization dialogues to shape the roadmap for Industrial Symbiosis standardization in 2025.

1.4. Summary

While both Circular Economy (CE) and IS concepts aim for sustainability, CE emphasizes materials and products of all kinds, whereas IS specifically focuses on industrial waste and by-products. IS is a more targeted action and a tool to implement Circular Economy CE in the industry, aiming at downstream actions for better use of resources. Still, it does not necessarily have to be completely circular. CE has a broader scope than IS, and it is a more complex approach that includes upstream actions and prevention, closing the loops, and acting as a philosophy we want to follow as a sustainable society. The main characteristic features of sectors of activity can help distinguish between CE and IS entities; however, the division does not need to be unequivocal, as both concepts might overlap widely.

2. Identification: how to identify opportunities for symbiotic exchanges

2.1. Type of symbiosis/resources available

Industrial Symbiosis (IS) involves companies/industries cooperating and exchanging materials, energy, water and/or waste and by-products and sharing services, utilities and/or facilities (Table 1). For any IS to be realized, opportunities for symbiosis need to be identified. Therefore, identifying potential symbiosis/resource exchanges between industries is essential for promoting IS in practice. Types of resources available for synergies under IS concerning materials and waste exchanges include:

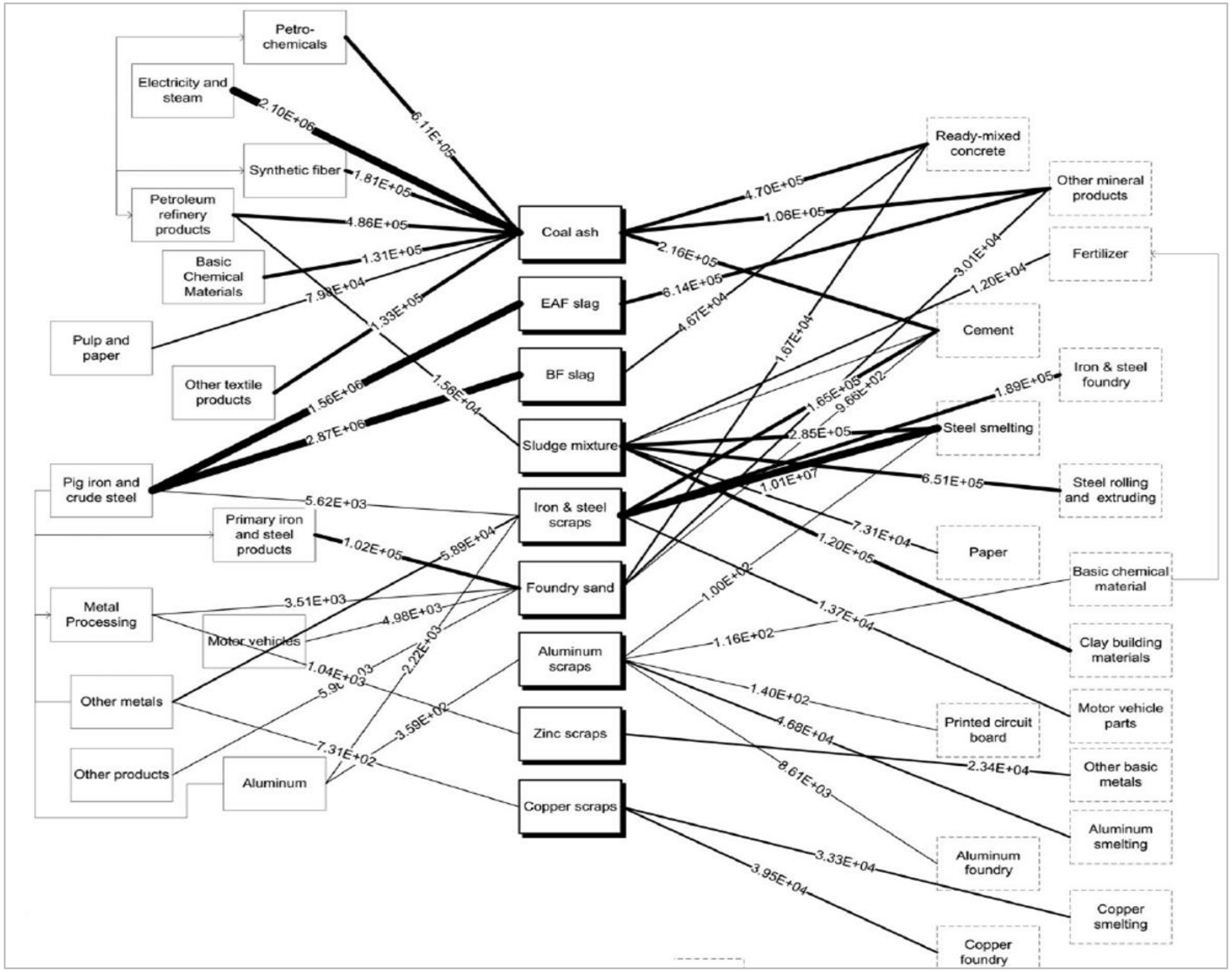
- **Raw materials** are primary inputs in manufacturing processes to produce goods or products. These include metals, minerals, chemicals, and natural resources such as timber, peat, and metal ore. In IS, raw materials surplus from one company can be utilized as inputs by another, reducing the need for new raw materials and promoting resource efficiency.
- **By-products** are the secondary outputs generated during manufacturing processes that may not be the primary-intended product but still have potential value. This includes various materials in the side or waste streams, for example, dissolved in a process or wastewater. Waste streams refer to materials or substances discarded as unwanted or unusable by one company. In IS, by-products and waste streams from one company can serve as valuable inputs or resources for another, promoting waste valorisation and Circular Economy principles.
- **Energy resources,** such as electricity, heat, and steam, are essential for various industrial processes. In IS, excess energy generated by one company, such as heat or steam from manufacturing processes, can be utilized by neighbouring companies for heating, cooling, or powering their operations, reducing energy consumption and emissions. Utilities such as compressed air and warm water also have synergistic potential.
- **Water** is critical in industrial cooling, cleaning, diluting, mixing and manufacturing operations. In IS, treated wastewater from one company can be reused by others for non-potable purposes, such as agricultural irrigation water, cooling water, or processing water, reducing freshwater consumption and minimizing environmental impacts. Moreover, wastewater from various industrial plants located in geographical proximity can be treated in common facilities for wastewater treatment.

Types of resources available for synergies concerning sharing include:

- **Utilities and infrastructure** assets, including transportation networks, storage facilities, land, and industrial infrastructure, to support industrial operations. In IS, shared infrastructure and facilities within industrial parks or clusters can optimize resource use, reduce costs, and enhance operational efficiency through shared services and infrastructure investments.
- Logistics **services,** including transportation, warehousing, purchasing, and distribution, play a crucial role in the industrial ecosystem's movement of goods and materials. In IS, companies can collaborate to optimize logistics operations, share transportation networks, and consolidate shipments, reducing transportation costs, emissions, and congestion (UNIDO 2018).

- Expertise, skills, and specialized **knowledge** possessed by individuals or companies within the industrial ecosystem are valuable resources for collaboration and innovation. In IS, companies can share technical know-how, best practices, and research findings to improve processes, optimize resource use, and develop sustainable solutions collaboratively.

Figure 2. Examples of Industrial Symbiosis (IS) where waste is transformed into raw materials based on process industry



Source: Pi-Cheng and Hwong-Wen, 2015

Table 1 provides information on the type of resource exchanged (i.e., what resources are being exchanged between companies) and the type of processing required (i.e., the degree to which the "wasted" resource is processed before it can be utilized by the other company(ies) involved in the synergy project).

Table 1. Different types of industry synergies

TYPE OF RESOURCE EXCHANGED	TYPE OF PROCESSING REQUIRED
Material resources: raw materials, etc.	**Direct use or reuse**: without any further processing except for transport and storage
Waste and by-products: Organic, inorganic, solid, effluents, etc., derived from diverse processes and manufacturing	**Material recovery**: involves separation and recovery processes to reclaim specific materials found in the by-product/waste stream for the beneficial use
Non-process waste: waste generated during maintenance, packaging materials, machinery components, general household waste, landscape waste, and construction or demolition debris.	**Conversion into a functional product**: processing to produce a different useful product
Energy: shared use of energy infrastructure, co-generation and/or recovery of waste heat from steam and electricity generation	**Energy recovery or alternative fuels:** covers waste heat recovery and alternative fuels for boilers and kilns. Shared electricity and gas utilities and co-generation facilities also fall into this category.
Water: exchange and reuse of cooling water and process water, any collective treatment and recycling of wastewater	**Environmentally sound disposal**: collective treatment of wastewater to enable its safe disposal + recovery/reuse
Utilities/facilities: shared use of a common infrastructure that can be shared	not relevant
Service: shared use of a standard service provided by others	not relevant
Knowledge: shared use of competencies, know-how, etc.	not relevant

2.2. Data collection as part of the identification of resources/services for exchange

A significant step in realizing an Industrial Symbiosis (IS) is to identify the resources, raw materials, by-products, waste, underutilized services, heat, effluents, etc., that can be subjects of collaboration and connections and the flows of these elements. In this regard, finding an appropriate data system or implementing an efficient data exchange system securely and reliably is crucial, enabling the necessary analyses to identify the most probable and efficient connections.

Here, the application of technological systems based on data digitization, with security systems allowing agents to provide reliable information about these aspects they are aware of and modelling tools (including artificial intelligence systems) that facilitate analysing and identifying connections, can be handy. However, it still requires substantial innovative development.

In a more advanced stage of implementing IS processes, adding other information variables detailing specific aspects of certain connections crucial for their viability, such as quantity and quality characteristics, availability incl., fluctuations, accessibility, etc. This aims to achieve a data system that identifies collaboration opportunities using any analytical system that can identify potential relationships. In some cases, data systems have not been generated; opportunities have been identified by activating dynamics among agents, conducting workshops, or conducting interviews to propose the identified potential symbiosis.

It involves an inventory (referenced geographically or not) of the company's demanded and surplus resources (material or immaterial) and quantifying their flows to facilitate the search for synergies among them. The information collection can be carried out in various ways or through a combination of the following methods:

- Available public environmental information.
- Visits to companies and critical agents for data collection.
- Voluntary submission and delivery of information to administrations or key agents.
- Individual and voluntary data entry through a platform that can include software for modelling the data, i.e., the resources and their characteristics (location, quantification, needs, etc.), for the subsequent detection of synergies.

Access to an industrial site’s technical and organizational knowledge is crucial for stimulating IS. However, due to confidentiality constraints in the industry, sharing data typically requires non-disclosure agreements and intellectual property rights to protect a company’s proprietary assets. These constraints limit the discovery of new potential exchanges between companies (Kastner et al., 2015). Most developed tools primarily focus on waste exchanges, necessitating secure systems to store information and allowing industries to choose what they are willing to share. Consequently, detecting new potential symbioses that have not been previously considered becomes limited, as users select only what they wish to exchange, potentially overlooking some valuable flows for IS. The platform’s effectiveness depends on a critical mass of registered users and a substantial resource database.

This highlights the need to access qualitative and quantitative data on industries’ materials, energy, and water inputs and outputs. However, there is a lack of comprehensive and systematic methodologies to generate such information. Publicly available, reliable, and comprehensive datasets on industrial sector operations could provide a foundation for IS platforms and serve as case studies in industrial ecology and related fields (Cervo et al., 2019).

Patricio et al. (2022) use a method that classifies industries, material inputs, and wastes using Eurostat standard nomenclatures, which correspond to similar nomenclatures used in other regions. Industries are classified using the Statistical Classification of Economic Activities in the European Community nomenclature, NACE (Eurostat, N/A). Products or material inputs can be used interchangeably and represent all goods used by industries. This includes structural products, auxiliary products, and investment goods. They are classified according to the Combined Nomenclature (CN), the classification used by the European Commission (N/A) for collecting and processing data on foreign trade. Industrial wastes are classified according to the European List of

Wastes (LoW) (Eurostat, 2015) nomenclature developed by the European Commission. Using this method, the matching process identified 96,622 potential matches between waste generators and potential material input receivers after applying filters that reflect the probability of waste generation or material input needs. These filters are based on frequency values relating to production and use in the datasets.

2.3. Roles of different actors in Industrial Symbiosis implementation

Different actors are involved in identifying opportunities for symbiosis and eventually implementing Industrial Symbiosis (IS) in practice, and they have different roles at the stages of IS identification and realization.

Different entities (e.g., government, institutions, businesses, etc.) have vital roles in accomplishing specific goals, such as reducing costs and achieving higher benefits while considering environmental improvement. The government and its institutions can lead by adopting programs like lowering taxes or providing economic incentives for companies that adopt symbiosis in their production systems. Research organizations can assist companies in adopting the IS concept by providing know-how, designs and information on resources and their utilization options to help them make better decisions. Facilitators from government, non-government, business, or research entities can help identify opportunities, map resources, matchmaking, and create business. Parties adopting IS may establish a dedicated department responsible for updating inventories of water use, energy use, waste generation, etc. This may increase initial production costs, but in the long run, it will enhance performance as parties won't need help from external organizations.

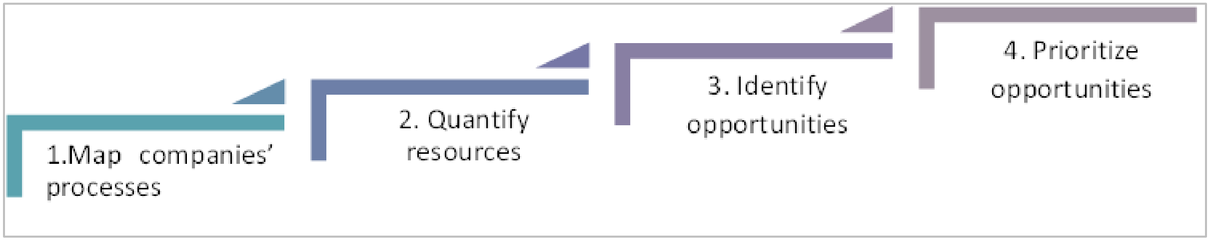
Since preparing companies for resource-efficient product design and production is multifaceted, it involves various departments, including management, product design, purchasing, production, sales, and maintenance. Consequently, the process requires a coordinated approach aligned with the company's management system. An example of such a process and support to establish one is the multidisciplinary and multistep Promoting Resource Efficiency in Small and Medium Enterprises (PRE SME) Toolkit drafted by UNIDO and UNEP (UNEP, 2010). The toolkit includes guidelines, self-assessment tools, operational indicators and benchmarks, training resources, case studies, etc.

2.4. Mapping of resource flows at a site

The Industrial Symbiosis (IS) process begins by understanding resource flows, services, facilities, or knowledge and documenting exchange opportunities to motivate companies to collaborate. In this report, the focus will be on the resource flows.

In IS, resource mapping refers to identifying, analysing, and visualizing the flow of resources—such as materials, energy, water, and by-products—within and between companies or industrial sites. This involves gathering data on what resources are produced as waste by one company and could serve as inputs for another. Resource mapping aims to uncover opportunities for collaboration between businesses, enabling them to exchange resources that would otherwise be discarded, thus promoting efficiency and reducing waste. It often considers factors like proximity, volume, and the nature of the resources to optimize IS partnerships. The mapping process typically involves four steps (Figure 3).

Figure 3. Steps of the resource mapping process Industrial Symbiosis



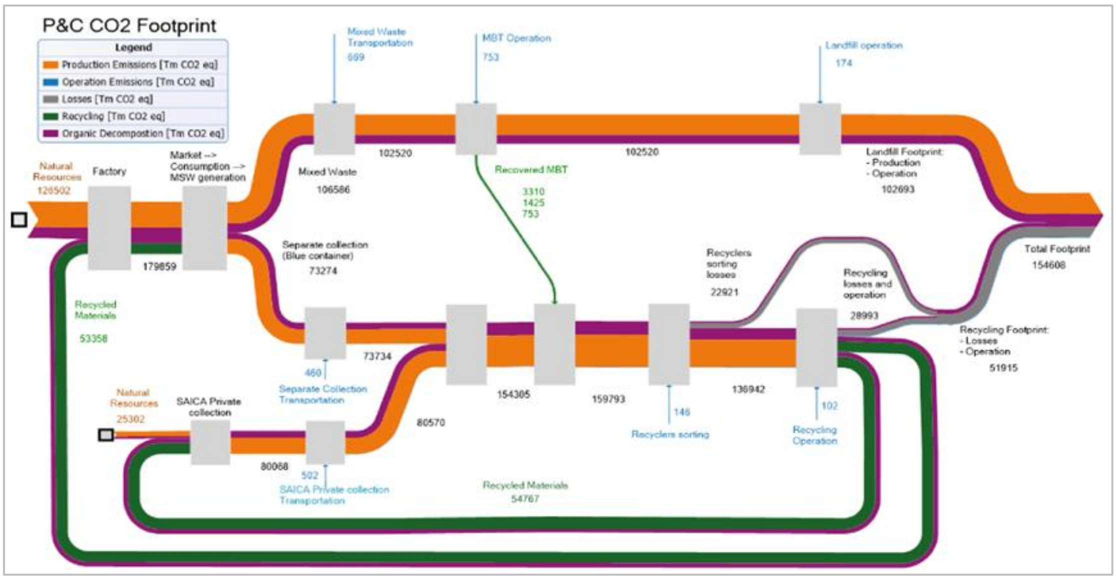
Source: adapted from Ramirez-Rodriguez et al., 2024

The first step involves mapping out the company's operational processes to understand all the resources used, what materials go in and out and identifying areas for potential collaboration with other businesses. The process mapping requires breaking down each stage of production or service delivery to understand all the subprocesses (e.g., heating, cooling, chemical reactions, assembly, etc.), identify all inputs (materials, water, energy) and outputs (by-products, waste, wastewater, excess energy, emissions) while considering any physical transformations, heating or cooling phases, or chemical reactions that may affect resource inputs or outputs.

Once the processes have been mapped, the next step is **quantifying the available resources**. This helps understand the potential scale of resource exchange opportunities and pinpoint inefficiencies. All relevant data on inputs and outputs is quantified: energy, water, and materials being used, wastewater volumes, types and quantities of solid waste, any gases or emissions, and the associated costs. The first two steps are primarily **data collection**, which is crucial for mapping. Excess unities are linked with excess materials, water or energy, the possibilities for reutilization, and available by-products.

Resource mapping and quantification are thoroughly developed and visually represented. Typically, a flowchart visualizes a mapping and quantification process, where boxes depict process steps and material, water, and energy flows, which are indicated by arrows. Sankey diagrams (Figure 4) are examples of mapping tools and a data visualization technique that emphasizes flow/movement/change from one state to another or time to another. In the Sankey diagrams, the width of the arrows is proportional to the flow rate of the extensive property depicted. Sankey diagrams can also visualize the energy accounts, material flow accounts on a regional or national level, and cost breakdowns. Diagrams are often used to visualize material flow analysis. This graphical tool aids in tracing waste and emissions back to their origins, highlighting potential points for improvement.

Figure 4. Sankey diagram of the carbon footprint of the industrial ecosystem (IE) for the P&C in the current scenario



Source: Valero et al., 2021

While resource flows are mapped and quantified, the focus should be identifying inefficiencies within companies' processes, applying measures to increase resource efficiency, and **identifying opportunities for symbiosis**. Therefore, after resource mapping is completed for an individual site or entity, the synergies between the two or more sites/entities can be explored, and synergy opportunities identified. Mapping will eventually be extended to all companies located in geographical proximity.

Considering its complexity, the **data collection** could be facilitated by using specially designed databases and tools to allow the contributions of all companies situated in the park and to facilitate the identification of IS opportunities within and between the partner industrial parks. One example of an open specialized database is the Data Modelling and Data Integration for Material Flow Analysis, an Industrial Ecology Data Commons containing more than 200 industrial ecology-related datasets from the literature, including stocks, flows, process descriptions, IO tables, material composition of products, and many more. The database is open and documented in a public GitHub - IndEcol/IE_data_commons. The target materials based on the quantitative and qualitative characteristics of the materials and waste generated and treated within the industrial parks can then be prioritized. Organizing the data into resource categories such as materials (metals, plastics, organics), energy (waste heat, steam), water, and waste types (hazardous, non-hazardous) and standardizing the information ensures that resources are classified consistently (e.g., using international waste codes or NACE codes for industries) for compatibility and easier matching. In addition, creating a geographical map of participating businesses, including analysis of transportation and logistics and highlighting their proximity, further enhances **identifying and prioritising the Industrial Symbiosis opportunities.**

2.5. Types and methods for establishing Industrial Symbiosis synergies

After understanding material flows, prioritizing target materials based on quantitative and qualitative characteristics is essential. Various approaches exist for identifying and prioritizing the target resources and synergies based on waste and resource exchange facilitation. These methods for IS synergies identification/prioritization will be discussed in this section. Examples of water and energy will be addressed.

Upon prioritization of IS synergies, pre-feasibility assessments are conducted to analyse waste generation, processing costs, and economic profits from environmental effects (UNIDO, 2017a). Identifying supplying and receiving firms follows, with agreements reached among companies based on their roles in IS.

2.5.1 Methodologies for Industrial Symbiosis Synergies Identification

Several methods can be used to identify potential IS partnerships: the classical "bottom-up" approach and the more modern "top-down" approach.

In the "bottom-up" approach, synergies result from opportunistic individual companies' cooperation, whereas in the "top-down" approach, synergies result from planned decisions and interventions, e.g., eco-industrial parks. Those methods include new process discovery, relationship mimicking, material budgeting, and input-output matching (Grant et al., 2018; Holgado et al., 2018):

- New Process Discovery is based on creating a novel approach to transform a by-product into a usable resource.
- Input-output matching occurs by identifying a resource associated with one organization and finding complementary resource inputs or requirements for another organization.
- Relationship Mimicking is based on replicating proven relationships introduced by similar organizations elsewhere.

Input-output matching is perhaps the most used method. It involves finding potential IS matches by analysing characteristics of output streams (i.e., wastes and by-products) from industries and the material inputs they require before matching one to the other (Bin et al., 2015; Hein et al., 2016). Some tools used for input-output matching include material flow analysis, material databases, GIS and LCA-based methods, and input-output analysis.

1. **Material Flow Analysis (MFA)** is a systematic methodology that quantifies the flow of materials within a system, such as an industrial park or a specific sector of the economy. It involves mapping material inputs, outputs, and internal flows to identify inefficiencies and opportunities for waste reduction, reuse, and recycling (UNIDO, 2017a).
2. **Geographic Information Systems (GIS)** leverage spatial analysis tools to analyse and visualize geographic data related to material flows, infrastructure, and environmental factors. GIS helps identify spatial patterns and connectivity between material sources and potential recipients, facilitating the identification of symbiotic relationships (UNIDO, 2017b).
3. **Material Matching Databases** provide online platforms where companies can list their waste streams, surplus materials, or resource needs and search for potential users or recipients. These virtual waste and resource exchange marketplaces foster collaboration and Circular Economy practices.
4. **Life Cycle Assessment (LCA)** evaluates the environmental impacts of products, processes, or systems throughout their life cycle. It is used for assessing resource flow. It considers all stages, from raw material extraction to end-of-life disposal, identifying opportunities for waste reduction, resource efficiency improvements, and material substitution (Holgado et al., 2018).
5. **Input-Output Analysis (IOA)** examines the interdependencies between sectors within an economy by quantifying the flows of goods and services between industries. It identifies

opportunities for Industrial Symbiosis and waste exchange at a macroeconomic level, considering economic activities' direct and indirect effects (UNIDO, 2017a).

There are several different tools and digital platforms dedicated to fostering IS and facilitation of resource exchanges, such as the UNIDO Industrial Symbiosis Identification Tool, the SYNERGie® (International Synergies), the Excess Materials Exchange (EME, N/A), the Industrial Symbiosis Platform (ISP), and others (Krom et al. 2022). Some are international, while some are local-oriented. For example, in Spain, at the local level, one can find the following: Recircular (https://recircular.net/), Syner (https://synerplatform.com/), Incubus (https://incub-is.eu/). UNIDO Industrial Symbiosis Identification Tool (2024) aims to support identifying Industrial Symbiosis opportunities (by-product and waste exchanges) between companies. This tool can be used in existing industrial parks (brownfields) to provide stakeholders with an indication of the symbiosis opportunities related to companies operating in the park. Alternatively, the tool can be used for new industrial parks (greenfields) to highlight possible IS between companies in the park, thereby assisting in planning infrastructures and utilities to enable these connections. SYNERGie® - software developed by the UK-based International Synergies to facilitate Industrial Symbiosis. It is a resource-matching platform designed by IS practitioners to allow the identification and advancement of resource reuse opportunities. In use by experts (facilitators) since 2009, SYNERGie® has hosted data on over 100,000 resources from 30,000 organizations in over 30 countries. Its technology list maps technologies to EWC codes for ease of solution identification. The platform tracks opportunities from ideas through to completion and reporting.

In a bottom-up approach, identifying resource efficiency opportunities and possible synergies is focused firstly on improving resource efficiency within individual companies, following the principles of Resource Efficient and Cleaner Production (RECP). RECP aims to apply preventive environmental strategies to processes, products, and services to increase efficiency and reduce risks to humans and the environment (UNIDO, 2016). This involves addressing aspects of production efficiency, environmental management, and human development. The following approach aims to enhance resource efficiency at the industrial park level through IIS, which involves trading material, energy, and water by-products among companies within a park, neighbourhood, or region (UNIDO, 2020). Industrial synergies within an industrial park could be included in four groups: i) supply synergies, ii) utility synergies, iii) service synergies, and iv) by-product synergies and waste exchanges.

Identifying available resources and potential synergies requires a systematic approach and appropriate methodologies, comprising the following main steps:

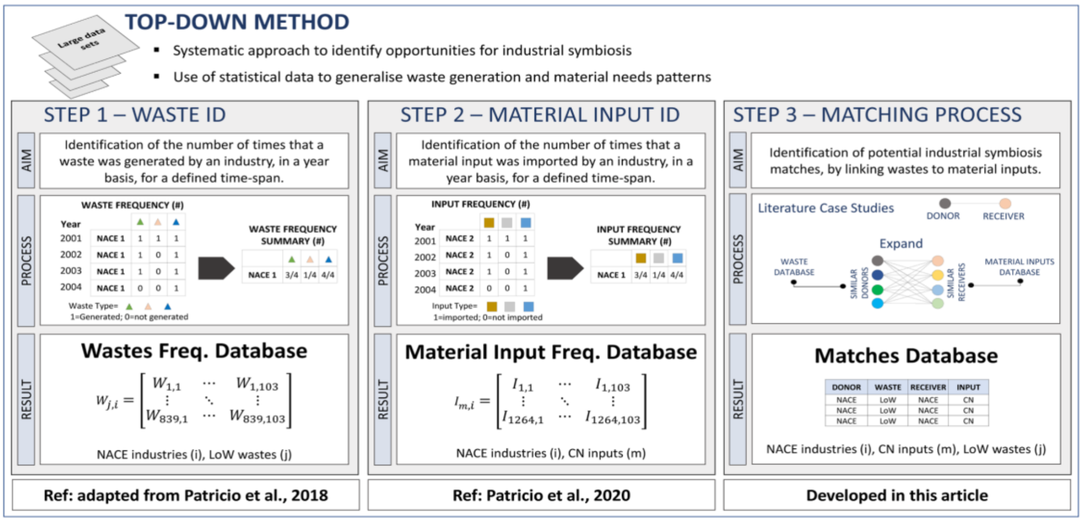
- Discover symbiosis potential through resource mapping. This phase involves comprehensive company surveys and assessments to map available resources and their geographical distribution (see 2.2 for details).
- Engaging stakeholders from industries, local or regional authorities, and communities to gather insights and perspectives on resource availability and potential synergies is equally essential.
- Estimate the impact of IS by performing techno-economic analysis, more specifically, evaluating the technical feasibility and economic viability of resource utilization and synergy projects through rigorous study and modelling (UNIDO, 2020).
- Execute pilot projects to demonstrate the benefits of IS and motivate companies.

Bottom-up approaches, while effective in identifying opportunities for IS partnerships, face limitations. Companies must engage in activities like registering resources or wastes on web platforms and participating in workshops or meetings to obtain necessary data. However, data confidentiality, lack of awareness of value gains, time constraints, and high costs can hinder data acquisition. Some companies are reluctant to share confidential information, such as raw material consumption or waste generation, while others see no clear value gains in sharing information. Time constraints also play a role, as companies may not have the time to engage in these activities. Conducting audits and interviews to gather information can be costly and time-consuming. Additionally, some companies may not be considered for workshops or forget to register their waste online or complete questionnaires. The barriers to IS are further discussed in section 2.4 of this report.

The top-down approach proposed by Patricio et al. (2022) comprises three main phases, as presented in Figure 5:

- Step 1: Typical waste identification - Identifies types of waste generated by different industries based on NACE codes, assuming similar industries produce similar wastes. A matrix of typical waste was developed using the Industrial Waste dataset, indicating the frequency of specific waste types generated by industries over four years (developed between 2012 and 2015).
- Step 2: Identify typical material inputs for industries using international trade statistics. A Material Inputs Frequency database was developed, indicating how frequently industries imported products over fourteen years (between 2000-2013).
- Step 3: Matching process - Potential Industrial Symbiosis partnerships between NACE industries are identified using IS case studies and frequency databases. The process involves:
    - IS Case Study Details: Identifying proven waste-material input links from literature.
    - Expansion: Identifying potential waste donors and material receivers using frequency databases
    - Matching: Expanding IS case studies to identify more potential matches.
    - Results Printing: Registering potential matches into a final database.

Figure 5. Top-down method for identifying Industrial Symbiosis Opportunities



Source: Patricio et al., 2022

This structured approach leverages existing data to systematically identify and expand potential Industrial Symbiosis opportunities, enhancing industry resource efficiency and waste management. The method utilized Eurostat standard classifications, which align with comparable classifications in other global regions. Furthermore, the technique has undergone testing in a spatial context, examining potential Industrial Symbiosis prospects while considering the distances between companies (Patricio et al., 2022).

2.5.2. Examples of methods for materials symbiosis synergies

The methodology for identifying symbiosis synergies as an example for water and energy is provided below.

Water symbiosis synergies

Water consumption and treatment can be complex at the park level due to multiple factors and variables. Understanding the objectives of increasing industrial park water efficiency is crucial. This usually implies identifying, quantifying, and characterizing various water flows and factors influencing water use and wastewater generation. These are essential steps in understanding the causes of water losses and identifying internal water efficiency solutions and symbiotic water treatment solutions.

Establishing a database to manage water balance data at the park level, integrating information on water consumption, discharge, and observations from company visits. The water balance compilation should include data such as park area, number of companies, water withdrawal, industrial effluent discharge, and water consumption by industry (UNIDO, 2020b). Analysing water consumption and effluent discharge data provides insights into water utilization efficiency and waste generation. For example, an analysis of 12 industrial parks in Vietnam revealed that water consumption in production processes accounted for 28–53% of industrial water withdrawal, while effluent discharge ranged from 40–45%. Factors influencing water use and treatment in industrial parks include water scarcity, pollution, park configuration, industry types, water volume, quality requirements, and technology levels (Pham et al., 2016). Internal water efficiency strategies focus on reducing water demand within companies. These strategies include modifying process units to reduce water usage and reusing outlet water for other operations. Systematic reuse strategies can significantly reduce freshwater usage and wastewater discharges, enhancing efficiency and minimizing capital investment in treatment facilities. External strategies for water efficiency involve collaborative approaches within industrial parks. Key elements include centralized wastewater treatment, infrastructure-integrated symbiotic models, and water reuse initiatives. Centralized treatment plants can efficiently remove pollutants from wastewater, while infrastructure-integrated models optimize water and energy flows between park facilities. Water reuse offers businesses environmental benefits and cost savings, with various applications such as processing water, cooling, cleaning, and irrigation.

Identifying water symbiosis opportunities involves systematically analysing water flows, understanding different industries' water needs and characteristics, and finding synergies for water reuse and treatment within industrial parks (UNIDO, 2020b). The following methodologies are usually applied:

- Data Collection and Analysis: gathering data on water consumption, discharge, and quality from companies within the industrial park and compiling information on the types of industries, their water needs, processes, and effluent characteristics is the critical first step. Analysing the water balance data to understand the relationship between water inputs, consumption, and effluent discharge and identify areas of inefficiency, such as high-water consumption or untreated wastewater discharge, are equally important. Information on the inputs and outputs will be the basis for the matchmaking process.

- **Water Pinch Analysis** is a systematic methodology to identify water reuse opportunities and optimize water networks. First, it evaluates the water reuse potential by analyzing the interactions between water sources and sinks within the industrial park. This implies the identification of wastewater streams with characteristics suitable for reuse in other processes or industries and identifying potential matches between water sources and sinks based on quality requirements and treatment needs.
- **Process Integration**: this phase explores opportunities for integrating processes to facilitate water reuse and minimize waste generation. This may involve identifying processes where wastewater from one operation can be treated and reused in another operation within the same company or different companies. Evaluation of the feasibility of integrating water treatment processes into existing operations to maximize resource utilization and minimize environmental impact is also required.
- **Technological Assessment.** While assessing available technologies for treating wastewater and purifying water for reuse, it is essential to consider factors such as treatment efficiency, cost-effectiveness, energy consumption, and compatibility with existing processes. This helps evaluate the potential for implementing advanced treatment technologies, such as membrane filtration, biological treatment, or chemical precipitation, to meet water quality requirements for reuse.
- **Feasibility Assessment** is necessary to evaluate the technical, economic, and environmental viability of identified water symbiosis opportunities and consider factors such as capital investment requirements, operational costs, potential savings, regulatory compliance, and environmental impact. Feasibility assessment supports the development of a prioritized list of water symbiosis projects based on their feasibility and possible benefits.
- **Implementation and Monitoring.** Develop an implementation plan for selected water symbiosis projects, including timelines, responsibilities, and resource allocation, and monitor the implementation progress and performance of water reuse and treatment initiatives. Continuously assess and optimize water management practices based on feedback, data analysis, and changing regulatory requirements.

Energy symbiosis synergies

The methodology for identifying energy symbiosis solutions in industrial parks is a systematic and collaborative process involving data analysis, stakeholder engagement, international benchmarking, specialized software tools, consultation with experts, and implementation of integrated solutions tailored to each industrial park's specific needs and characteristics.

- **Data Collection and Analysis.** This step involves collecting detailed data on energy consumption, production, and distribution within the industrial park. Various energy sources are considered, including electricity, thermal, and renewable energy. Additionally, factors influencing energy use, such as production processes, equipment efficiency, and operating schedules, are analysed to understand energy flows within the park comprehensively.

- **Energy Pinch Analysis** is a powerful tool for identifying inefficiencies and energy losses within the industrial park. Examining the energy balance and identifying areas where energy supply exceeds demand or vice versa can uncover potential opportunities for energy symbiosis. This analysis helps prioritize areas for improvement and optimization.
- **Stakeholder Engagement,** including company staff, park management units, and other relevant parties, is crucial for gathering insights and perspectives on energy usage and potential synergies. Discussions and workshops are conducted to exchange ideas, identify challenges, and explore collaborative opportunities for energy optimization.
- **Matching inputs and outputs** is a crucial aspect of energy symbiosis, which matches energy inputs (such as energy demands) with outputs (such as waste heat) from different companies within the industrial park. By identifying complementary energy needs and opportunities for heat recovery, synergistic relationships can be established to optimize energy use and minimize waste.
- **Reviewing International Experiences, case studies, and best practices** in industrial energy symbiosis provides valuable insights and inspiration for potential solutions. By learning from successful examples elsewhere, industrial parks can adapt proven strategies and approaches to their specific context and challenges.
- **Analysis of Park Infrastructure** refers to assessing the existing infrastructure within the industrial park, including park management, utility services, and common infrastructures, which is essential for identifying opportunities for optimization and collaboration. This analysis helps determine the feasibility and potential impact of the proposed energy symbiosis solutions.
- **Utilization of Specialized Software** to manage energy input/output data, visualize energy flows, and identify optimization opportunities within the complex structures of industrial parks. These software tools enable detailed analysis and modelling of energy systems, facilitating more informed decision-making and planning.
- **Implement Integrated Solutions** to optimize energy use, reduce costs, and minimize emissions within the industrial park. This may involve deploying clean energy technologies, implementing waste heat recovery systems, integrating innovative grid technologies, and adopting energy conservation measures.

2.6. Drivers and Barriers to Industrial Symbiosis

When analysing drivers and barriers, literature differentiates between different divisions of these indicators. However, it should be noted that in addition to the terms ‘drivers’ and ‘barriers’, other terms such as: ‘opportunities’, 'enablers', 'challenges', ‘benefits’, and ‘incentives’ are used in various reports, reviews and papers. The shortest division of factors refers to those that "can unlock, facilitate and support the consolidation of synergies (enablers, drivers, triggers), and factors that can block or hinder the concretization of an initiative (barriers, challenges)" (Henriques et al., 2021:7). For this report, ‘drivers’ also included opportunities, benefits, enablers, incentives, triggers, motivators, etc., whereas ‘barriers’ also include challenges, and so on.

Most often, authors distinguish: 1. financial, 2. technological, 3. regulatory and 4. institutional **drivers and barriers** (Fraccascia et al., 2021;), but there are also more detailed ones. Henriques et al. differ regarding social, economic, policy, management, informational, geographical, and intermediary enablers and barriers. Rahman et al. (2016) enumerates technological, financial, informational, and lack of trust among organizations (organizational barrier), regulatory barriers, and risk and uncertainty.

Järvenpää et al. (2018: 77) state that Industrial Symbiosis faces different drivers and challenges, such as legislation, taxation, land use planning, investments, financial support, data availability, digital services, innovations and new businesses. Financial represents monetary benefits and investments; technological is related to the technical condition that influences the implementation of IS; regulatory refers to different forms of legislation and institutional concerns, issues related to the organizational structure of involved firms, their business models, and their strategic behaviour in implementing Industrial Symbiosis (Fraccascia et al., 2021: 4802). However, apart from challenges, every barrier category can represent drivers or enablers stimulating Industrial Symbiosis (Golev et al., 2014: 142).

IS involves using waste or by-products from one company as resources for another to achieve environmental and economic **benefits**. IS practices also include enhancing resource efficiency, which presents significant economic opportunities, reducing costs and improving competitiveness (Chertow, 2000). This practice fosters a Circular Economy by reducing industrial waste and optimizing resource efficiency. Industrial symbiotic relationships have been **driven** by several factors, such as resource-saving economic gain benefits that meet environmental requirements, e.g., reducing greenhouse gas emissions, scarcity of natural resources and reducing waste that would otherwise end up in landfills and incinerators. The IS concept uses symbiotic cooperation and company linkages to close the loop. Garnering significant attention in both developed and developing regions, numerous studies have explored their potential, challenges, and implementation strategies.

Historically, IS has evolved organically. One notable example is the industrial ecosystem in Kalundborg, Denmark, which emerged from opportunistic business decisions rather than planned interventions. This case underscores the importance of recognizing and supporting existing symbiotic relationships (i.e., **drivers**) instead of creating them artificially. According to Chertow (2007), IS typically develops through practical business collaborations that form 'kernels' of cooperation driven by mutual benefits and regulatory pressures. These initial collaborations can expand into more extensive networks as trust and benefits are realized, illustrating the potential for organic growth in symbiotic systems.

Transitioning to the context of Australia, research on regional synergies in mineral processing areas like Kwinana and Gladstone highlights the reuse of by-products and shared utility infrastructure as critical strategies for Industrial Symbiosis. Van Beers et al. (2007) identify several **barriers** to IS implementation, including low waste disposal costs, confidentiality concerns, and a primary focus on core business strategies over sustainability initiatives. Despite these challenges, economic **benefits** such as cost savings, the availability of information, corporate citizenship, and active community engagement are significant **drivers** of IS adoption. The study concludes that a regional approach to IS can improve environmental outcomes and deliver economic benefits, with organizations like the Centre for Sustainable Resource Processing playing a crucial role in facilitating these synergies.

Similarly, Watkins et al. (2013) explore the development of products from primary industrial residues using IS concepts in the European Union. They identify significant institutional **barriers**, such as inadequate market incentives, regulatory instruments, and classification issues under existing legislation. Advocating for an enabling environment that includes market incentives and cooperative policy design, the authors emphasize the need for a systemic approach to treat industrial systems as integrated ecosystems. By fostering such an environment, IS can contribute to **benefits** such as a more sustainable and efficient industrial landscape, aligning with broader European sustainability goals.

Africa presents considerable potential for IS due to the continent's rich agricultural resources and the growing integration of sustainability into education. Olayide (2015) highlights the **barriers** faced in adopting IS, such as implementation time lags, the scale of agriculture, and socio-governance issues. Nonetheless, the study identifies significant **opportunities** for IS, particularly with active government and private sector involvement, supported by international cooperation. For instance, IS practices can help address waste management challenges and enhance resource efficiency in agricultural and industrial sectors, promoting sustainable development across the continent.

In Spain, studies focus on the potential for Small and Medium-sized Enterprises (SMEs) to engage in IS within industrial parks. Puente et al. (2015) examine 161 firms in the Besaya region, revealing diverse **opportunities** for symbiotic activities, such as resource substitution with waste products and shared waste management services. However, **barriers** like low individual motivation, isolation of SMEs, and legal hurdles concerning by-product status must be addressed. This study underscores the importance of adopting new business models focused on systemic sustainability and long-term life cycles to facilitate IS.

Further emphasizing the global nature of IS, Corder et al. (2014) provides a comprehensive overview of the challenges and potential enablers of Industrial Ecology (IE) in Australia. The study categorizes **barriers** into several groups: regulatory, informational, community, economic, technical, cooperation and trust, and commitment to sustainable development. Overcoming these barriers could enhance the adoption of industrial ecology in Australia. The study suggests the need for customized approaches to integrate international best practices within the country's unique economic, cultural, and regulatory landscape, highlighting the importance of context-specific solutions.

Mauthoor (2017) investigates the feasibility and **benefits** of implementing IS practices within Mauritius's industrial sector. By applying an IE approach to waste exchanges, the study advocates using simple technologies to reduce waste that would otherwise be landfilled or stored on-site. Critical **factors for developing** environmentally harmonious industrial networks include technology, funding, regulatory frameworks, stakeholder involvement, and support from the public and non-governmental organizations. The research recommends developing robust recycling infrastructure, leveraging simple technologies for waste management and by-product exchanges, and securing funding from international and local organizations. Emphasizing the need for a supportive regulatory framework, stakeholder engagement to foster collaboration, and active involvement of the public and non-governmental organizations. This study builds community support and awareness for Industrial Symbiosis.

Transitioning to the role of local governance, Södergren and Palm (2021) explore how local governments can **facilitate Industrial Symbiosis** as part of the Circular Economy. They propose a theoretical framework for understanding local governments' roles, such as acting as facilitators to coordinate material exchanges, investing in necessary infrastructure, and offering financial incentives. Developing clear strategies for IS integration into physical planning, promoting knowledge sharing, and including IS considerations in urban planning are emphasized. By adopting these roles, local governments can overcome various barriers to IS and significantly contribute to its successful implementation at local and regional levels.

Further exploring governance, Rodin and Moser (2021) delve into industrial energy cooperation within industrial parks, aiming to enhance energy efficiency and sustainability through initiatives like waste heat exchange and renewable power plant operations. Energy symbiosis models mainly aim to simultaneously minimize costs and emissions related to energy exchanges, optimize energy efficiency, and reduce carbon emissions. Applying energy efficiency strategies and energy symbiosis solutions provides many **benefits** for participating companies: it reduces the investment costs for plants and installations of infrastructure, along with operational expenditures (fuel, maintenance), favourable prices for collectively purchased utilities, and controls the load curve by bundling the energy demands of different firms (Afshari, 2017). Despite the apparent benefits, numerous barriers impede the realization of such cooperative efforts. These **barriers** include social and informational issues, technical and engineering challenges, and framework barriers related to policies, action plans, and legal frameworks. The study emphasizes that overcoming these barriers requires a multidisciplinary approach involving policy intervention, information dissemination, technical innovation, and social engagement. By addressing these multifaceted challenges, industrial parks can achieve significant energy efficiency and sustainability advancements.

In Slovenia, the potential of IS and urban symbiosis is explored through urban strategies. Momirski, Mušič, and Cotič (2021) highlight the **challenges** of implementing IS and urban symbiosis, including the absence of specific guidelines in urban strategy, insufficient waste conversion to energy, and minimal reuse of by-products. Despite these barriers, the study identifies opportunities for integrating IS and urban symbiosis in brownfield redevelopment and improving waste management practices. Legislative support aligned with EU regulations and increased awareness are critical **drivers** for IS and urban symbiosis in Slovenia. This underscores the importance of comprehensive legislative and strategic frameworks in fostering IS and urban symbiosis.

Shifting the focus to the manufacturing sector, Jaeger and Upadhyay (2020) identify significant **challenges** in adopting the Circular Economy model. High start-up costs, complex supply chains, and difficulties in business-to-business cooperation are vital **barriers**. The study underscores the need for targeted strategies to address these barriers and leverage the drivers of the Circular Economy to foster more sustainable operations within the sector. Manufacturing industries can transition towards more sustainable and efficient practices by developing robust frameworks and support systems.

In China, Ji et al. (2020) aims to identify the factors influencing enterprises' participation in Industrial Symbiosis and validate an analytical approach. Using data from the Tianjin Economic-Technological Development Area, the study finds that environmental regulations are a primary **motivator** for enterprises already participating in IS. At the same time, geographic disadvantages are significant constraints for non-participating enterprises. Key **barriers** include a lack of awareness about IS among waste-producing companies, insufficient government support, and difficulties reaching agreements for waste-utilizing companies. The study advocates for developing targeted policies based on specific barriers and drivers to advance IS participation.

Neves et al. (2019) provide a comprehensive overview of IS activities across Europe, highlighting its role in promoting sustainable and integrated industrial systems. The study identifies significant growth in IS activities **driven** by public and private initiatives, with key IS networks varying in size, geographical distribution, and resource streams traded. **Barriers** include weak economic incentives due to undeveloped secondary markets, regional policy differences, and legislative complexities related to waste transport. Despite these challenges, the European Commission's Circular Economy package offers opportunities for Industrial Symbiosis development. The findings highlight the potential of IS to contribute significantly to the Circular Economy CE, underscoring the need for further research to address challenges and leverage opportunities for IS development.

Addressing non-technical barriers is crucial to effectively implementing IS. Tools like the IS maturity grid, which assesses and monitors industry collaboration levels, play a pivotal role. Golev et al. (2014) highlight the importance of effective communication and data exchange systems for fostering IS development. The maturity grid evaluates a region's IS maturity through several defined stages, helping identify strengths and areas needing improvement. This structured approach ensures that regions can systematically enhance their IS capabilities.

A historical perspective on IS reveals the evolution of the concept from a traditional view of industries as harmful to the environment to an integrated approach where industries and environmental sustainability are interlinked. Islam et al. (2016) emphasize that supportive policies are essential to foster IS development and overcome technological, economic, informational, organizational, and regulatory barriers. By integrating these policies, regions can create an enabling environment for IS.

The interest among SMEs in Spain for collaborative activities driven by potential economic benefits and improved environmental performance underscores the importance of broad stakeholder collaboration and aligning interests within the value chain for successful transformation to a Circular Economy system. Rincón-Moreno et al. (2020) highlight the significance of stakeholder engagement and the need for clear roles and responsibilities to overcome barriers such as lack of collaboration and government coordination. Effective stakeholder management is critical to the success of IS initiatives.

Kosmol and Otto (2020) comprehensively analyse IS implementation challenges, categorizing 402 barriers into economic, technological, financial, cooperation, management, knowledge, information, policy/regulation, and public/market challenges. The authors propose that a structured overview of these barriers can help develop effective strategies for mitigating them and advancing Industrial Symbiosis practices. This comprehensive categorization allows targeted interventions to address specific challenges and promote IS.

The role of individual champions in fostering IS initiatives is crucial, as leadership and innovation are necessary to navigate organizational and institutional contexts. Kokoulina et al. (2019) emphasize that champions can drive IS initiatives through their ability to coordinate and inspire collaboration among stakeholders. Geographical proximity, environmental and economic benefits, and the presence of a core player to lead initiatives are pivotal drivers for IS. By fostering organizational leadership, Industrial Symbiosis initiatives can gain the momentum needed for success.

Henriques et al. (2021) extensively analyse IS development, highlighting sector-specific enablers and barriers. They use the Kalundborg Eco-Industrial Park as a successful case study to illustrate the long-term benefits of IS. Critical barriers to IS implementation include a lack of coordination among parties, companies' lack of motivation due to operational demands, resistance to sharing sensitive data, and limited willingness for stakeholder collaboration. Integrating changes into existing operations and committing to complex projects also poses significant challenges. However, economic benefits such as cost savings, tax advantages, and environmental motivators like reduced emissions and better resource efficiency drive IS adoption. The study emphasizes the need to understand sector-specific dynamics to develop targeted strategies that facilitate IS, concluding that a clear understanding of enablers and barriers allows policymakers and industry stakeholders to design effective frameworks and incentives.

Examining IS within Mo Industrial Park, Jakobsen and Steinmo (2021) identify high investment costs, regulatory challenges, and long-term contract needs as significant barriers. Drivers include economic gains and existing infrastructure. The study highlights the importance of adaptive management practices and supportive regulatory frameworks. They conclude that while financial incentives and infrastructure are crucial for IS, supportive regulatory frameworks and dynamic knowledge exchange are essential for sustaining these practices.

In Norwegian industrial clusters, Havem and Karlsen (2023) identify critical economic and environmental drivers such as cost savings, environmental responsibility, stakeholder demands, and international regulations. Barriers include technical, organizational, social, financial, and institutional challenges. The study proposes solutions such as fostering community pride, having third parties facilitate symbiosis, and promoting a collaborative culture. The importance of building trust, enhancing knowledge about IS, and finding practical solutions to technical and organizational challenges is highlighted.

Yang et al. (2022) use a Group AHP-TOPSIS model to evaluate IS barriers in China, identifying technological, economic, safety, and informational challenges. The study highlights the importance of prioritizing these barriers to enhance IS implementation and recommends further research to validate the model in other contexts. Although the study does not provide specific solutions for overcoming these barriers, it presents a model to help stakeholders and IS practitioners better understand and address them.

Corsini et al. (2024) investigate IS integration into companies' strategies to achieve a Circular Economy CE, identifying significant barriers such as regulatory constraints, high investment costs, and challenges securing financing. Political and managerial actions, like supportive regulatory frameworks, financial incentives, and fostering a culture of collaboration and data sharing, are necessary to overcome these barriers. The study emphasizes that the primary obstacles are economic and regulatory rather than logistical or networking concerns. Understanding the levels of IS adoption among companies helps tailor specific interventions to promote the transition to a Circular Economy CE.

Investigating the integration of Integrated Product and Service Offerings (IPSO) with Industrial Symbiosis, Päivärinne and Lindahl (2016) focuses on enhancing Excess Heat (EH) utilization. The study supports the idea that combining IPSO with IS provides benefits such as improved productivity, resource efficiency, and environmental sustainability. However, it also highlights the necessity for inter-organizational collaboration, which can be challenging. Barriers include technological limitations, social factors, reluctance to change, and economic constraints. Drivers for this integration include environmental concerns, regulatory pressures, and the push towards a service-oriented economy.

Patrício et al. (2018) examine IS among SMEs in Västra Götaland, Sweden, identifying primary motivations for economic benefits, improved environmental performance, and marketing advantages. Barriers include time constraints, finding suitable partners, and lack of knowledge about IS practices. The study highlights that some SMEs already practice ISby sharing by-products with other companies or using them to create valuable products. Regional authorities can promote

IS by linking companies and helping them understand the benefits, thereby improving waste management, environmental performance, and possibly marketing outcomes.

Henriques et al. (2022) propose a framework for identifying and assessing IS incentives, emphasizing risk assessment and mitigation actions to facilitate IS implementation. The study highlights the importance of financial and legislative support for promoting IS. To address these challenges, the authors propose a comprehensive framework for identifying and assessing incentives based on best practices and expert consultations. This framework includes risk assessment to identify economic, social, and policy-related risks. It suggests mitigation actions tailored to various stakeholders, such as national and local governments, intermediaries, knowledge agents, and businesses.

Exploring IS implementation in emerging and frontier market countries, Cárcamo and Peñabaena-Niebles (2022) identify barriers such as a lack of academic literature, early development stages, and environmental challenges. Drivers include supportive legislation, economic and ecological benefits, and cross-sectoral partnerships. The study emphasizes the need for cross-sectoral collaboration and the development of conducive legal frameworks to foster IS growth. By identifying the barriers, opportunities, and drivers, the research provides actionable insights for policymakers, researchers, and industry professionals aiming to promote IS in emerging and frontier markets, ultimately contributing to sustainable industrial development and resource efficiency.

Oni et al. (2022) examine the potential for IS in Africa, identifying legislative limitations, bureaucratic challenges, and funding shortages as barriers. Drivers include economic, environmental, and social benefits. The study emphasizes a coordinated national approach and enhanced legislative frameworks to foster IS. The success of IS depends on multiple interconnected factors, including regulatory environments (Erceg et al., 2017; Činčurak Erceg, 2024), financial incentives, and business community engagement, necessitating collaborative efforts from governments, businesses, and other stakeholders.

In conclusion, the reviewed studies highlight the multifaceted nature of Industrial Symbiosis and the various barriers and enablers (Table 2) affecting its implementation. Economic incentives, regulatory frameworks, and awareness are critical drivers, while challenges include a lack of infrastructure, weak regulatory support, and informational deficits. The role of local governments, state institutions, and supportive policies is paramount in overcoming these barriers and promoting sustainable industrial practices. IS can significantly contribute to the Circular Economy and sustainable development by addressing these challenges and leveraging the identified opportunities.

Table 2. Summary of the different Industrial Symbiosis drivers and barriers

#	DRIVERS	BARRIERS
1	Economic benefits, cost reduction, financial incentives	Infrastructure and Technology
2	Environmental performance benefits, environmental responsibility, waste minimization, emissions reduction (GHGs, wastewater, etc.)	Data Management and Information Sharing
3	Social (increased awareness, community engagement, stakeholder demands)	Health, safety and environment

4	Regulatory pressure, environmental regulations, supportive policies	Governmental, Regulatory and Policy Barriers
5	Sustainable industrial production, enhanced resource efficiency	Economic and Financial Barriers
6	Improved competitiveness, improved productivity,	Market and supply chain barriers
7	Marketing advantages, cross-sectoral partnerships	Organizational and Managerial Barriers
8	-	Cultural and Social Barriers
9	-	Other

Source: authors

2.6.1. Current Situation and Future Prospects

The Industrial Symbiosis (IS) landscape is marked by a growing awareness of its benefits and increasing implementation across various regions and sectors. However, the full potential of IS is yet to be realized due to persistent barriers such as regulatory hurdles, lack of financial incentives, and insufficient awareness among stakeholders. Despite these challenges, successful cases like Kalundborg in Denmark and regional synergies in places like Kwinana and Gladstone in Australia provide valuable models for other regions to emulate. These examples demonstrate that IS can bring significant environmental and economic benefits with the right combination of financial incentives, supportive regulatory frameworks, and stakeholder collaboration.

The future of IS looks promising, driven by the increasing emphasis on sustainability and the Circular Economy in global policy agendas. The European Union's Circular Economy package and other international initiatives will likely spur further development and adoption of IS practices. Technological advancements and innovative business models will also play a crucial role in overcoming existing barriers. For instance, integrating digital platforms for waste sharing and developing advanced recovery technologies can enhance the efficiency and feasibility of IS. Additionally, fostering a culture of collaboration and trust among industries, facilitated by local governments and third-party organizations, will be essential for expanding IS networks.

Policymakers, industry leaders, and researchers need to continue their efforts to identify and address the specific barriers and drivers of IS in different contexts. Tailored strategies will be crucial, considering each region's unique economic, cultural, and regulatory landscapes. Furthermore, ongoing research and case studies will provide deeper insights into effective practices and emerging trends in IS. By building on the successes and lessons learned from existing IS initiatives and leveraging technological innovations and policy support, IS has the potential to become a cornerstone of sustainable industrial development worldwide.

2.7. Summary and conclusion

For the identification or detection of synergies between the resources and waste of different entities with potential for implementation in IS, various methodologies can be used:

- **Government and Institutional Actions:** Governments can reduce taxes or provide economic incentives for companies adopting symbiosis in their production systems. They can also encourage companies to submit voluntary data to administrations or critical agents.
- **Research Organizations:** Provide designs and resource information to help companies make better decisions.
- **Dedicated Departments within Companies:** Establish departments responsible for updating inventories of water use, energy use, waste generation, etc., enhancing long-term performance and establishing teams of experts to analyse and evaluate data to identify potential synergies. Here, it is essential to incorporate detailed information variables (e.g., quality characteristics, availability, accessibility), which are crucial for the viability of connections.
- **Interactive Platforms for Data Exchange:** NISP and eSymbiosis facilitate inter-company data exchanges using advanced IT techniques. Technological Systems and Data Analysis Software are crucial aspects here. Use software tools to detect synergies and analyse data, facilitating identifying connections between entities. Implement secure and reliable data exchange systems and apply modelling tools (including AI) to explore and identify connections. Using Standard Nomenclatures: Classify industries, material inputs, and waste using NACE, CN, and LoW for accurate data matching.
- **Company Visits and Key Agent Engagement:** Collect data through direct visits to companies and engagement with critical agents.

These methodologies emphasize the importance of systematic data collection, secure data sharing, expert analysis, and technological tools to effectively identify and implement IS opportunities. Correctly communicating these identified synergies is crucial to understanding the potential interest in their application and addressing Confidentiality Constraints to overcome data-sharing challenges through non-disclosure agreements and intellectual property protections.

3. Evaluation: What criteria are necessary to assess the potential for Industrial Symbiosis implementation?

3.1. Criteria

Assessing the potential for Industrial Symbiosis (IS) implementation involves several critical criteria that help determine the feasibility and effectiveness of collaborations between companies. By systematically evaluating these factors, companies and stakeholders can make informed decisions about the potential and long-term viability of implementing Industrial Symbiosis. This involves, in part, identifying the main drivers of IS, which, according to Neves et al. (2019), include the diversity of industries, geographical proximity, facilitating entities, and supportive legislation, plans, and policies. The criteria can be categorized as follows:

- Type of Economic Activity
- Resource flow analysis
- Cost Evaluation
- Stakeholder Engagement
- Political and Regulatory Framework
- Geographical Factors
- Technology Compatibility
- Company Readiness

3.1.1. Type of Economic Activity

To assess the potential for implementing IS in an industrial park, it is crucial to begin with the economic activity characterization. This initial step involves understanding the financial activities of the companies involved to contextualize potential symbiosis scenarios. According to the CEN Workshop Agreement (2018), economic activity characterization is essential as it provides a comprehensive understanding of the operational landscape and helps identify company synergies. Ruiz-Puente et al. (2015) emphasize that industrial activity density, type, and nature significantly influence the propensity toward IS. This insight is vital because IS-based collaborations are increasingly recognized as effective strategies for resource management and environmental impact mitigation. However, such collaborations are more prevalent in developed regions with larger-sized industries, while developing areas and SMEs exhibit fewer such partnerships (Akhtar et al., 2022).

a. Industry Mix

A diverse industry mix is critical for a successful IS network. Various industries engaging in different economic activities foster knowledge transfer and innovation. The UK's National Industrial Symbiosis Program (NISP) experience demonstrates that over 70% of synergies involve innovation, with 50% arising from cross-sector knowledge transfer and best practices and 20% from new research and development due to close links with universities. A diverse industry mix creates opportunities for waste materials from one industry to be used as inputs for another, enhancing the viability of symbiotic relationships. Moreover, having multiple companies engaged in similar economic activities ensures a steady flow of waste materials, crucial for maintaining continuous symbiotic exchanges (Neves et al., 2019). Counting the number of different NACE (Nomenclature of Economic Activities) codes will help measure the diverse industries. A higher diversification indicates a broader range of industries, enhancing Industrial Symbiosis's potential.

b. Predominance of Key Industries

According to Neves et al. (2019), the predominance of certain types of industries, such as large consumers of resources and emitters of greenhouse gases (e.g., the steel and iron industry in China), can drive the creation of IS networks. Due to their significant resource needs and waste generation, these industries provide ample opportunities for symbiotic exchanges. Indicators to look out for are the number of manufacturers and companies in the construction and food sectors. Manufacturing stood out as the sector with the highest potential for establishing symbiosis relationships (Neves et al., 2019).

c. Presence of Anchor Tenants

Anchor tenants play a pivotal role in driving IS relationships. They are primarily large multinationals, and these companies, due to their size and influence, can attract and sustain a network of companies by providing a steady supply of materials and facilitating the reuse of waste. Anchor tenants help stabilize and grow the IS network by creating a reliable base for symbiotic activities (Neves et al., 2019).

3.1.2. Resource flow analysis

The second most crucial step in assessing the potential for IS implementation in an industrial park is conducting a Resource Flow Analysis. This analysis focuses on identifying the types and quantities of waste, by-products, energy, and other resources available for exchange among industries. It involves mapping out the inputs and outputs of each potential participant in the IS network. Resource Flow Analysis is essential because it is the foundation for evaluating all other criteria. It helps identify and characterize the waste streams (solid, liquid, gaseous) generated by each industry in the potential IS network. Assessing these waste streams' volume, consistency, and quality is critical to identifying feasible synergies.

According to Neves et al. (2019), the most common types of waste streams in potential Industrial Symbiosis networks include organic materials, plastic and rubber, wood, and metallic materials. Understanding the types and quantities of these waste streams is vital, as it allows for the identification of potential by-products that could serve as valuable resources for other industries. For example, measuring the tons of waste generated per unit of product output can help evaluate the viability of these materials for reuse.

Once resources are mapped, evaluating IS implementation's social, economic, and environmental impacts becomes possible. This analysis can determine if the available resources are sufficient to achieve goals such as reducing greenhouse gas emissions and minimizing waste sent to landfills. According to Neves et al. (2019), most IS cases aim to achieve environmental, economic, and social benefits. The ecological component is frequently measured due to international and national constraints on emission reductions and waste management. Metrics such as reduction in waste, decreased energy consumption, and lower greenhouse gas emissions are crucial for assessing the environmental benefits of IS. These metrics help estimate the potential impact of IS implementation and guide decision-making.

Resource Flow Analysis also enables estimating how far resources will travel and what synergies can be created. Various factors, including market prices, regulations, and legislation, influence the distance resources can be transported. For example, documented NISP® synergies have moved textiles, metals, minerals, and paper/card over 200 miles in England, while steam and heat synergies are typically limited to local opportunities.

3.1.3. Cost Evaluation

Evaluating the economic viability of IS projects is another critical step. This involves assessing potential cost savings, revenue generation from waste sales, and investment returns. Indicators like these help gauge whether IS initiatives will be financially sustainable.

One key aspect to consider is the comparison of raw material prices versus recycled waste material prices. According to Neves et al. (2019), in a chemical industrial park in the west of Urumqi City, China, one company did not benefit economically from IS because the price of raw materials was lower than some types of industrial solid waste used for brick production. Additionally, the price companies are willing to pay for garbage might not always be economically advantageous for the waste-producing company, potentially discouraging waste diversion from landfills. It is also essential to consider the costs of managing resources, including potential savings from reduced waste disposal fees and increased resource efficiency. Evaluating these factors can provide a clearer picture of the economic benefits of IS. Assess IS implementation's costs and potential financial benefits, including transportation, processing, and infrastructure upgrades. The lack of knowledge about potential valorisation routes for residuals and by-products can be limited. Key performance indicators (KPIs) should also be evaluated, such as the payback period for initial investment in IS infrastructure and processing and market price variability (%).

3.1.4. Stakeholder Engagement

Stakeholder engagement is another critical criterion for assessing the potential for IS implementation. Public stakeholder involvement is crucial for providing initial funding and supporting innovation. Assessing the willingness and commitment of companies to collaborate and participate in an IS network is essential. Open communication and a collaborative spirit are vital for successful Industrial Symbiosis implementation.

According to Neves et al. (2019), barriers to IS include a lack of trust among potential collaborators and a lack of knowledge of IS. Therefore, it is essential to determine if the industrial park has an active park manager or business associations that can bridge the gap between companies and help build trust. These entities can identify new partners for infrastructure sharing and joint provision of services, provide training, facilitate information exchange, foster cooperation, and coordinate potential symbiosis relationships. What’s more, in places where no synergy networks have been established, the role of these facilitators can be highly relevant.

The knowledge level of CE and IS among companies can be assessed through surveys or by reviewing past events and activities. This is important because established IS networks can create new synergies and extend the network to new companies, leveraging existing internal structures and trust relationships.

Evaluating potential partnerships that facilitate or hinder IS implementation is also essential. This includes assessing the social and community impacts of the IS project, both positive and negative. Financial incentives and support, such as subsidies, grants, and tax incentives, encourage companies to invest in new processes resulting from IS collaborations. Key performance indicators for stakeholder engagement include the number of participants at IS events or workshops, the amount of financial incentives received, and the number of financial support programs utilized. These factors and a supportive regulatory and political framework are essential for the flexibility needed to invest in new IS processes.

3.1.5. Political and Regulatory Framework

Ensuring compliance with all relevant regulations regarding waste management and environmental impact is critical. This involves identifying potential regulatory barriers for waste and hazardous substances. According to Neves et al. (2019), current legislation can restrict the integration of new waste materials into productive processes due to toxicity concerns and regulatory limitations. Neves et al. (2019) highlight several regulatory barriers, such as low taxes on landfill disposal, a lack of policies that encourage and regulate IS, insufficient funds to promote this practice, and deficient regulatory frameworks. These barriers can limit the implementation of synergy relationships, especially if existing legislation is too rigid, unclear, or inconsistent. This includes identifying regulations or permitting requirements that could affect waste stream transportation, treatment, or use in an IS network. Ensuring compliance with environmental and safety regulations is critical. Key performance indicators could include the regulatory hurdles identified for specific waste stream exchanges, such as the permits required to transport and utilize a particular industrial byproduct. With resource flow analysis, it is possible to identify which resources may encounter legal or regulatory barriers for synergy implementation.

Political incentives can also play a crucial role in overcoming these barriers. For example, in a chemical industrial park in Urumqi City, China, one company did not receive economic benefits from IS because the raw material price was lower than the industrial solid waste used for brick production. However, the environmental benefits, such as reduced consumption of natural resources and lower greenhouse gas emissions, justify the implementation of IS networks. In such cases, it is essential to map local or national governments' economic incentives to encourage companies to create these synergies.

3.1.6. Geographical Factors

Geographical proximity is another crucial criterion for assessing the potential for IS implementation. It significantly impacts transportation costs and the feasibility of synergies. According to Neves et al. (2019), in some cases, geographical location is not a constraint, and waste materials can be transferred to several locations. For example, waste materials from common industries available in most countries can be used to extend the range of IS applications. However, in other cases, geographical location can either condition or incentivize using certain waste materials in the symbiotic process. The strong presence of a particular type of industry can enhance IS by providing new solutions to manage waste generated by the production process.

Ideally, industries considering IS should be geographically close to minimizing transportation costs and environmental impact. Assessing the existing infrastructure for moving materials between potential symbiosis partners is essential and helps determine the feasibility of resource exchanges. KPIs for geographical proximity include the distance between potential symbiosis partners. The closer the industries are to each other, the more practical and cost-effective the IS implementation will be.

3.1.7. Technology Compatibility

Technological compatibility is another vital criterion for assessing IS potential. Evaluating whether existing technology can be readily applied to mapped resources is essential. This involves examining the availability of funding for these technologies, existing case studies, and cataloguing links with local universities and research centres.

According to Neves et al. (2019), increased investment by governments in research and development and greater involvement with research teams from universities or business associations is crucial. Assessing if the quality and form of waste streams require any pre-processing before use by another industry is critical. Evaluating the technical feasibility of integrating waste streams into existing production processes helps identify knowledge gaps and support needs. Neves et al. also note that the lack of available technologies and the high equipment costs inhibit the realisation of IS. Therefore, checking for existing economic incentives (public sector financing) and links with research centres for potential innovation and technology transfer is crucial.

Key performance indicators for technological compatibility include the percentage of waste streams requiring pre-processing before use in another industry and the number of technological adaptations necessary. Additionally, the number of successful case studies referenced and the Infrastructure Availability Index, which assesses existing infrastructure such as transportation networks, utilities, standard facilities, environmental management systems, security services, R&D centres, and support services, can be monitored.

3.1.8. Company Readiness

To complement the final decision-making, it is essential to identify the internal and external factors that can influence the company's implementation of the IS process. Conducting a SWOT analysis is a strategic tool for gathering and organizing information needed to evaluate an organization's positive and negative factors. This analysis helps focus on strengths and opportunities while addressing weaknesses and avoiding threats. Assessing the internal capabilities of each participant, such as technological capacity, financial stability, and human resources, is crucial. This includes identifying areas where companies excel or may face challenges. Additionally, it is essential to analyse which policies apply to each type of company and whether they hinder or incentivize participation in IS.

Furthermore, assessing the maturity of an individual company for IS involves identifying and characterizing its economic activity. Maturity models and tools can evaluate the company's current state in various areas, including material flows and associated management practices. This evaluation helps companies understand their behaviours and monitor their practices concerning material and surplus flows and destinations.

Assessing the flexibility of a proposed IS arrangement is crucial for ensuring long-term viability. This involves adapting processes and business models to incorporate IS practices, integrate new technologies, and respond to market or regulatory changes. Additionally, evaluating the scalability and replicability of IS initiatives in different contexts or geographic locations is essential. Thus, possible KPIs for measuring flexibility include the number of adaptable processes, the percentage of new technologies integrated, responsiveness to market or regulatory changes, scalability of initiatives, and the success rate of replicating IS practices in various contexts or locations.

In conclusion, assessing the potential for IS implementation in an industrial park requires a comprehensive evaluation of multiple criteria to determine IS initiatives' feasibility and long-term viability. According to Azevedo et al. (2021), once the economic potential of the surplus is defined, it is essential to characterize the main factors that might positively or negatively influence the implementation of the symbiotic process. By thoroughly analysing these factors (listed above), stakeholders can identify opportunities and address challenges, ensuring that IS projects are practical and beneficial. This holistic approach enables informed decision-making and paves the way for successful and sustainable IS practices in industrial parks.

3.2. Tools for analysis

IS is the interaction between two or more companies connected by material streams, energy streams, economic relations, or a combination of these. When a waste producer and user establish a relationship with IS, the waste produced by the former can be utilized by the latter to replace inputs in production processes or create new products. This relationship between waste producers and users results in environmental benefits for society, such as reduced waste discharge and emissions and decreased usage of primary inputs, including raw materials, energy, and water. Establishing IS between the two entities result in a mutually beneficial relationship that provides economic and environmental benefits.

A practical way to achieve a mutual relationship between companies is by employing the following methods: efficient use and management of resources, including steam, energy, water, and waste; sharing utility and infrastructure; offering joint services to meet every day needs related to business, safety, hygiene, transport, and waste management; and exchanging materials that were traditionally considered waste or by-products instead of commercial products or raw materials. IS has been established as the driving force behind advancing a Circular Economy in Industry 4.0. The sharing of resources among diverse companies and information integration throughout the entire value chain, from suppliers to consumers, are critical components of Industry 4.0's growth.

Literature sources (Scafà et al., 2020) provide insights into the design of IS models, including IS districts, eco-industrial parks, and network designs for Industrial Symbiosis. The involved organizations must be located near one another to develop IS districts, particularly with a 'short mental distance' between managers. To foster collaboration, four key pillars must be present: pragmatic environmental mentality, opportunities to explore possibilities, mutually beneficial initiatives, and a dominant need that drives a proactive search for solutions.

Eco-industrial parks are strategically developed and managed, focusing on ecological principles and IS. They comprise various IS instances that facilitate the exchange of energy and materials between participating companies. Unlike IS districts, eco-industrial parks can be planned top-down. Local administrative institutions, research centres, or universities typically manage these parks. A widely accepted definition of eco-industrial parks is an industrial system that promotes planned material and energy exchanges to minimize energy and raw material consumption waste generation and foster sustainable economic, ecological, and social relationships. To successfully implement eco-industrial parks, it is crucial to prove that the financial and environmental benefits achieved through collaborative efforts surpass those of individual companies. However, proximity is not a requirement for developing IS platforms.

UNIDO (2024) has created tools for identifying and applying eco-industrial parks. An Industrial Symbiosis identification tool was used between these tools. This tool aims to facilitate the detection of IS prospects, including by-product and waste exchanges between businesses. This tool applies to existing industrial estates (brownfields) and new estates (greenfield). In brownfields, stakeholders are offered a glimpse of the symbiotic potential linked to companies within the park, for greenfield help in planning infrastructure and utilities to enable connections between companies, thereby enhancing IS. IS networks serve as cognitive and relational tools to facilitate interactions and resource sharing between companies, focusing on fostering mutually beneficial relationships. These networks connect individuals and organizations to promote industry collaboration, innovation, and sustainability. By encouraging dialogue and facilitating the exchange of information, these networks help identify potential opportunities for synergy and cooperation, ultimately leading to more efficient use of resources and reduced waste. If the focus is on the renewable energy sources used in IS, then new forms of industrial parks can exist: Positive Energy Industrial Parks (Anastasovski, 2023).

The implementation of IS can be assessed by examining case studies before or after its inception using methods that yield the following types of information: data collection, qualitative analysis, environmental, economic, and social impact, network analysis, and other analytical techniques. These methods are essential for evaluating Industrial Symbiosis's advantages and disadvantages and determining their overall effect.

Some methodologies have been classified for IS design and analysis (Fraccascia & Giannoccaro, 2020). These are divided into four main groups: Flow Analysis, Thermodynamic methodologies, Life Cycle Assessment, and Network Analysis. Process Integration (PI) methods such as Pinch technology and Total Site Integration can be added as separate groups. Flow analysis consists of Material Flow Analysis (MFA) or adapted Material and Energy Flow Analysis (MEFA), Substance Flow Analysis (SFA), and enterprise input-output (EIO) approach. Thermodynamic methodologies include emergy analysis and exergy analysis. The LCA is a separate methodology. Network analysis uses the following methods: social network analysis, stakeholder value network, ecological network analysis, and food web analysis.

3.2.1. Flow analysis

Material and Energy Flow Analysis (MEFA) (Klemeš, 2013) is a fundamental method for identifying specific physical material flows and stocks in each system and all energy streams. Analysing the material and energy streams within the system makes it possible to identify waste streams that can be utilized by other processes within the company or inter-company connections. The goal of the MEFA is to assess the material and energy balance of the system and optimize the material and energy use in the system. MEFA can be used to identify opportunities for improving the efficiency of a system, reducing waste and emissions, and identifying potential cost savings. This is a valuable tool for companies seeking to enhance their sustainability and competitiveness by reducing their environmental impact and increasing resource efficiency. The initial step in these methodologies is data collection. This entails analysing comprehensive data for all material and energy streams to identify specific components crucial for production. These material streams are then meticulously examined to determine whether they can be recycled in the earlier stages of the production process with or without additional treatment, enhancing both the efficiency of the production process in terms of raw materials and its environmental impact.

Furthermore, it is crucial to consider the material streams that exit the production system and are directed to drainage or wastewater treatment plants as potential sources of valuable components that can be utilized in established or future production processes within an industrial park or region.

In the case of energy streams, a thorough analysis of streams carrying energy in various forms (primarily heat energy) must be conducted. Energy flow analysis identifies and classifies hot and cold streams based on their cooling or heating requirements. A cold stream is defined as a flow that requires heating, such as a stream with a temperature of 150°C that must be raised to 200°C. Conversely, a hot stream is defined as a flow that requires cooling, such as a stream with a temperature of 10°C, which needs to be lowered to -10°C. These classified hot or cold streams are considered waste heat energy that other nearby processes or companies can utilize. System data can provide valuable insights by mapping the material and energy flows without conversions.

Substance Flow Analysis (SFA) (El-Halwagi, 2017) monitors the movement of individual substances, such as chemical elements or compounds, into a specific system. This methodology is beneficial for analysing substances that raise environmental and health concerns. In the Information Systems field, SFA maps carbon flows among companies and production processes involved in IS synergies to assess the reduction in carbon emissions achieved using IS.

Enterprise Input-Output (EIO) models are a specific type of input-output (IO) model that focuses on individual production units rather than the entire sectors of national economies. These models help map the physical and monetary flows between production processes within a single enterprise or multiple enterprises in an IS network. EIO models provide a comprehensive view of an enterprise's internal operations by considering material input and waste or product output. These models are valuable tools for businesses to optimize production processes and improve efficiency. EIO can be used to evaluate the material and monetary flows among firms within an IS network (Albino et al., 2016).

Given that the "waste output-production input" relationship is closely connected to the costs and benefits of production processes, EIO is an appropriate method for determining the potential economic benefits of an IS relationship. In addition, an EIO model was developed that provides a cost-benefit analysis in IS relationships, and they computed the potential financial benefits in specific quantity mismatch scenarios (Yazan & Fraccascia, 2020). EIO models can serve as accounting tools, mapping the physical (i.e., materials, energy, and water) and monetary flows between production processes within single or multiple companies. EIO models are valuable for analysing logistical exchanges between various corporations and facilitating coordination policies. These models provide several economic benefits, such as decreased production expenses and increased revenues. Moreover, EIO models can be used to assess the specific structural aspects of Information Systems at the level of IS relationships.

3.2.2. Thermodynamics tools

Two methodologies belong to this category: emergy and exergy analyses. Emergy analysis has been developed as a tool for resource quality evaluation and environmental policy in assessing complex system dynamics. Emergy analysis has a conceptual basis grounded in thermodynamics and systems theories. "*Emergy is defined as the sum of all inputs of available energy directly or indirectly required by a process to provide a given product or flow when the inputs are expressed in the same form (or type) of energy, usually solar energy*". Emergy analysis considers a given system as a network of energy flows and determines the emergy value of each stream and the overall system. Hence, this method assesses the quantity and quality of the energy required to produce a given product or service and provides information concerning energy efficiency. In this regard, such an approach for resource consumption accounting helps assess the eco-efficiency of a given system and compare similar systems.

Emergy analysis allows the computing of indicators at the system level. Five emergy indicators can be proposed to assess the sustainability of a system (Brown & Ulgiati, 1997): percent renewable, non-renewable to renewable ratio, emergy yield ratio, environmental loading ratio, and emergy investment ratio. Percentage renewable energy measures the percentage of the total energy driving a process from renewable sources. Only processes with high values for this indicator are sustainable in the long run. The non-renewable-to-renewable ratio is computed as the ratio between the non-renewable energy contribution and the renewable contribution to a process. The energy yield ratio is calculated as the ratio between the energy of the output of the system and the energy of the inputs to the system that are fed back from outside the system. It measures the ability of a system to exploit its local resources. The environmental loading ratio measures the pressure of the process in the local ecosystem. Such an indicator can be considered a measure of environmental stress caused by production activities. Compared to other alternatives, the energy investment ratio measures whether the system is a good user of the energy invested.

3.2.3. Life cycle assessment

Life-cycle assessment (LCA) (Wahidul & Michele, 2022) is a tool that evaluates the environmental aspects and potential environmental impacts of products throughout their life cycle. Two international ISO standards define this methodology, and they rely heavily on data, making it essential to collect data cautiously. However, impact factors reflect the national average and not the specific factors of individual enterprises, making it challenging to use them as a basis for assumptions about by-products.

3.2.4. Network analysis

Network analysis uses quantitative methods to analyse physical and social interactions among entities belonging to a system. The system is conceptualized as a network composed of nodes and links, where each node represents a given entity, and the relationship between two entities is a link between the corresponding nodes. Various links can be modelled via network analysis, such as material and energy flows, information, financial transactions, and social interactions. In the IS field, four methodologies related to this approach have been used: social network analysis, stakeholder value network approach, ecological network analysis, and food web analysis.

- **Social network analysis** has mainly been adopted to measure the structural features of ISNs. Here, companies belonging to the network are represented as nodes within, and a link between two nodes represents waste flow between the respective companies. This approach has proposed several indicators describing the network structure, such as density and centrality measures. Furthermore, according to a resilience perspective, centrality measures computed at the node level are used to identify the most critical nodes for the ISN in the case of disruptions. The study of social aspects of Industrial Symbiosis examines the interactions between stakeholders in symbiosis networks and their collective efforts and tendencies. Social Network Analysis (SNA) is used as the primary method in this group of documents to evaluate the placement of organizations in IS networks and their connections (Vahidzadeh et al., 2021).

- **The stakeholder value network** (Vahidzadeh et al., 2021) approach models value flows among companies into ISNs. Value flow represents the transfer of utility between the two companies. Here, utility depends on two factors: urgency and importance. Urgency is related to how quickly a user company requires a resource. The importance score is related to the specific company that supplies a resource, ceteris paribus; this score is much higher because the supply of resources depends on a particular source company. According to the utility flows, the relative power can be computed for each company, and the most critical waste for the ISN can be highlighted.
- **Ecological network analysis** (Dong et al., 2022) concerns the integrated assessment of utility resulting from the exchange of waste among companies in each ISN. Such an analysis can reflect the ecological relationships among companies belonging to the ISN. Accordingly, four types of relationships were identified: exploitation, control, competition, and mutualism. According to these ecological relationships, companies belonging to an ISN can be divided into the following three clusters: producers, primary consumers, and secondary consumers.
- **Food web analysis** (Genc et al., 2020) is a methodology based on biomimicry, which is traditionally used to investigate interactions among organisms in an ecosystem. Here, energy flows among organisms are represented by food chains. A food web matrix shows the materials and energy flow in a natural ecosystem and helps assess prey-predator relations between species. In the Industrial Symbiosis field, a food web matrix describes the waste flow between companies belonging to an ISN, where companies are distinguished between predators and prey. Specific indices based on this matrix have been computed, such as the pray-to-predator ratio (i.e., the ratio between the amounts of waste producers and waste users), generalization (i.e., the number of waste producers interacting per waste receiver), and connectance (i.e., the number of waste flows implemented compared to the theoretically possible flows).

3.2.5. Process integration

Process integration methodology (Chew et al., 2014) can be considered part of flow analysis or as a separate methodology that concerns the detection of quantity and heat and mass systems for exchange between companies (the study result). It is divided into two main groups: Heat Process Integration and Mass Process Integration. Heat Process integration focuses on minimizing energy consumption in industrial processes or any process that involves heat energy. The other group is mass-process integration, which minimizes using raw materials or specific components. That raw material can be water, one of the primary raw materials in the process industry (Kahawalage et al., 2023). However, some essential components in producing the final product can also be focused on. These methodologies can be implemented using Pinch technology and Total Site Integration (TSI) (Klemeš, 2013). Pinch Analysis is an industrial application that is the most widely used targeting method. It is an efficient tool for early-stage and retrofit design communication with decision-makers. Total Site Integration is a framework and process that expands upon the Pinch Analysis. It was initially developed for heat recovery and extended to Combined Heat and Power Integration. This approach is based on the understanding that processes seldom operate in isolation and that considering the entire site as an integrated system can optimize resource use and recovery. Pinch Analysis originates from integrating a single production process, whereas Total Site Integration focuses on applications across an entire processing facility encompassing numerous production and support units.

Different locations in cities and industrial areas are commonly known as Total Sites. The heat integration analysis aims to recognize the potential for energy savings (target) by identifying the possible exchange of heat flows and facilitating the design of a heat exchange network. The methodology of extended Pinch Analysis has evolved into various forms, such as Carbon Emission Pinch Analysis. The core principle of setting targets, breaking down problems into smaller subregions, and solving them remains a strong foundation for the methodology. However, Pinch Analysis for Heat and Mass Integration has been established. These led to the founding of Water Pinch, Hydrogen Pinch, Footprint Pinch (CO2 emissions or pollution values equivalent to CO2 emissions, land use), and Exergy Pinch. Solid Waste Integration is still in its early stages of development.

3.3. Quantification - methods to quantify the synergies generated through Industrial Symbiosis initiatives

While the nature and mechanics of the linkages, collaborations, etc., are sometimes well described in academic and grey literature, this part of the report focuses on a specific yet essential challenge in IS research: quantification methods used to quantify the synergies generated through IS initiatives. Neves et al. (2020) have an excellent summary of this challenge.

Some minimal, early efforts on quantification of IS synergies focused only on water and/or energy and/or some materials (by-products) of industrial processes of fossil origin (Ehrenfeld & Gertler, 1997) and less on non-fossil origin as the sustainability and Circular Economy (CE) terms started appearing more prominently in the early 2000s.

Kastner et al. (2015), to assess quantitative tools of IS cases, concluded that what should be established is a basis for comparison between methods to develop a standardization framework for the effectiveness of Industrial Symbiosis. They indicated that depending on the industrial park (IP or EIP, for example, or nature of business) and co-existing industries, there is still not a systematic way to classify IS based on specific quantification criteria such as waste, energy (heat, power), water, carbon footprint. At the same time, few mentions of the water footprint are made.

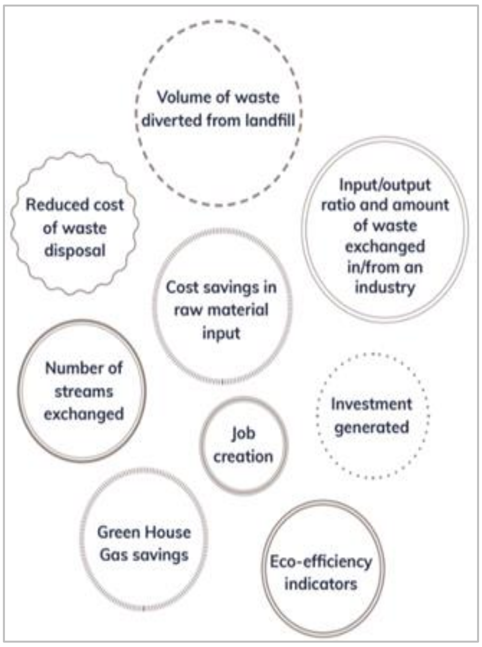
According to the same researchers (Kastner et al., 2015), the number of EIPs where Industrial Symbiosis embedded as a concept was still low in number (approximately 100-150), and in those, any quantification models have had either specific goal, i.e., focus on a particular waste which generated or energy consumption minimization and how to optimize or how to design a more resilient and sustainable system. Other yet limited areas of interest in that direction are the utilities (water/steam use) or, lately, the greenhouse gases (GHGs) emitted to the environment with still a primary focus on carbon dioxide (CO2) emissions. The latest indicates that any quantification attempt is made based on physical facts such as how much waste, energy, etc., is exchanged rather than a collective effort to include all aspects of synergies between all elements of interest affecting the synergies during realization of EIPs and the Industrial Symbiosis. One possible reason for this is the non-technical barriers, such as not understanding from all key players what to measure, how, why, and how to combine all critical factors to describe and measure (quantify) accurately Industrial Symbiosis synergies.

Martin (2015) indicated that few quantification examples exist in the literature related to IS or their associated economic and environmental benefits. It depends on the nature of the industries and, for example, for the biofuels industry, it was noted that their method is based on exchanges to be shared with companies taking part in the Industrial Symbiosis network, something which might, though have some implications for tax incentives, marketing, expansion and environmental awareness.

Recently, Fraccasca and Giannoccaro (2020) reviewed a wide range of indicators, mainly numerical, of a variety in terms of definition, scope, application and purpose to quantify (measure) IS. Based on a literature review, they suggested an indicator-based taxonomy to answer the following questions: 1) what, 2) where, and 3) how to measure those quantifications.

Recognizing these challenges, one of the most famous Industrial Symbiosis projects, which is operating successfully, the Kalundborg Symbiosis project (Kalundborg Symbiosis, N/A), based on their own hands-on experience, suggested what indices advisable to measure aiming to be the paradigm example of symbiotic exchanges working in practice, as specific Industrial Symbiosis park which aims to be the world leading and with the highest Symbiosis Readiness Level (SRL), a term tending to replace the Technology Readiness Level (TRL) used in process industry. Based on key players of the Kalundborg, the key indicators to track are associated with costs, utilities, job creation, eco-efficiency indicators, amounts and ration of in or out of wastes between industries and diverted from landfills as shown in Figure 6.

Figure 6. Essential suggestions on indicators to track, as suggested by the Kalundborg Symbiosis know-how experts.



Source: Adapted from Transition Aps, 2021

To summarize, a wide variety of methods have been developed today, and they, broadly speaking, tend to focus on a) environmental, b) economic, or c) social levels in isolation.

a. Environmental indicators such as Life Cycle Assessment (LCA) are commonly used to quantify IS compared to business-as-usual approaches. Energy analysis was also widely used, allowing practitioners to establish various energy indicator sets. Material Flow Analysis

(MFA) was commonly employed to quantify physical material flows. It was deployed and described across numerous pieces of literature, while exergy measurements were deployed to quantify functional energy flows. Greenhouse Gas Emissions (GHG) and carbon equivalent quantifications such as carbon foot printing have also been deployed in IS cases.

b. Economic impacts of IS systems tend to be reported as cost savings from raw materials, disposal of waste, and revenue income due to the sale of by-products/waste, lately quantified via Techno-Economic Analysis (TEA) and
c. Arguably, social indicators have been the most challenging to quantify, and in general, these tend to focus on increased employment, new business opportunities, and reduced pollution burdens in the locality.

3.3.1. Quantification methodology

The quantification methodology followed to track publicly available information on the quantification of IS is like a semi-systematic literature review. It is designed to quantify IS and then narrow it to the abovementioned locations. Case studies of IS examples are from four European and four international locations. This type of literature review seems suitable for multidisciplinary researchers (Snyder, 2019) and stakeholders within diverse disciplines (for example, agribusiness, process engineering, environmental scientists, environmental economics, business management, know-how sharing from stakeholders, etc.). The adopted literature review strategy focused on how research in the field of any quantification of synergies of IS projects, and specifically some of the most known in the EU and internationally, have possibly recorded and progressed and/or developed over time.

The steps first, each case study location was searched in the most used academic Scopus Database (Elsevier) (Table 3) using the terms *LOCATION OF SYMBIOSIS + "INDUSTRIAL SYMBIOSIS" in article title, abstract and keyword searches.

Table 3. Scopus Search, number of papers returned, note papers marked with an * were deemed to be not related to the search parameters and – not open access

CASE STUDY	SCOPUS DATABASE NUMBER OF PAPERS	QUANTIFICATION OF SYNERGIES: YES/NO	REFERENCE
Port of Rotterdam, The Netherlands	8	No	Steenmans, 2021
		No	Baas and Boons, 2007
		-	Suciu et al., 2019*
		-	Nair et al., 2016*
		No	Lenhart et al., 2015
		No	Baas, 2011
		No	Baas, 2008
		No	Baas and Huisingh, 2008
	2	No	Ferrão et al., 2015

Relvão / Chamusca Industrial Symbiosis, Portugal		No	Costa and Ferrão, 2010
Kwinana, Australia	13	No	Oughton et al., 2022
		No	Oughton et al., 2021
		-	Faria et al., 2021*
		No	Corder et al., 2014
		No	King et al., 2020
		Partially	Rosano and Schianetz, 2014
		No	Zhu and Ruth, 2014
		No	Mohammed et al., 2013*
		-	Mathews and Tan, 2011*
		No	Kurup and Stehlik, 2009
		Yes, referencing Van Beers et al., 2007 and Van Berkel et al., 2006	Harris, 2007
		Yes	Van Beers et al., 2007
		Yes	Van Berkel et al., 2006
Tianjin, China	4	No	Wang et al., 2015
		Yes	Yu et al., 2014
		No	Qi and Wang, 2011
		Yes	Shi et al., 2010
Kalundborng, Denmark	41	No	Ghisellini, et al.,2023
		Partially	Giannoccaro et al., 2023
		No	Zhe et al., 2021
		No	Steenmans, 2021
		No	Turken and Geda, 2020
		No	Tolstykh, Shmeleva and Gamidullaeva,2020
		No	Zhang and Chai, 2019
		No	Momirski, 2019
		-	Jacobsen, 2006

		-	Pedersen, 2017
		No	Maillé and Frayret, 2016
		No	Valentine, 2016
		-	Nair et al., 2016
		-	Caiati and Declich, 2015
		No	Branson, 2016
		-	Stock et al., 2015
		No	Chopra and Khanna, 2014
		No	Zhu and Ruth, 2014
		No	Valero et al., 2021
		No	Liao and Mha, 2013
		No	Wells and Zapata, 2012
		No	Chopra and Khanna, 2014
		Partially	Ashton and Bain,2012
		-	Yang and Tong, 2012
		-	Huang, 2011
		Partially	Domenech and Davies, 2011
		No	Sopha et al., 2009
		-	Wang et al., 2010
		-	Jacobsen, 2009
		No	Hewes and Lyons, 2008
		No	Song and Shi, 2008
		No	Yang and Feng, 2007
		No	Chertow, 2007
		No	Salmi and Toppinen, 2007
		No	Wolf and Petersson, 2007
		No	Haskins, 2006
		Partially	Jacobsen, 2006

		No	Matani, 2006
		No	Krrishnamohan, 2001
		No	Ehrenfeld and Gertler, 1997
Uimaharju Industrial Symbiosis, Finland	8	No	Ramin et al., 2024
		No	Korhonen and Snäkin, 2005
		No	Yeşi̇lkaya et al., 2020
		No	Sokka et al., 2011
		No	Herczeg et al., 2018
		No	Lehtoranta et al., 2011
		No	Bellantuono et al., 2017
		No	Uusikartano et al., 2021
Kawasaki, Japan	8	No	Dong et al., 2022
		-	Takeuchi and Motoki, 2017
		Partially	Ohnishi et al., 2017
		Partially	Dong et al., 2013
		Partially	Dong et al., 2014
		Partially	Liao and Mha, 2013
		Partially (--_	Hashimoto et al., 2010
		Partially	Van Berkel et al., 2009
Ulsan, South Korea	6	Partially (waste heat)	Kim, H.-W. et al., 2018
		Partially (CO_2)	Kim et al., 2018
		Partially	Kim et al., 2018
		No	Mat et al., 2015
		Partially	Park and Behera, 2014
		No	Park and Behera, 2015
		No	Park et al., 2008

Source: authors

In most searches, only a few works were returned, indicating the lack of or difficulty in presenting actual numerical data of studies in quantifying synergies. In Tianjin's case, more results were returned, and the search was refined to articles containing Tianjin in the article title.

4. Selection: how to select the most promising opportunities?

4.1. Criteria

Industrial Symbiosis (IS) is an essential concept for achieving a carbon-neutral industry, whereby a network of companies collaborates to share resources to reduce adverse environmental impacts. Nevertheless, corporations need to consider a multitude of factors to adopt such a practice successfully, and these can be summarized as follows:

- Resource and technological compatibility
- Geographical considerations
- Environmental impact
- Economic viability
- Regulatory Compliance

In this subsection, these criteria will be delineated.

4.1.1. Resource and Technological Compatibility

The collaboration of partners for IS entails analysing the compatibility of resources (mainly material) and technologies, as this ensures efficient material exchange and seamless integration of operations with minimal modifications and adjustments. Indeed, these aspects are the first to be considered by companies to adopt such an approach (Yeo et al., 2019). This, however, has its challenges, primarily that relevant information is complex to come by as companies are reluctant to share it (Chen et al., 2022). As a result, new tools are being developed to tackle this issue. One such example is a new tool that compiles database data to accurately predict material flow and waste. Another example is a multi-criteria tool that helps companies automatically select the best partnerships depending on the criteria specified by the user (Chen et al., 2022; Ghisellini et al., 2016; Yeo et al., 2019).

With technology advancing at a rapid pace, the lack of compatibility gives rise to companies being innovative and developing new technologies, allowing for further material processing and giving potential for further alliances between companies. This is especially true for large enterprises as they have sufficient resources to explore new techniques (Atanasovska et al., 2022; Patricio et al., 2018; Ramin et al., 2024). One such example relates to the construction industry, as technological advancements have allowed new material processing techniques to be explored, allowing waste construction material to be reused. Indeed, construction waste, primarily limestone, is mixed with furnace slag and fly ash to form alkali-activated cement (Xie et al., 2023). Another example is the technological advancements in the energy sector, where organic waste is mixed with chlorine-depleted pyrolyzate, which increases the combustibility of the material and is used for energy production. This has high potential in developing countries as their waste composition reaches 60% of organic matter (Kyriakopoulos et al., 2019). These examples highlight that the lack of compatibility should not be used as an excuse not to adopt IS practices, as companies should always strive for new and alternative solutions to address the issues.

4.1.2. Geographical Considerations

Regional attributes are also crucial for companies to consider while they collaborate, and these characteristics should be analysed and characterized in detail early in the process (Yeo et al., 2019).

The proximity of the companies plays an essential role in the adoption of IS as corporations operating in the same vicinity can transport material easily, reducing logistical costs and transportation-related emissions. Indeed, this is the main reason industrial parks are set up in a single area (Faria et al., 2022). Taking the Kalundborg eco-industrial park in Denmark as an example, 13 public and private companies have been set up within a 4 km radius, facilitating material exchange between all entities (Kalundborg Symbiosis, 2024).

Other aspects must also be considered, which vary according to the region. For instance, the method of disposing of and processing waste material varies depending on the area. Another consideration is that for less developed countries, information regarding material flow is less available than in other countries, making it more challenging to adopt IS practices (Zhang et al., 2021, 2023). To this end, according to the research by (Neves et al., 2020), the most accessible country to share resources is China since the industrialization boom pushed for numerous technological and financial incentives to be offered, with the latter being discussed in detail further in the section. The same study, which provided a comprehensive review of IS, highlighted that 34% of the studies addressed IS case studies from China when the research was conducted. To give perspective, studies relating to Europe amounted to 39% (Neves et al., 2020).

4.1.3. Environmental Impact

The leading scope for developing the IS concept is to reduce environmental impacts, such as global warming, by mitigating waste and using resources efficiently to alleviate emissions and align with broader sustainability goals (Nyakudya et al., 2022). This has proved successful, with several documented examples, such as the one from China. Indeed, by realizing that China's industrial sector contributed to copious amounts of greenhouse emissions, with 2019 figures showing that China contributed to 43% of the global emissions from this sector, resource sharing was heavily promoted (Sandalow et al., 2022). In fact, through energy-based IS synergies, including the reuse of excess heat, the energy consumption from the iron and steel sector is on track to reduce by 6% from 2017 levels, which directly results in emission reductions (Fraccascia et al., 2021). Despite this, multiple studies claim that the main objective for companies to consider IS relates to financial reasons, being government incentives, less money spent on resources, etc., with environmental savings being considered as a by-product (Barona et al., 2023; Walls & Paquin, 2015; Yang et al., 2022). This highlights that further work is required to shift company culture towards prioritizing environmental sustainability.

4.1.4. Economic Viability

The biggest motivation for companies to adopt resource-sharing practices revolves around economic return, transitioning from expensive manufacturing to income-generating production (Ramin et al., 2024). Indeed, there are many financial benefits as different production aspects become cheaper, including reducing material and energy costs. Industrial Symbiosis also gives corporations new revenue streams as by-products, which are usually considered a burden due to expenses related to disposal, can be utilized as input by other companies (Kyriakopoulos et al., 2019). The concept of material exchange can also help increase productivity, with one example being in Singapore, as recycled construction material from different companies helped improve productivity in this sector by 50%, as the material could be sourced faster (Kerdlap et al., 2019). Over the years, the environmental impacts of bad sustainable practices have become evident. Thus, consumers have become increasingly aware of the products they purchase, primarily searching for eco-friendly products. Consequently, resource sharing can be part of the company's green marketing campaign, which can help boost sales (Patricio et al., 2018).

Implementing IS practices is not without challenges, with technological barriers being one of the main ones. Consequently, governments offer different incentives to promote this concept (Xie et al., 2023; Yang et al., 2022). In fact, according to Neves et al. (2020), the main reason why China has become the country with the most IS examples is that numerous incentives are being offered, such as tax incentives and grants to promote research. This is especially important for small and medium enterprises, as they have limited resources compared to large-scale companies (Patricio et al., 2018). Though incentives are available, research shows that further work is required to offer more attractive financial packages, with a study by Barona et al. (2023) highlighting various shortcomings of current incentives. Most notably, it was underscored that, in general, governmental enticements tend to reward linear model practices as when adopting a circular model, the tax must be paid on up-cycled products, meaning that for the same product, the tax must be paid twice.

Furthermore, additional tax incentives should be offered to reduce labour costs, as it is cheaper to use virgin materials than to reuse and recycle material. Another issue that must be tackled is that in developing countries, minimal incentives are currently offered to promote IS due to the lack of information available. Thus, efforts should also focus on developing new inducements in these regions (Zhang et al., 2021).

4.1.5. Regulatory Compliance

As mentioned, implementing IS practices has challenges, including cultural barriers, such as hesitant company culture and lack of system thinking. Consequently, different regulations, standards, and policies have been set up to encourage the adoption of such practices (Kristensen & Mosgaard, 2020). One such example is the European Green Deal policy, which strives for a carbon-neutral continent, stipulating that by the year 2050, Europe must have net-zero greenhouse emissions (European Commission, 2020b). Consequently, different eco-friendly techniques are being explored to achieve this goal.

In the last decade, a global effort has been made to introduce new rules and standards to accelerate the adoption of IS practices. This was seconded in the review study by Walls et al. (2015), which stressed that such directives play an essential role in implementing resource-sharing techniques, as these offer guidelines that companies should follow. It was also added that before 2015, literature regarding standards and policies was minimal, suggesting that there have been increased efforts to adopt such procedures in the last ten years.

Despite these efforts, further work is still required to facilitate companies' implementation of these practices (Kyriakopoulos et al., 2019). Indeed, one of the main concerns multiple corporations face is that specific processes used to process the recycled material are not standardized, which can be addressed through new standards and regulations. For instance, in the Netherlands, companies are reluctant to develop or make use of construction materials made from recycled waste, such as cement made up of reused limestone, as insurance companies are hesitant to offer coverage for buildings making use of such material due to the lack of standards assessing the quality of the matter (Chen et al., 2022). Another example is the petroleum industry since no regulations stipulate waste originating from fuel production, making it difficult for companies to set up resource exchange practices (Fraccascia et al., 2021). The lack of standards for component disassembly has also been mentioned to cause reluctance in implementing IS as this makes it difficult to dismantle objects efficiently, making the reuse of specific material not feasible (Cappelletti et al., 2022).

Attention should also be given to promoting consumer social responsibility, which drives companies to implement sustainable techniques. Indeed, with consumer campaigns, policies and regulations should be drafted to help achieve this goal. For instance, introducing the Energy Labelling regulation, which stipulates that all appliances within the European Union should be labelled according to their energy consumption, helps consumers choose the most energy-efficient product (European Commission, 2024). A similar concept could be adopted, including information regarding the IS properties of the product in question. This is especially important in developing countries as the lack of information makes it difficult for consumers to know such details (Ghisellini et al., 2016; Merli et al., 2018).

What is important to note is that during the development of these regulations, a one-size-fits-all approach should not be considered but instead tailored for the requirements of the region or country (Xavier et al., 2023; Zhang et al., 2023). For instance, a low-carbon transition plan in the United Kingdom has been enacted to drive for net zero emissions by 2050, driving high-polluting industries to be phased out. However, care had to be taken to consider areas such as Redcar, where steel production, which amounts to 14% of the country's manufacturing emissions, is a significant part of the region's economy. Indeed, if such an industry were to be eliminated, many of the enterprises in this region would not survive. Thus, these regulations had to be eased in these specific regions (Xie et al., 2023).

4.2. Evaluation of techno-feasibility/viability of Industrial Symbiosis feasibility studies

Many industries can participate in IS, but production is the area with the most significant influence, where materials are converted into new products. These industries produce the largest waste but have the highest capacity to absorb waste and by-products and incorporate them as raw materials in production processes. The most common activities in the field of IS in the world are chemical industries and cement, paper, and metals industries. Industries characterized by high energy consumption have the highest potential for introducing measures to reduce consumption. Activities related to waste and water management and recycling can also occupy an important place in industrial symmetry, not only in creating a connection between industries but also as an active link in turning waste into new products. The agricultural sector - both plant crops and animal crops - also occupies an essential place in the potential for IS. The greater the variety of industries in each region, the greater the potential for creating synergies.

Similarly, IS among SMEs occurs at a regional rather than local level to address lack of financing, difficulties in implementing new technologies, limited management capabilities, and regulatory pressures. Thus, in most cases, the IS between SMEs aims at reducing the amounts of raw materials they purchase and their dependence on these materials. In Europe, IS has a significant advantage in industrial parks or industrial clusters that provide an opportunity to implement collaborations and produce economic and environmental benefits, but IS can also break out of the boundaries of industrial parks and exist between geographically distant factories and companies (Ayalon et al., 2020; Azevedo et al., 2021; Charles et al., 2018; Neves et al., 2020; Patricio et al., 2018; Taddeo et al., 2017, Tabellini, 2023).

ISin Europe is aligned with the guidelines of the Waste Framework Directive (European Commission, 2024) and the Circular Economy Action Plan (European Commission, 2020a), defining the criteria for ending the definition of material as "waste" while ensuring a high level of environmental protection and economic profit. Waste materials cease to be defined as waste after restoration and meeting some end-of-waste (EoW) criteria. For a material to be able to turn from waste to a resource and meet the criteria for EoW, it must meet four requirements: (i) has a use for specific purposes; (ii) is in demand; (iii) meets the technical requirements for use in a manner that complies with the provisions of any standard, legal requirement or benchmark of the product; (iv) its use will not cause an excess negative effect on health or the environment. The price of the material or product must be competitive (including costs involved in handling and transportation- the bottleneck); for this purpose, the willingness of the regulator to subsidize the material or product is sometimes required so that the price is economical. In addition, regulation is needed for risk management, especially when it comes to hazardous waste.

4.2.1. Frameworks related to feasibility/viability of Industrial Symbiosis

From the experience gathered from many project and research investigations, the techno-economic assessment of IS can be performed based on different scenarios, elaborated from (Di Pasquale et al., 2024; Fraccascia et al., 2021):

1.By industrial sectors

  a. high-energy demanding industries such as chemical, polymer/plastic, cement, metallurgic (iron, steel, aluminium), pulp and paper, power;
  b. SME manufacturing industry;
  c. agri-food industry.

2.By level of implementation (boundaries within IS relationships develop):

  a. micro (individual companies engage in symbiotic relationships),
  b. mezzo (interactions between companies with geographical proximity, e.g., eco-industrial parks),
  c. macro (interactions occurring at regional or national scale).

3.By methods of sharing resources: exchange of by-products or waste; sharing infrastructure or process services (water, energy, heat supply systems, wastewater treatment plants); sharing ancillary services (transport, security, cleaning, catering).

4.By methods of formation: spontaneous/emerging from below (Bottom-up) or designed/governed by a central authority (Top-down); a single company with multiple production processes within it or two or more companies engaged in a synergy, exchanging at least one type of waste or by-product.

A practical concern for the techno-economic evaluation of IS outcomes is the hierarchy of scales involved in the synergistic activities, ranging from single-unit processes to multi-unit-process plants to the interconnected network of plants and utilities systems and subsystems, creating a high degree of complexity. Another challenging and complex issue is the overall evaluation of energy efficiency. The most successful and prominent cases of industrial symbiosis are within eco-industrial parks comprising energy-intensive industries. This is mainly because of the magnitude of industrial partners and partly due to transport cost scales, capacity for exchanging by-products and sharing infrastructure and utilities, as well as energy efficiency and waste treatment (Di Pasquale et al., 2024; Fahmy et al., 2021; Fraccascia et al., 2021; Lawal et al., 2021).

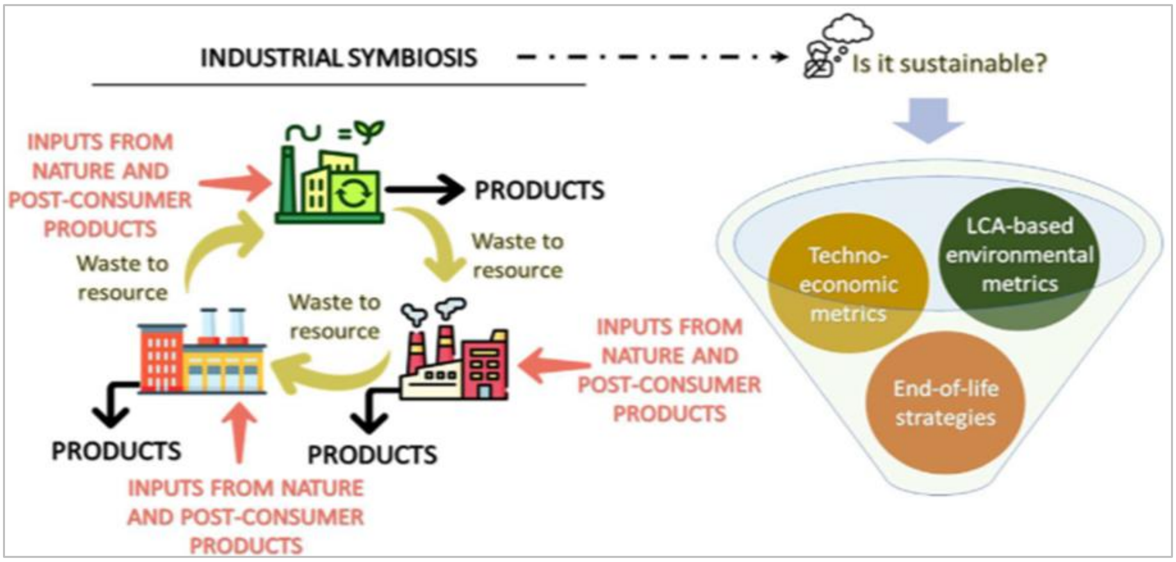
A well-known example of bottom-up synergism is the Kalundborg industrial park in Denmark, which is mainly driven by rational business interests among enterprises. Typical examples of top-down strategic planning are the Kawasaki Ecological Park serving the Keihin Industrial Belt in Japan, the Kokkola Industrial Park (KIP) in Finland, an ecosystem of the inorganic chemical industry, and the Ulsan Eco-Industrial Park in Korea (Di Pasquale et al., 2024; Shah et al., 2020) at Kwinana Industrial Area (KIA), Perth, Australia, synergies in the mineral industry developed through a facilitated deployment approach that is a combination of self-organized and planned approaches (Van Beers et al., 2007). The Humber Industrial Cluster in Northeast England is a central hub of industrial activity and trade, initially centred on top-down infrastructure projects with significant capital investment but following a bottom-up approach to engaging industries in the area (Bailey & Gadd, 2016).

Simplified models combining heuristic methods, thermodynamic principles, and mass and energy balances at the plant level and the entire complex may facilitate the input-output metrics. Numerous techniques, analyses and indicators are used to evaluate the IS concerning sustainability, development, performance, and relations between companies, followed by economic impacts. Although several have a comprehensive application, others have been explicitly created for IS. Some examples are Input-Output Analysis (IOA), Ecological Network Analysis (ENA), Life Cycle Assessment (LCA), Environmental Impact Assessment (EIA), Carbon Footprint Analysis (CFA), Material Flow Analysis (MFA), Ecological Footprint Analysis (EFA), exergy/emergy analysis, Econometric Analysis (EMA), Cost-Benefit Analysis (CBA), Social Network Analysis (SNA). IOA tools include FaST (Facility Synergy Tool), DIET (Designing Industrial Ecosystem Tool), and REaLiTy (Regulatory, Economic, and Logistics Tool), all commissioned by the US-EPA (Fahmy et al., 2021; Fraccascia et al., 2021; Neves et al., 2019a; Shi, 2019; Valenzuela-Venegas et al., 2018).

A literature review concerning the life cycle environmental and economic assessment of IS networks identified eight different LCA and LCC methodologies. Each methodology was analysed regarding the foreground and background of the IS networking systems, waste-to-resource exchanges between entities, and multi-level analysis (Kerdlap et al., 2020). Many IS implementation-support tools have been developed under the H2020 Research and Innovation funding scheme and the SPIRE (Sustainable Process Industry through Resource and Energy Efficiency) partnership. Projects such as MAESTRI, FISSAC, EPOS, SHAREBOX, and SCALER contributed to the dissemination of IS supporting tools such as methodologies, platforms, frameworks, databases, repositories, and information and communication tools (Branca et al., 2021a; Branca et al., 2021b; Branca et al., 2022; Dias et al., 2020). Below are some relatively recent case studies.

Briassoulis et al. (2023) elaborated an exciting framework for assessing life-cycle sustainability for producing biopolymers for diverse use in agriculture, packaging, pharmaceuticals, and post-consumer recirculation through IS. This could be achieved through the LCC approach, which jointly assesses techno-economic, environmental, and social aspects. Indicators assessing the sustainability of industrial activities should denote the complexity of symbiotic systems. A series of indicators for the metrics of the different stages of the framework of the assessment is described (Please consult this review for the definition of the other indicators), including (i) Environmental sustainability assessment, (ii) Social life cycle assessment (S-LCA); (iii) Techno-economic assessment (TEA); (iv) End of life (EoL) recirculation of postconsumer materials assessment. A schematic representation of the framework of the study is summarized in Figure 7.

Figure 7. Sustainability assessment of industrial symbiotic systems



Source: Briassoulis et al., 2023

Kusch-Brandt (2020) reviewed the synergies to achieve business advantages and resource efficiency through IS of several well-known industrial parks (Kalundborg, Denmark; Styria, Austria; Guayama, Puerto Rico; Campbell, Hawaii; Shenzhen Huaqiang and Tianjin, China; Ulsan, Korea; Kwinana, Australia; Rotterdam, the Netherlands). She concluded that the dynamics of IS and its contribution to a more efficient CE must be understood beyond the characterization of residual material flows and identification of potential valorisation pathways.

A dedicated framework named Technical Viability Analysis of Industrial Synergies (TVAIS) is proposed to evaluate the synergic drive for IS among companies. The framework provides guidelines and defines a technical viability analysis to support the implementation of potential synergies. The following synergies were identified: (a) synergy compliance, defining whether the synergy is suitable from the technical standpoint for further consideration for implementation; (b) synergy characterization, considering the main procedures involved, the definition of the necessary operations and the required technologies; (c) synergy feasibility, assessment of the overall technical feasibility of the synergy for large-scale implementation and qualification of the complexity and potential for implementation. TVAIS was validated for the case of slag, fly ash and sludge from the aluminium and steel industry, coal power plants and refineries as waste suppliers and cement, ceramics, glass and copper industries as receivers (Dias et al., 2020).

An analytical framework for assessing a wide range of Industrial Symbiosis outcomes that will aid research design has been developed based on data gathered from 56 IS research articles. The framework provides a base for including generic and specific effects and outcomes (economic, environmental, and social) and a diverse set of clearly defined actors. The results show that market-based outcomes are the dominant form of monetary value reported or evaluated and that nonmarket evaluations are absent. Environmental outcomes mainly include decreased CO2 emissions, chemical pollution and water use. Social outcomes include private income and work and network effects for the companies involved in the IS (Wadström et al., 2021).

A generic and systematic decision support tool based on the wood industry aimed at identifying and evaluating options for facilitated symbiotic development of industrial clusters within the Kawerau industrial site in New Zealand was elaborated. The approach was developed with insight and feedback from industry, community and government stakeholders focused on early-stage engagement of diverse stakeholders. The methodology integrated cluster design by superstructure optimization. It is based on a combination of heuristics methods and thermodynamics principles to provide a range of metrics for investment profitability, macroeconomics and environmental impact to suit diverse stakeholder needs (Fahmy et al., 2021).

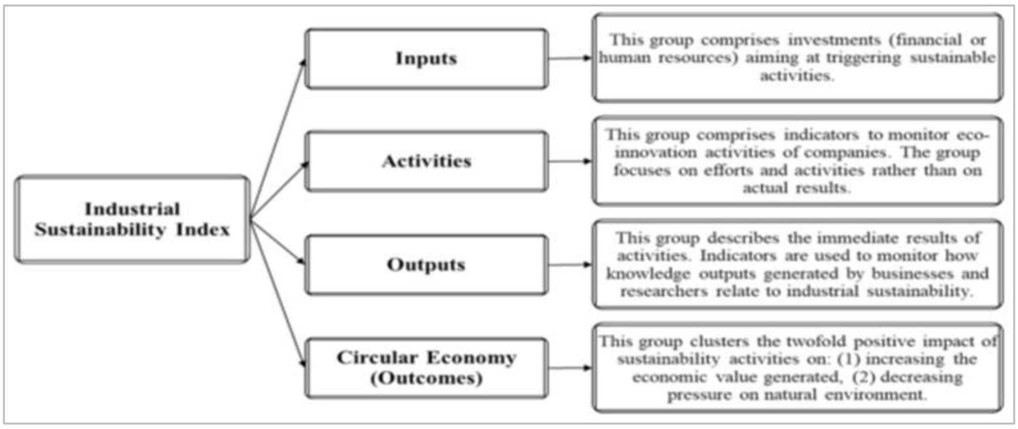
To conclude this section, a brief discussion of IS vulnerability is presented. IS relationships can be vulnerable to disruptive events that reduce the willingness of companies to cooperate in Industrial Symbiosis synergies. Disruptions affecting a given IS relationship may be responsible for creating a technical and economic impact on the overall supply chain performance, incorporating waste or by-products through remanufacturing IS (Di Pasquale et al., 2024; Fussone et al., 2024). An enterprise input-output model aimed at mapping the physical and monetary flows resulting from IS synergies among companies was applied to assess the impact and causes of disruptive events on physical and financial flows created by the IS relationship. The IS between companies creates specific supply chains triggered by resource use (Fraccascia, 2019). A resilience indicator of IS eco-parks has been developed and verified for two well-established cases, Kalundborg in Denmark and Ulsan in South Korea. The methodology is based on the capacity of each flow to change its magnitude when a participant suddenly stops sharing flows within the network. Although the indicator developed measures the resilience of material flow, it can also be adapted or extended for heat/energy transfer within the network (Valenzuela-Venegas et al., 2018). Models predicting disruption of the supply chain and disturbance of IS on either material or energy flow could facilitate the design of appropriate countermeasures of partners and policymaker’s policy actions and help towards the development of IS relationships resilient to perturbations (Fraccascia et al., 2021).

4.2.2. Indexing benefits and outcomes of Industrial Symbiosis

The main benefits associated with IS are economic/technological (production & commercial cost savings, waste disposal cost savings, access to improved technologies), environmental (higher energy efficiency/GHG emission reduction, efficient reduction, reuse, recycling and restoration for the byproducts/waste management-4R approach, water reuse/saving, virgin raw materials saved, hazardous waste elimination) and social (job creation and preservation, skills improvement) (Branca et al., 2021b; Di Pasquale et al., 2024; Dias et al., 2020; Fraccascia et al., 2021; Neves et al., 2019a, 2020; Neves et al., 2019b). Several numeric indexes have been formulated to help evaluate the techno-economic, environmental, and social impact of IS and industrial sustainability. Some examples are detailed below.

An Industrial Sustainability Index (ISI) and four sub-indices (inputs, firm activities, outputs and resource efficiency outcomes) have been developed to evaluate industrial performance and outcomes concerning IS, sustainability and Circular Economy. The methodology for building the ISI is based on the OECD standard guidelines and methods for sustainable development evaluation, comprising normalization (cross-unit comparisons without affecting the original data content), principal component analysis (correlation among the selected indicators to obtain a shorter set of variables), weighting and aggregation (rank each statistical unit according to their scores). The disparity index procedure was applied to evaluate the distance of each statistical observation from an efficient solution. A scheme of the ISI framework is presented in Figure 8. The approach was tested for data encompassing the three dimensions of sustainability, environmental, economic and social, from 36 OECD countries. Overall, 28 out of the 36 countries tested display undesired levels of industrial sustainability, suggesting that solid interventions for policymakers and governments are needed to support the accomplishment of Circular Economy principles, both at the national and international standards level (Arbolino et al., 2022).

Figure 8. Scheme of the ISI framework and boundaries of the four sub-indices



Source: Arbolino et al., 2022

Shah et al. (2020) defined an industrial eco-efficiency index correlating industrial waste consumption and energy with gross industrial production output as a function of time, emphasizing the trade-offs between environmental and economic aspects of the IS development between the period analysed and giving equal emphasis to both aspects. The eco-efficiency change analysis was performed at the industrial park and regional levels for the Ulsan area in South Korea, involving 11 industrial parks/complexes. The output evaluated for the period 2000-2015 indicates a substantial eco-efficiency improvement at the regional level, driven by a significant reduction in waste (35%) and energy intensities (21%) attributable to technological improvements due to urban-Industrial Symbiosis).

A simplified version of ISI relates in a simple arithmetic equation on an annual basis the resource value addition (economic value of materials and energy: outputs-inputs) with the total number of employees and the total CO2 emitted during production and is widely used. At the same time as other indexes for quantification of the efficiency of IS, the ISI addresses all three sustainability IS goals (social, economic and environmental). It can also compare different types of industries, such as small, medium or large scale, and for any product (Briassoulis et al., 2023; Latif et al., 2017; Pandey and Prakash, 2019).

The economic benefits, both in the form of raw material & waste disposal costs reduction and potential revenues, are a crucial driver for IS activities and a decisive factor of its success and are prone to effective quantification. The environmental benefits, when encouraged by local and national incentives and policies, which could also promote the implementation of resource exchanges, are more complex to evaluate and quantify, especially regarding global climate change. The social dimension is the most difficult to quantify and the least analysed. The associated benefits are expected from the stimulation of new jobs and the creation of new companies, as well as the development of new relationships between firms (Azevedo et al., 2021; Branca et al., 2021a; Branca et al., 2022; Di Pasquale et al., 2024; Fraccascia, 2019). The success or failure of a synergistic relationship depends on multiple factors and a combination of variables that generates a positive or negative influence on part or all the symbiotic interaction. Good training and efficient networking among participants can be critical to the long-term success of IS.

IS at confined geographical interaction or regional activities encourages employment and job development (Pandey & Prakash, 2019; Taddeo et al., 2017). A comparative study between two industrializing countries depicted the positive effect of IS on employment and job retention. The impact was both on the quantity (number of jobs created) and quality (gender, informality, working time and wages) of the employees. However, the quality of the jobs created is not guaranteed and requires skills development (De Gobbi, 2022).

The role of technology in sustainability improvement in IS is critical when the technologies used by the industries are efficient and sustainable (Pandey and Prakash, 2019). Improvement in technology is crucial for the success of Industrial Symbiosis. Autonomous technologies, new robotics, smart sensors, artificial intelligence, and machine-to-machine communication are expected to optimize processes and increase symbiotic network chains' productivity. They can be applied to lower the environmental footprint of production processes, which in turn will reduce ecological emissions (Branca et al., 2022).

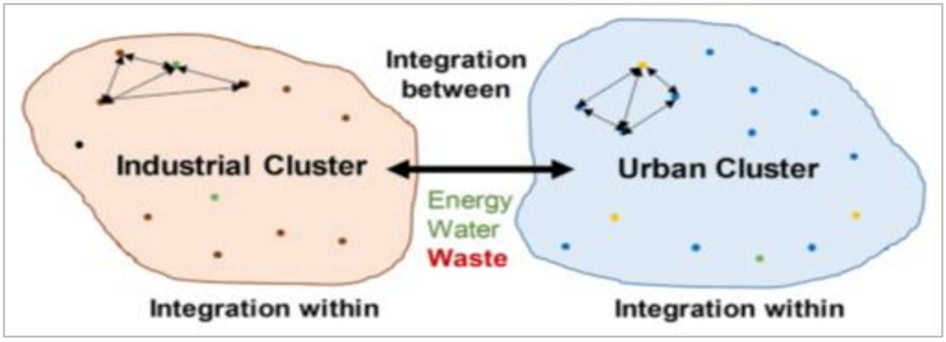
4.2.3. Environmental issues related to the feasibility of Industrial Symbiosis

One of the most critical points for decision-making frameworks, stakeholders, and legislation is Industrial Symbiosis's techno-economic/technical feasibility in achieving competitive and sustainable production within the development of Circular Economy processes. Whereas the feasibility criteria and viability examples seem clear regarding material/resources and by-product exchange and their environmental impact (EoW criteria), they appear more complex regarding energy generation and exchange, besides waste-to-energy conversion. Indeed, energy exchange among different IS partners is more difficult to implement and often consists of sharing common energy resources rather than exchanging them. A more controversial issue is how IS processes contribute to Green House Gas (GHG) emission control and climate change in the long run, which is part of the intrinsic sustainability of Industrial Symbiosis (Briassoulis et al., 2023; Cao et al., 2020; Di Pasquale et al., 2024; Fraccascia et al., 2021; Gast et al., 2022; Mendez-Alva et al., 2021). This seems especially critical for manufacturing businesses, SMEs, and the agro-industrial sector, which generally are associated with IS on a regional scale.

The impact of IS on efficient energy utilization, and GHG reduction has been widely documented over the years, especially in the case of industries characterized by high energy consumption, such as chemical, plastic, cement, metal and paper, which have the highest potential for introducing measures to reduce raw fuel consumption. Some examples. Quantitative analysis of the industrial activities in the eco-town of Kawasaki, Japan, using MFA, carbon footprint and emergy methods, depicted that material exchanges throughout urban and Industrial Symbiosis in steel, cement, chemical, and paper companies along with recycling businesses, has a significant influence on both, reduction of waste and by-products diverted from incineration or landfill and a high impact on carbon footprint and GHG emission reduction (Berkel et al., 2009; Hashimoto et al., 2010; Ohnishi et al., 2017). Similar results were reported for the Songmudao chemical industrial park in Dalian, China, applying an LCA to evaluate each material substitution for primary energy and different environmental impact categories (primary energy, GHG emission, acidification and eutrophication potential) (Zhang et al., 2017).

Environmental savings is an essential family of IS assessment metrics, often assessed through classical energy and material saving analysis during manufacturing processes and diversion from landfilling or incineration. A more theoretical understanding of environmental savings can be achieved using energy-related metrics such as exergy (energy available to be used) or emergy (energy consumed to make a product or service). Due to the importance of climate change and stringent regulations, greenhouse gas emissions using metrics such as carbon dioxide equivalent are a must (Shi, 2019). A Pinch analysis for solid waste incorporation with energy recovery at an eco-site integrating urban and IS. Solid waste management remains one of the biggest economic, environmental, and social challenges and is critical in implementing the Circular Economy. Pinch analysis is a methodology for minimizing energy consumption by calculating thermodynamically feasible energy targets (or minimum energy consumption) and achieving them by optimizing heat recovery systems, energy supply methods and process operating conditions. The rationale behind this co-integration is presented in Figure 9. The designed integrated symbiosis is envisioned to increase the energy recovered from the solid waste in both sites and landfilling diversion and reduce carbon fingerprint and GHC emission, benefiting both the urban and industrial sites (Fan et al., 2021).

Figure 9. Scheme of waste sharing among and within the urban and industrial integrative symbiosis



Source: Fan et al., 2021

Quantification of Energy Conservation and Emission Reduction (ECER) in the symbiosis structure system formed by the iron, steel, thermal power and cement industries and the social sector was forecasted for 2030 at a national level in China. A combination of the traditional bottom-up model with life cycle material metabolism theory assessed performance evaluation of the nationwide Industrial Symbiosis system testing the current state and symbiotic technologies of 118 industrial parks. These industries are high energy resource consuming and intensively polluting, owning large-scale and high-temperature furnaces that enable them to co-utilize various industrial and municipal wastes in their production processes. The results depicted that such a nationwide-Industrial Symbiosis can save approx. 36 Mtons of coal equivalent reduce about 190 and 140 ktons of SO2 and NOx emissions, respectively, along with 64 ktons of particulate matter emission. These values all together contribute to approx. 14% ECER reduction of the situation in 2020, which, in addition, has the potential to promote the development of new energy efficiency technologies and end-of-pipe technologies in every single industry, as well as for metal recovering (iron and zinc) (Cao et al., 2020).

Geng and coworkers made an emergy-based assessment on IS in the Shenyang Economic and Technological Development Zone, an industrial park of more than 400 km2 serving a population of over 8 million and many heavy industrial and business sectors. The five more important industrial companies are chemicals, equipment manufacturing, the construction material industry, pharmaceuticals, and food processing. Results show that non-renewable inputs, imported resource inputs, and associated services could be saved by approximately 90, 33, and 16%, respectively, indicating that IS could effectively reduce material and energy consumption and improve the overall eco-efficiency (Geng et al., 2014).

EU regulations and policies are focused on reducing emissions, improving energy efficiency and encouraging renewable energy to improve sustainability and economic competitiveness (Branca et al., 2022). Private companies prioritize value-added processes over energy-related projects, especially those requiring specific expertise, which is often unavailable individually. Cooperation within industrial parks can help overcome the lack of technical know-how on renewable and low-carbon technologies at a reasonable cost by collectively consulting a service provider. Eco-industrial parks (EIP), created to reduce the environmental footprint, represent a cooperative model suitable for promoting the integration of renewable energy sources in the industrial system (Butturi et al., 2019).

Cooperation within different industrial sectors can overcome the lack of technical knowledge on low carbon and renewable technologies, reduce emissions, and increase cost savings. Synergies among companies aim to optimize energy consumption and typical productions to minimize the use of fossil fuels and, consequently, the carbon footprint, reducing maintenance and management costs and infrastructure investments. Technological development, closely related to implementing IS and energy efficiency, affects all areas of industrial manufacturing, incredibly energy-intensive industries (Branca et al., 2021b; Branca et al., 2022). Indeed, the results of a semiempirical global Industrial Symbiosis model developed to estimate the global mass flow for the production of cement, steel, aluminium and paper with increasing levels of symbiosis and their influence on the carbon footprint suggests that symbiosis within the bulk material process can contribute to the mitigation of GHG emission to a limited extent (up to 7% due to alternative fuel use in cement production and negligible in the other industries).

In contrast, introducing new heat recovery technologies is envisioned to enable further emissions reductions (up to 18%). Still, the necessary infrastructure and technologies are not yet ready for implementation (Gast et al., 2022). Similar conclusions were attained from a projection analysis from 2015 to 2050 of symbiotic utilization of inorganic solid waste resources in energy-intensive industries such as steel, cement, and power in China. Four scenarios were considered to assess the overall energy-saving and emissions-reduction potential: business-as-usual, product structure optimization, low-carbon technology application, and policy advancement. Product structure optimization and promotion of IS, fostering the application of advanced technologies, were the most impactful ways for industries to achieve future energy-saving development and emissions reduction (Zhang et al., 2022).

4.2.4. Challenging Industrial Symbiosis scenarios

Since material flow for metals, plastic, wood, minerals, etc. has a clear impact on mining & processing, including energy expenditure and carbon footprint, besides environmental severe consequences, it gained economic importance at the top of the EoW criteria and therefore became a central 'player' in the IS of all kinds. Although industry accounts for about 20% of natural water consumption worldwide, because of the complexity of the purification treatment and requirements for reuse, in most cases, IS of water is still controversial, either for services, e.g., heat exchange, or for processes purposed (Hu et al., 2020; Pham et al., 2016). In addition, stringent environmental health regulations tend to limit IS in the water sector. Thus, water innovation might be considered a latent case of emergent IS, claiming for further research. Ramin et al. (Ramin et al., 2024) reviewed the global water innovation practices. They concluded that most symbiotic cases in the water sector involve public utilities and shared water facilities rather than private bodies.

Another challenging sector for implementing IS is the agroindustry system in general and agri-food, in particular. IS is being applied in aquaculture and animal husbandry despite its complexity. Water reclamation for irrigation in agriculture, which is by far the largest water volume reused worldwide, is a kind of symbiotic activity indirectly connected to the agri-food industry and food security and directly linked to climate change/water scarcity/water saving. However, at different high throughput industries, in which IS is of a local nature, i.e., industrial parks (IP), the agricultural sector, both plant crops and animal breeding, has potential for symbiotic interaction at the regional and transregional level. Therefore, IS in the agricultural sector is often harmed by the cost of transporting materials. The distance between the waste producer and the potential consumer is, in fact, one of the most important economic factors that must be considered when evaluating the viability of symbiosis.

Nevertheless, the greater the variety of industries in each region or adjacent regions, the greater the potential for creating synergies (Hamam et al., 2023). Research and innovative initiatives on this construction may advance IS in the agro-industrial sector. The proximity of eco-parks to agri-food clusters may help push IS forward, so rethinking and redesigning this aspect is also required.

A final example of a challenging IS activity is in industrializing countries, where the development of IS networks can not only economically benefit the participants, either private or public, turning waste into raw material or new products and energy but also establishing the basis for development of environmental protection, sustainability, and Circular Economy tools and well as legislation and regulation means. Examples of these can be drawn from South American and African countries as well as southeast and south and central South Asia countries (Boom Cárcamo & Peñabaena-Niebles, 2022; De Gobbi, 2022; Noori, 2022; Pham et al., 2016).

4.3. Symbiosis readiness level

The interest in IS is growing worldwide due to the scarcity of resources and the increase in waste generation. Natural resources are the basis of the economic system, and recently, there has been an increase in the demand for these resources, which has led to a great interest in implementing a more efficient CE in the consumption of resources. Based on the study of material and resource flows, IS allows the extension of the materials cycle and reduces the volume of resources in landfills (Agudo, 2022). However, there is an interest in evaluating whether companies are prepared or not to implement IS. There are still gaps in the development of evaluation systems that allow companies to quantify and motivate them to adopt IS, so it is necessary to identify factors that drive or interfere with the capacity of companies to implement IS (Agudo, 2023).

This context needs a simplified assessment to consider the dimensions facilitating Industrial Symbiosis. The literature shows two main types of IS: the exchange of resources (water, energy, waste and by-products) and the exchange of capabilities (trust, information, infrastructure).

Currently, existing tools are insufficient to identify an IS implementation's initial requirements and synergies. Therefore, it is necessary to establish a methodology that helps companies assess their maturity level (symbiotic readiness) and identify priority areas for carrying out actions to promote circular production. This level of maturity (symbiotic readiness) implies that the company is willing and able to implement IS.

The European Commission proposed using the Symbiosis Readiness Level (SRL) inspired by the TRL to identify and define the level of maturity of symbiotic interactions and to measure the progress of implementing IS. This concept is similar to the TRLs widely used in evaluating European projects (Sommer, 2020).

Technology readiness levels (TRLs) (MINTUR, N/A) emerged at NASA during the 1970s to evaluate technology in space programs. Still, they have been generalized to apply to any project, not necessarily aeronautical or space-related.

TRLs are divided into nine levels ranging from the new technology's basic principles to successful testing in a natural environment.

This scale allows us to determine whether the technology is in a proof-of-concept stage (TRL1 – TRL3), whether the technology is in the development and validation phase (TRL4 – TRL7), or whether it is a mature technology or technology that has been successfully tested in natural environments (TRL8 – TRL9).

However, TRLs alone are not sufficient to adequately describe the progress of an Industrial Symbiosis project. To assess the implementation of IS, it is necessary to consider the following dimensions:

- Technology
- Business
- Ecology
- Level of technical and management maturity

These concepts are introduced into a matrix with nine levels in the same way as the TRLs, allowing IS progress to be measured in the four dimensions.

Table 4. Proposal for defining the symbiosis readiness level

SYMBIOSIS READINESS LEVEL	TECHNOLOGY	BUSINESS	ECOLOGY	MANAGEMENT
9	Commercialization	Business cases are continuously controlled, reported and shared	Sustainability benefits proven	Resilient partnership
8	Extended operation	Finalise legal framework	Benefits are routinely monitored and reported	Practical operation and management start
7	Demonstration	Partners committed	Monitoring and reporting begin	Senior management is involved and supports the Industrial Symbiosis case

6	Prototype demonstration 'looks like'	Business case with all details	Permits applied for	The concept of joint management is developed
5	Breadboard demonstration 'acts like'	Evaluate competitiveness	Sustainability assessment finalized	Partners start the joint evaluation of Industrial Symbiosis. potential
4	Proof of concept validation	Check resources and criteria	Sustainability assessment in progress	Partners indicate interest
3	Proof of concept research (bench scale)	Check the fit with strategies of partners	Thorough data collection	First contact with partners
2	Academic research	Develop concept	Rough estimate	Potential partners (*) identified
1	Initial ideas			

Source: Sommer, 2020

Since four dimensions need to be introduced instead of one, the SRL process is not linear, as not all sizes may be matched in the same preparation phase. Sometimes, changing a dimension may require restarting the entire process.

Also, the process is iterative and may undergo advances and setbacks before reaching the maximum level. Therefore, the SRL can realistically help assess a technology's current state. SRL is proposed as a practical tool to guide the gradual progress of IS (Skjodt, 2021).

These levels evolve from a good idea to more advanced stages of development to the final phase of full implementation, resulting in a permanent partnership. The practical progress of these nine steps can be understood as follows:

- SRL1: The brilliant idea or the challenge (initial stage). The potential is discovered, and dialogue is established between the interested parties (partners)
- SRL2: Resource mapping is drawn up: It is ensured which resources are available
- SRL3: Selection completed. Data on resources and flows between the interested parties is collected. The best way to share information is sought.
- SRL4: Proof of concept. Feasibility studies and pilot tests are carried out.
- SRL5: Finalization of sustainability studies
- SRL6: Qualification of the system. Overcoming legal barriers and necessary administrative procedures. Business launch
- SRL7: Commitment between the parties. The signing of agreements and dissemination of the commitment.
- SRL8: Commercial production. Legal barriers have been overcome, and the business model has been established.

- SRL9: The company partnership is strengthened, and a stable and resilient collaboration is achieved.

These stages can be grouped as follows:

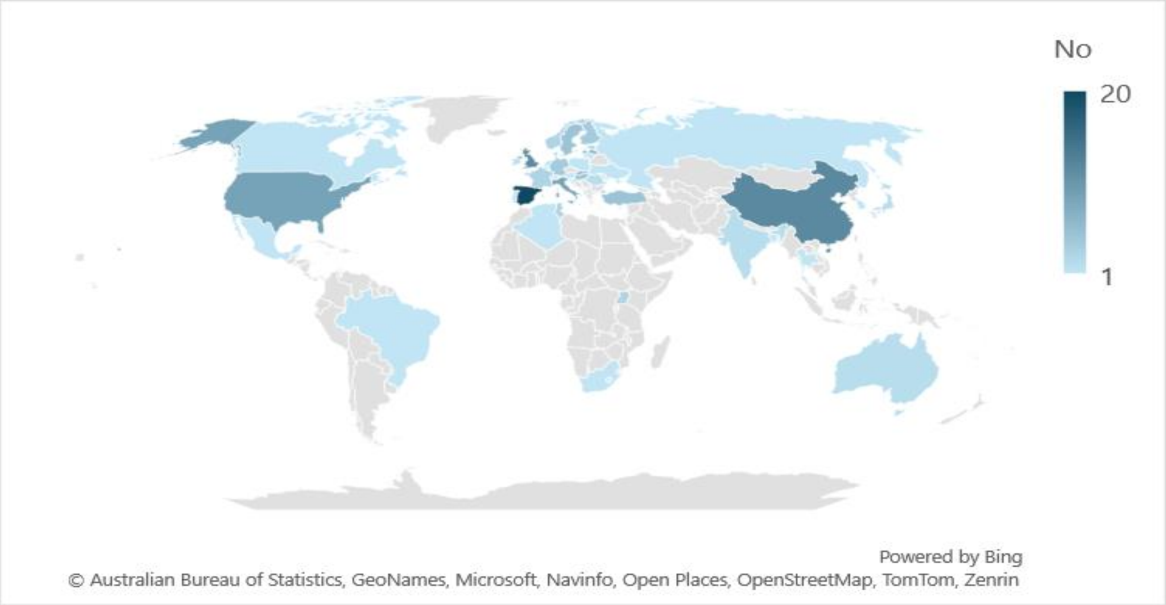
- **Emergent phase:** companies begin exchanging resources and establishing a limited network. SRL1, SRL2, SRL3, SRL4. In this way, finding complementary resources between companies corresponds to the lowest stages of the SRL. Sometimes, this process can be expedited by facilitators who present a more systematic approach when selecting resources and storing information.
- **Revelation phase:** emerging behaviour leads to revealing the positive externalities with exchanges made. SRL5, SRL6, SRL7. The connection between actors allows us to move from virtuality to reality, from idea to action.
- **Embedding phase:** An intentional and institutional expansion is established. SRL8 and SRL9. Negotiations and agreements are established between the parties.

However, SRLs are still in the early stages of development and require significant development to reach the desired maturity so a consensus can be reached on moving from a specific SRL to the next level. Although SRLs simplify the process of IS with a step-by-step approach, no generic model works for all companies and symbiosis relationships exist. However, these practices serve as a guide and facilitate the implementation of IS. For management processes, the simplicity and linearity of SRLs are more of a strength than a weakness, benefiting the dialogue between partners and potential stakeholders.

5. Examples of Industrial Symbiosis based on the mapping of LIAISE Cost Action

Within the LIAISE COST Action's objectives, a comprehensive worldwide mapping study has been performed to demonstrate the current situation in IS practices. Essentially, what is presented in this report section represents the state of the art with concrete examples worldwide, including Europe. Given that the contributions to the study have been limited to the project's working group members, the examples with the corresponding statistics cover mainly Europe, the USA, China, and Australia. One hundred fifty-six worldwide examples of Industrial Symbiosis (Figure 10) were identified. Although this is a high number of identified examples, these findings have limitations in the workgroup members' citizenship.

Figure 10. Worldwide examples of Industrial Symbiosis



Source: authors research, 2024

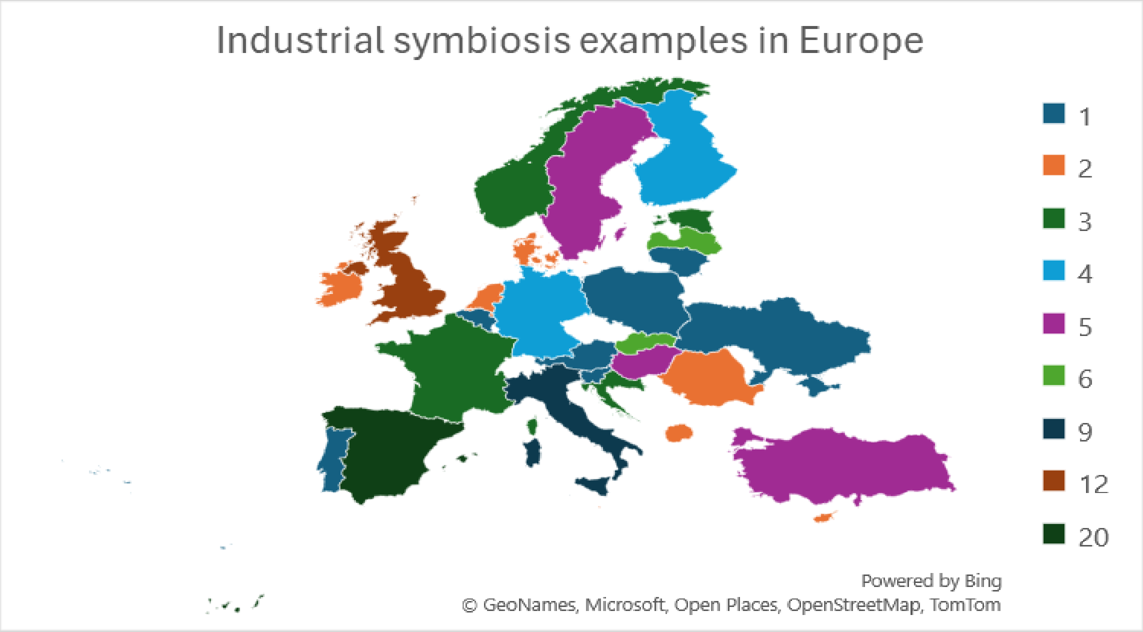
According to the data set in Figure 16, examples of IS have been found in 48 countries worldwide. Most of the identified examples are found in Europe (110; 70%), followed by Asia (20; 13%) and the Americas (14; 9%). The last examples have been identified in Africa. However, based on the latest research on IS, this might soon be changed, and more examples are likely to be found in Africa.

Most worldwide Industrial Symbiosis practices involve different industries (45; 29%), followed by waste management (12; 8%) and chemical industry (10; 6%). Research has identified IS in 33 different industrial sectors. Within various industries, 27 sub-sectors are involved in the chemical (18 cases) and metal (16 cases) industries as leaders. In the following subsections, the examples are divided into two, showing the European cases and the cases from the rest of the world.

5.1. Mapping Industrial Symbiosis cases in LIAISE countries in Europe

For the preparation of this report, 110 different examples of Industrial Symbiosis were identified in Europe (Figure 11).

Figure 11. Country-specific number of European Industrial Symbiosis examples

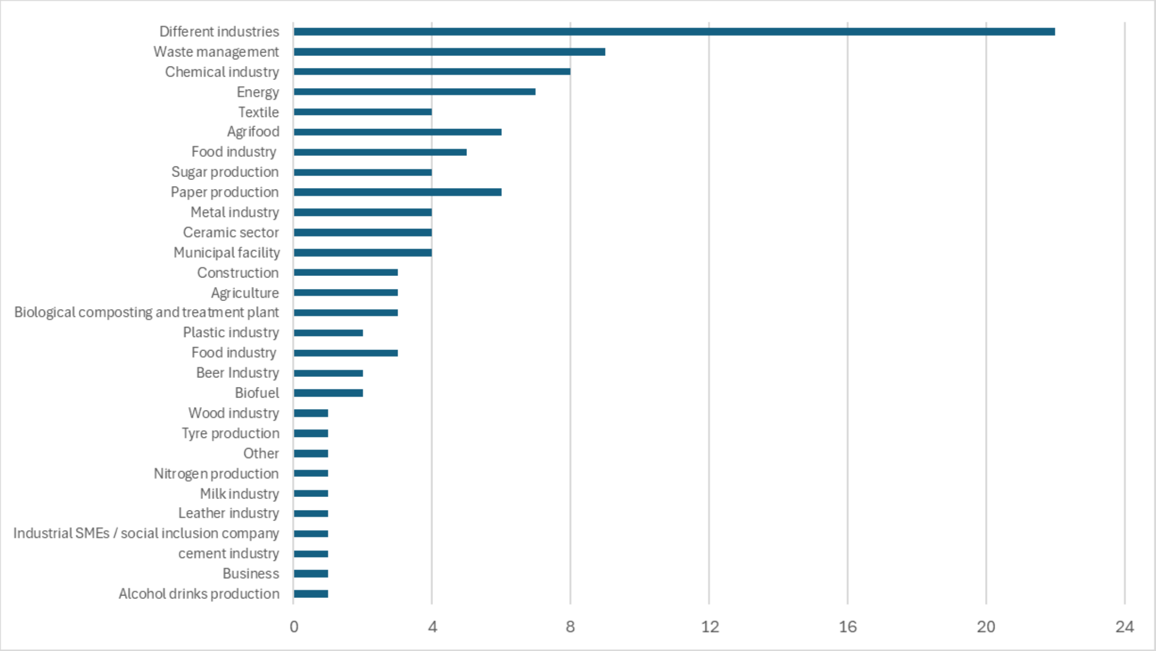


Source: authors research, 2024

As seen in Figure 11, most of the IS examples were identified in Spain (20), followed by the United Kingdom (12) and Italy (9). IS examples were identified in 28 European countries.

The type of flow and resources exchanged (Figure 18) shows that most IS practices involve material flow (74%), followed by energy streams (16%). The smallest share of identified examples involves logistics/transportation (2%) and infrastructure (1%).

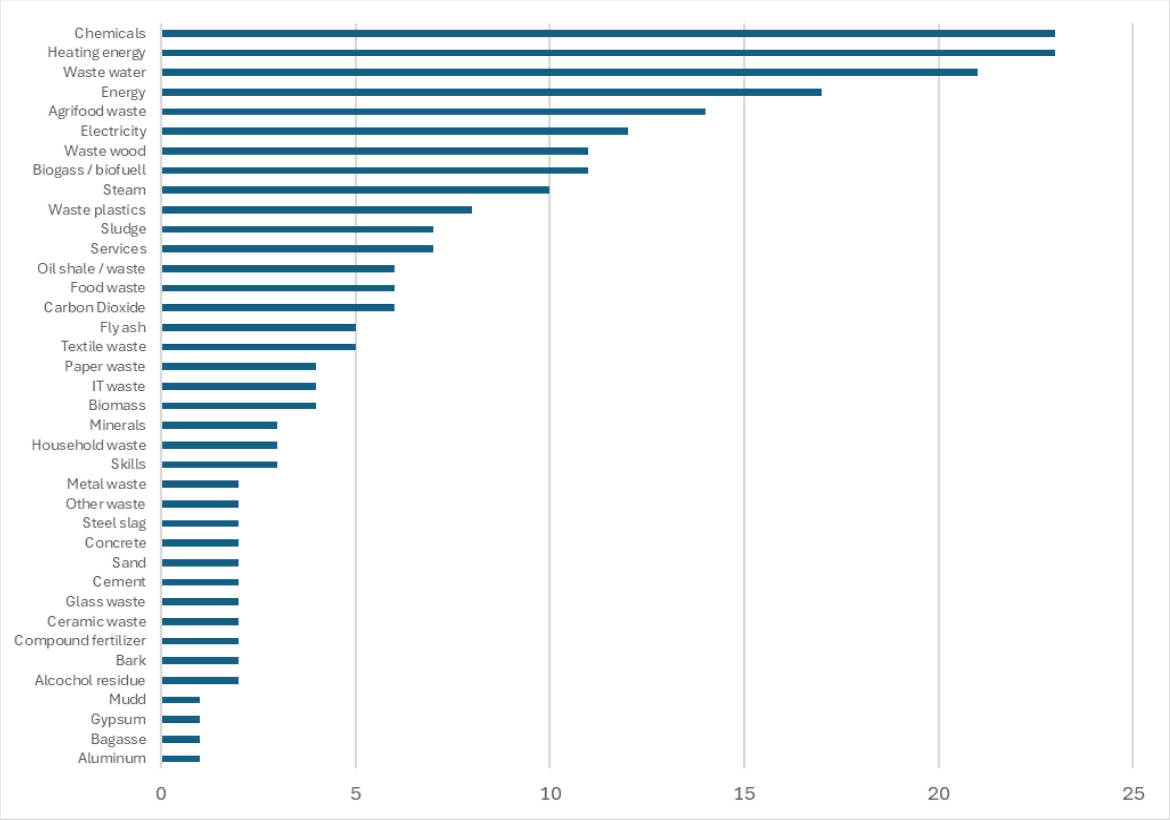
Figure 12. Industrial sectors involved



Source: authors research, 2024

Identified IS examples are seen in 28 different industrial sectors in Europe. Based on this analysis, most examples have different industries included, i.e., 22; 20%. They are followed by waste management (9; 8%), chemical industry (8; 7%) and energy sector (87; 6%). Within examples with different industries, the highest numbers have been observed in the chemical and food industries (each 8 cases), followed by different energy industries (7 cases) and metal industries.

Figure 13. Resources exchanged



Source: authors research, 2024

The maturity analysis of the identified examples of IS suggests that most of the examples have been running for over three years (73%). The rest indicate that the practices are in the early stage (1-3 years) at 6%, and new examples of Industrial Symbiosis have a share of 21%. Finally, most identified cases (79%) are running, followed by projects (17%). Only 2% of identified examples are no longer working.

Comparing both analyses (Table 5), it has been observed that more data is needed for worldwide cases to obtain more insights. However, with the available data, the Industrial Symbiosis practices are similar regarding sectoral choice and resources exchanged.

Table 5. Comparison of the European and Worldwide Cases

PARAMETERS	EUROPE	WORLD
# of cases	110	46
Top 3 sectors	Various sectors, waste management and the chemical industry	Various sectors, waste management, textile
The top 3 resources exchanged.	Chemicals, heat, wastewater	Chemicals, wastewater, metal tailings

Source: authors research, 2024

5.2. Review of European Industrial Symbiosis cases

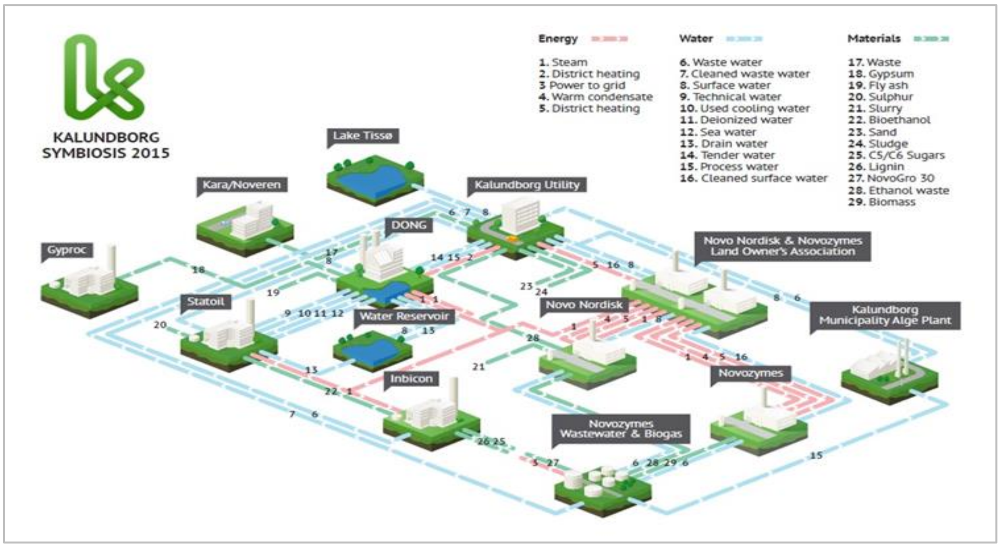
Among the 110 examples above of IS practices in Europe, for the report, the following best cases were selected to be assessed in more detail:

- Kalundborg, Denmark
- Port of Rotterdam, The Netherlands
- Uimaharju Industrial Symbiosis, Finland
- Chamusca Industrial Symbiosis, Portugal

5.2.1. Kalundborg, Denmark

Kalundborg is the world's most famous example of IS and is considered a reference case for similar projects. It represents a self-organized model in which companies spontaneously saw the benefits of symbiosis and entered contracts that eventually resulted in development of an industrial park (Redmond, 2023). It all began in 1961 with a project to use surface water from the lake for the needs of a new oil refinery to preserve the limited underground water supplies. The symbiosis began with cooperation agreements between several industrial companies to share an essential resource (water) and utilize waste resources (heat, steam and gas). Today, the Industrial Symbiosis between the six main partners (oil refinery, power plant, biotech company, gypsum board company, waste management company and soil remediation company) and Kalundborg Municipality is characterized by network cooperation based on the exchange of energy and resources such as heat, steam, water, gypsum, refinery gas, liquid fertilizer, biomass, sludge, ash, etc. In addition, new companies have joined the Kalundborg Symbiosis over time, and the exchange of resources and waste streams has expanded. Until recently, all this was achieved without a central coordinating body. Kalundborg is recognized as a system based on existing opportunities and shortcomings, the geographical co-location of industries in the port, and the political incentives that led to its success (Chertow, 2007).

Figure 14. Schematic representation of energy, water and materials exchange in Kalundborg



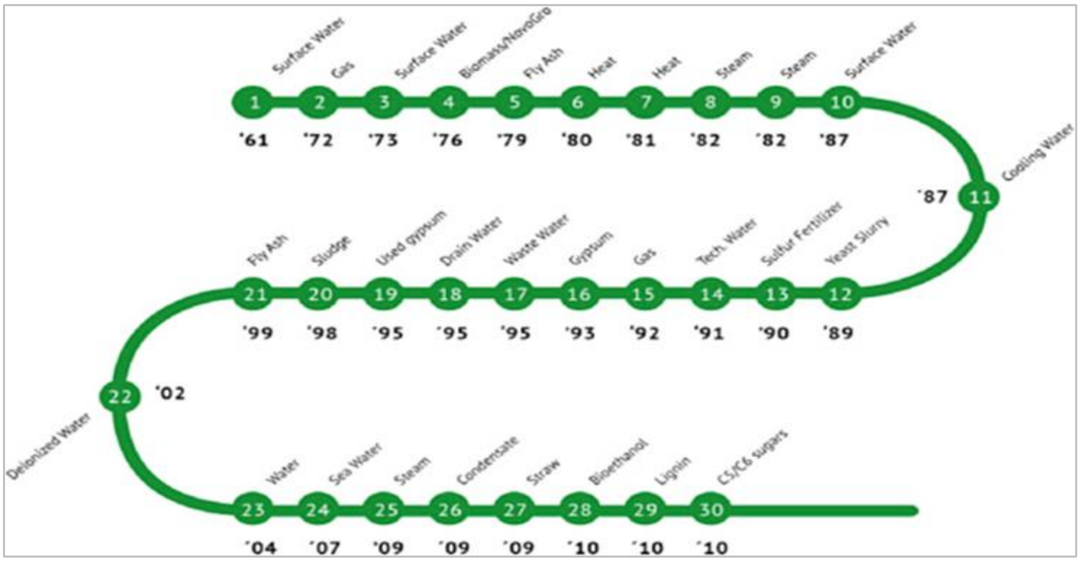
Source: Adapted from Nillson, 2016

Although Kalundborg has achieved impressive results, it still needs to be established to demonstrate the benefits of IS. Kalundborg was founded in response to the lack of groundwater, which prompted the partners to join forces. The project's development was driven by economic reasons (cost reduction), and it existed for quite a long time before it was recognized as IS. Although the project started from an external destabilizing factor, the relatively small size and isolation of Kalundborg influenced the establishment of regular communication between employees and managers, and the financial success of the initial implementation accelerated the overall effort.

Kalundborg Symbiosis is one of the few examples of an organically evolving network of strategically unconnected business entities that continue to work together to improve resource utilization and share knowledge. This unique network, which has existed for over 50 years (Figure 15), can provide valuable insights into the processes that drive ecological networks to move from one-off collaborations to sustainable cooperative relationships.

Later, an institutional platform - the Centre for Industrial Symbiosis - was established on the industrial park site. IS has not been driven by technological innovation because the technology used is conventional, but its use is what can be called innovative. There has been no significant increase in experimentation in recent years – the participants and exchange material have remained the same. However, over the years, internal symbiosis has been extended to external companies that process the waste of internal participants.

Figure 15. Evolution of utilities and materials waste sharing through the years



Source: Valentive, 2016

Kalundborg is successful in terms of the amount of waste reused and energy saved. Kalundborg forms more than 20 different streams of surplus resources that flow between companies and thus create a symbiosis of resource exchange that increases the resilience and profits of partners. Financial measurements play a significant role in the performance management system at Kalundborg since each project is mainly evaluated according to economic feasibility.

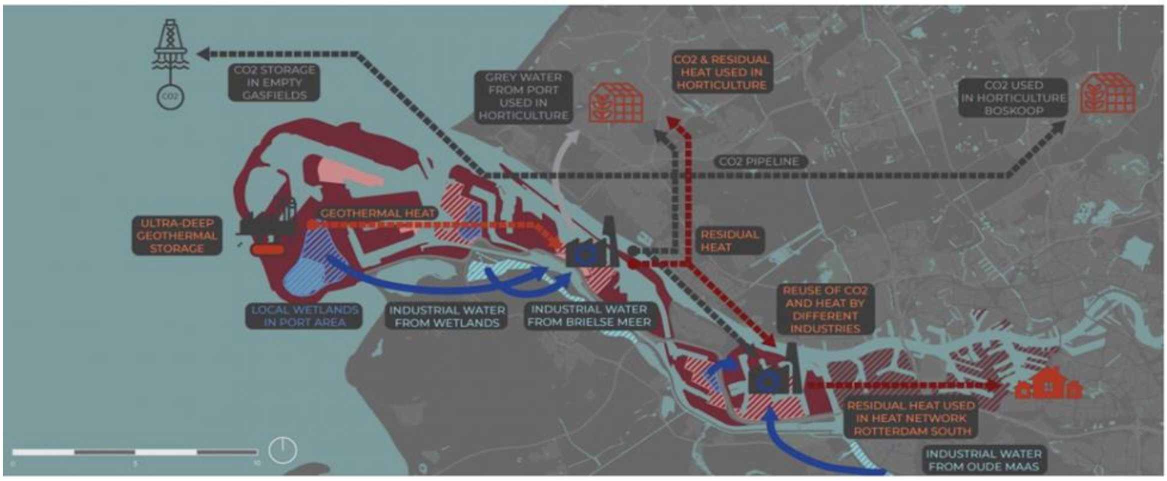
Many collaborations that developed within the Kalundborg Symbiosis served as prototypes for similar IS initiatives worldwide. Consequently, it should not be surprising that Kalundborg Symbiosis, one of the first examples of industrial symbioses, has reached a state of maturity that represents a different type of avant-garde and the challenge of expanding the scope of cooperation (Valentine, 2016).

Some of the main partners of the above symbiotic exchanges played a crucial role from the early stages of establishing this IS example. Statoil, Kalundborg Municipality Alge plant, enzyme producer Novozymes A/S, Asnæs Power Station, plasterboard factory Gyproc, pharmaceutical plant Novo Nordisk, oil refinery Statoil A/S, Bioteknisk Jordrens Soilrem, waste company Kara-Noveren were some only of the key players reported from as early as 2006 (Saikku, 2006). All those stakeholders collaborated by exchanging different forms of utilities (steam and water), waste, products and by-products such as heat, gas and gypsum, ash, fertilizer, yeast slurry, sludge, and other waste (Saikku, 2006). The same researcher (Saikku, 2006) reported that one of the main challenges was the environmental performance of the Kalundborg IS, the definition of the system boundaries and that the system still relied on imported fossil fuels (Statoil, for example, in the past).

5.2.2. Port of Rotterdam, The Netherlands

The port of Rotterdam is the largest in Europe and is home to many industries, including refineries, chemical plants, steelworks and food processing plants. The dense concentration of industries with different resource requirements fosters numerous symbiotic relationships. The port of Rotterdam in the Netherlands is strategically located on the Rhine-Meuse-Scheldt delta. It is an important logistics hub for Europe, handling over 440 million tons of cargo annually. The port contributes to the Dutch economy, providing over 385,000 jobs and generating billions in revenue. The port's industrial complex includes refineries, chemical plants, biofuel plants and vegetable oil refineries. Together with the storage of these products, the port of Rotterdam forms a solid and integrated chemical and petrochemical cluster. Many chemical companies and refineries in the Rotterdam port area ensure optimal efficiency (Baas, 2008). For example, oil refineries supply raw materials to the chemical industry and various chemical companies, then semi-finished products to other parties. There is also cooperation and sharing of tank storage, industrial gases, heat, steam, wastewater treatment and electricity. This synergy ensures a highly efficient and profitable business climate for all chemical companies operating in Rotterdam.

Figure 16. Flow of water and heat in the port of Rotterdam



Source: Den Hartog et al., 2021

The port promotes the Circular Economy by encouraging companies to develop products to be reused at the end of their life cycle. This approach helps to reduce waste and improve resource efficiency. The companies in the port exchange by-products to minimize the amount of waste. For example, the steel industry provides slag to the cement industry, reducing the need for raw materials and keeping waste out of landfills. The port has shared infrastructure, such as pipelines and storage tanks, which enable the efficient exchange of materials and energy between the industries. Advanced logistics and digital platforms allow efficient transportation and distribution of materials, reducing environmental impact and operating costs (Baas, 2011).

The network optimizes the use of resources by minimizing waste and maximizing the use of by-products from other industries. Reduced waste disposal costs, lower energy costs for participating companies and creation of new businesses focused on recycling waste. Significant CO2 emission reduction and water consumption reduction and promoting a circular industrial ecosystem in the port area. The surplus heat generated by the refineries and chemical plants is transferred to nearby greenhouses and residential areas for heating. For example, the residual heat from the Shell Pernis refinery is used in district heating networks. The industries in the port work together to capture and reuse CO2 emissions. The captured CO2 is stored underground in horticulture to promote plant growth (Port of Rotterdam Authority, N/A).

This example of IS faces challenges such as network complexity, logistics and infrastructure, standardization, and regulations. Managing a massive network with numerous companies and different resource exchanges requires robust communication and coordination efforts. Developing transportation and storage infrastructure is critical to efficiently exchanging materials and energy in the port. Ensuring the compatibility of waste streams and by-products with various industrial processes requires compliance with specific standards and regulations.

5.2.3. Uimaharju, Finland

One of Finland's best-known IS parks has been established around the forest (biomass waste) industry of the specific area, which was initiated with a sawmill where the bark waste from wood logs is combusted to generate energy (Saikku, 2006). Between 1960 and 2000, the Uihamarjou IS project (Uimaharju–Joensuu, N/A) was realized through the years via the symbiotic exchanges between a pulp mill and a power plant built alongside the sawmill. Figure 27 (Chapter 5.5.2.) depicts the exchange of energy (heat and power), water (fresh and wastewater) and materials (mainly of bio-based origin (solid, gaseous) in this case) between the four primary forestry-related industries sharing sources.

Uimaharju in Eastern Finland is a prime example of Industrial Symbiosis, where different industries work together to optimize resource use and minimize waste. It uses the principles of industrial ecology, where industries exchange resources (materials, energy, information), mimicking the closed cycle of a natural ecosystem. This reduces waste and promotes resource efficiency. The environmental benefits include less pollution, less waste generation and less resource consumption. It can also lead to economic gains for participating companies through cost savings and potential new revenue streams by selling by-products as resources to others.

This network includes a pulp mill, a sawmill and a pellet plant, all of which contribute to and benefit from the shared resources and by-products. According to Saikku (2006), the core actors of this self-organized IP were the following industries: Stora Enso, an integrated forest product company; with partners Enocell Oy, a chemical pulp mill, and Stora Enso Timber/Uimaharju, a sawmill. Nearby, too, is an ash treatment plant, a combined heat and power plant, an industrial gas plant and a wastewater treatment plant. The main flows shared in the Uimaharju IS project are energy (waste heat and power), utilities (steam), and the forestry by-products emerging from the sawmill, such as wood bark and chips, pulping chemicals from the pulp mills and ash from the energy generation plant.

The leading players in this symbiotic network are Stora Enso, a global pulp and paper industry leader, and local sawmills. Stora Enso's Uimaharju mill produces pulp, paper and bioenergy. It uses by-products and waste from its operations and those of neighbouring industries (Stora Enso, 2020). The pulp mill produces significant biomass waste, including wood French fries, bark and black liquor, a by-product of the pulping process. The bioenergy power plant converts the biomass waste from Stora Enso and the local sawmills into renewable energy (Biovoima, 2018). The plant generates heat and electricity and supplies it to industries within the symbiotic network and the local community. The local sawmills supply wood and bark, essential raw materials for the bioenergy plant. The sawmills benefit from the stable supply of heat and electricity generated by the bioenergy plant (Figure 27).

The Industrial Symbiosis in Uimaharju brings several economic and environmental benefits: (i) by converting waste into valuable resources, the industries reduce their raw material costs and their dependence on external suppliers; (ii) the joint production and use of renewable energy reduces dependence on fossil fuels, contributing to energy security and sustainability; (iii) the symbiotic relationship minimizes waste disposal needs and reduces greenhouse gas emissions, supporting Finland's environmental goals; and (iv) the collaboration strengthens the local economy by creating jobs and promoting innovation in sustainable industrial practices (Korhonen and Snäkin, 2005).

5.2.4. Chamusca, Portugal

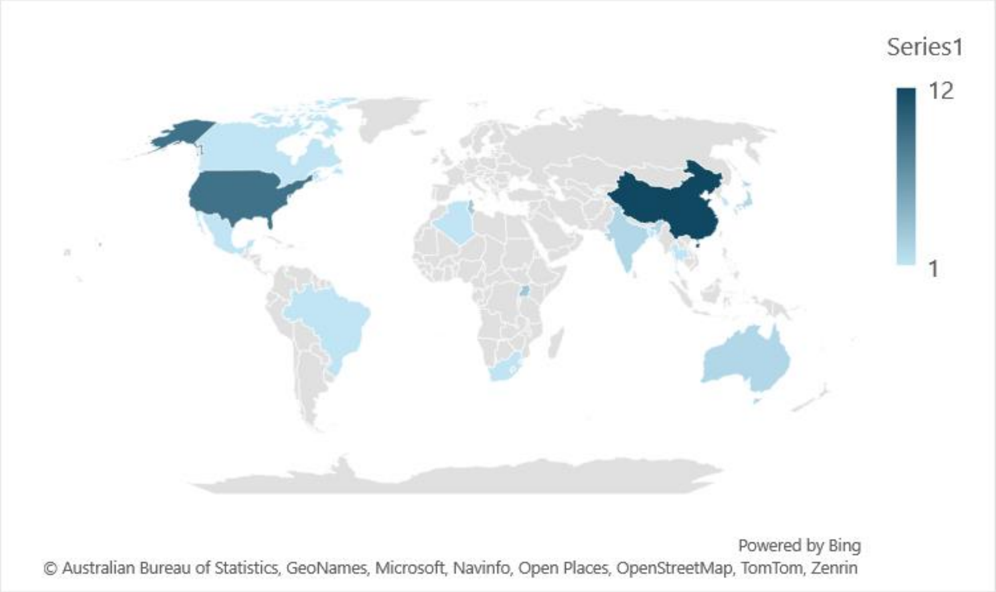
Taking advantage of a series of waste management regulations and waste recovery and treatment investments in their municipality, the local government in Chamusca reached for Industrial Ecology as a paradigm to develop Relvao Eco-Industrial Park (REIP hereafter), i.e., the first municipal eco-industrial park in the country. The concept for forming the eco-industrial park idea (Chamusca Industrial Symbiosis hereafter) is based on waste disposal. It is realized for many types of waste (urban, non-urban, medical, plastic, battery) (Costa & Ferrão, 2010a). Chamusca Industrial Symbiosis connects producers, farmers, and local entrepreneurs and aims to involve businesses and the local community. Chamusca Industrial Symbiosis is distinguished from other industrial symbioses because local public authorities understood that the current Portuguese waste management system favoured materials recycling through Resource Recovery companies.

As a consequence, the more considerable waste treatment and recovery facilities at the park (e.g., two national centres for the recovery, treatment and disposal of hazardous wastes, a resource recovery and treatment centre for municipal waste and a treatment facility for nonurban wastes) aimed to attract recyclers of various natures (e.g., batteries, plastics, biomass), waste sorters (e.g., medical packaging) or disassemblers (e.g., end of life vehicles), and soon managed to achieve their target (Costa & Ferrão, 2010b). Chamusca Industrial Symbiosis, in collaboration with the local government, deployed several actions to promote interactions and collaborations between Resource Recovery activities' managers and companies/institutions in the region surrounding the Relvao Eco-Industrial Park. The result is that not only is waste exchanged between manufacturers and some Resource Recovery companies in the Eco-Industrial Park, but services and waste materials are exchanged, or are in the process of being exchanged, between the Resource Recovery companies themselves. Readers can see that this means that, for example, the focus of car dismantlers is to strip the car of its various components, send the metal for fragmentation or recycling and send other materials (e.g., plastics, batteries, oils) to other companies within the REIP. The battery processor receives the car batteries and can separate the various components, sending the acid to be regenerated at the CIRVER and plastic to the plastics recycler. In the case of the battery processor, it developed a collaborative business strategy with a manufacturer of civil explosives, which will relocate to the vicinity of the REIP and use the lead recovered from the batteries in its production process, creating a symbiotic relationship. Chamusca Industrial Symbiosis is an excellent example of the adaptation of the IS paradigm to the regulatory idiosyncratic features of a region that achieved the critical objectives for its deployment, such as promoting the use of sustainable bio-energy resources, providing businesses (especially Resource Recovery businesses and other recyclers) with access to new markets, opening new markets for secondary raw materials, increasing the profitability for companies in the region and reducing the costs of production (Costa & Ferrão, 2010b). Key factors that contributed to this success are the diversity of actors involved, which allowed for exchanges of various types of by-products, achieving a balance of power between partners (especially Resource Recovery companies) without favouring anyone, and generating a high commitment to participants (Benedetti, 2017). These success factors mean that Chamusca Industrial Symbiosis is now a highly transferable IS that continues to attract companies in various activities – resource recovery and manufacturers alike. Also, projects are being deployed to encourage the development of synergies beyond the municipality, encompassing the Tagus Lezíria region surrounding it. Not only is waste exchanged between manufacturers and some Resource Recovery companies in Chamusca Industrial Symbiosis, but services are exchanged, or are in the process of being exchanged, between the Resource Recovery companies themselves, based on the principles of Chamusca Industrial Symbiosis. Critical characteristics of Chamusca that make it transferable are the utilization of standardized technology solutions and processes, the fact that the needs that it addresses apply to a wide range of areas, regions and countries, and the low risk of organizational resistance on behalf of participants since they all benefit from the functions of REIP.

5.3. Worldwide Industrial Symbiosis cases

As a result of the search for worldwide examples of IS, 46 different cases have been identified (Figure 17).

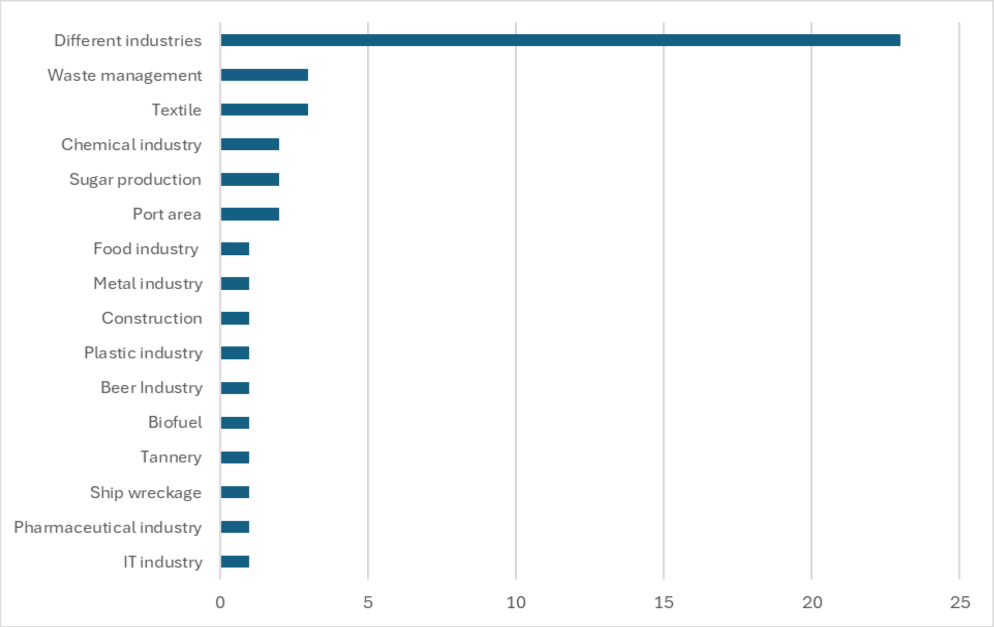
Figure 17. Worldwide Industrial Symbiosis examples



Source: authors research, 2024

Identified examples are in all continents and 19 countries. Most are in Asia (20; 44%), followed by the Americas (14; 18%). The lowest number (9) of identified IS is in Africa. China (12) is the leading country, followed by the USA (9). The other countries have 1 to 3 identified examples of IS. Looking at the type of flow and resources exchanged, most IS cases involve material flow (91%). Other flows (water, energy, other) share the remaining 9% in identified examples.

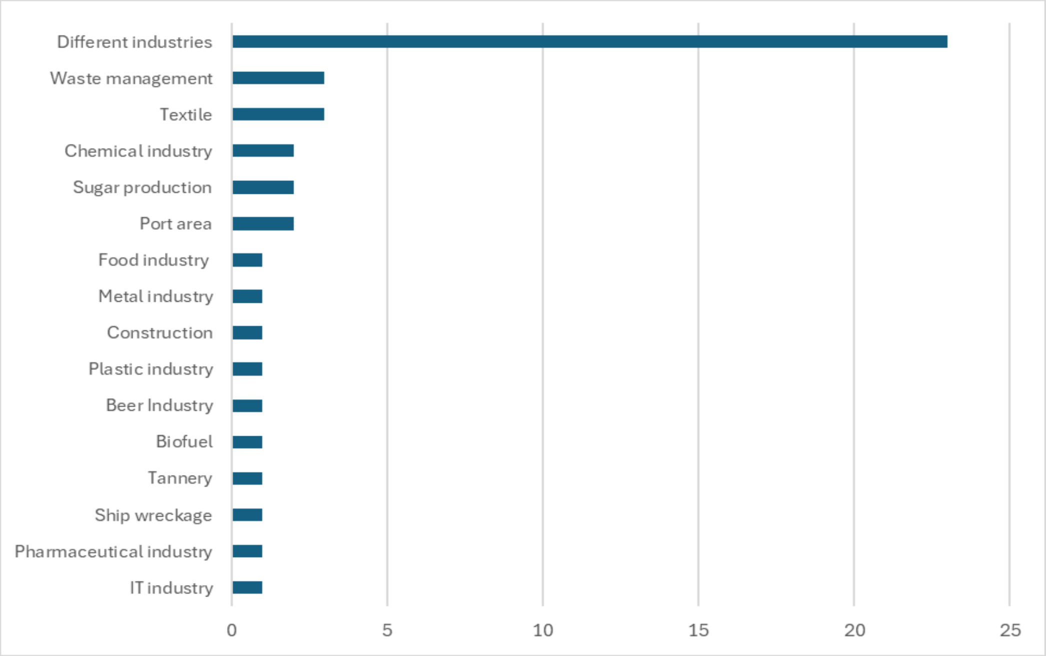
Figure 18. Industrial sectors involved



Source: authors research, 2024

Figure 18 shows that most identified examples have different industries in the IS (23; 51%). They are followed by waste management (3; 7%), textile industry (3; 7%) and chemical industry (2; 4%). Identified IS are seen in 15 different industrial sectors. Within examples from various industries, the highest number belongs to the metal industry (11 cases), chemical (10 cases), plastic industry (6 cases), and cement industry (5 cases). Different industries involve 22 different sectors.

Figure 19. Resources exchanged in worldwide examples



Source: authors research, 2024

Based on collected examples, 34 resources are exchanged. Most exchanged resources fall under chemicals (different types) (17), followed by wastewater (16), waste metal (14) and waste plastics (12). Looking at the maturity of the identified examples of IS, most of the examples run for over three years (91%) and are in the early stage (1-3 years) 9%. Finally, when looking at the state of symbiosis, most of the identified cases (89%) are running, followed by projects (9%) and ideas (2%). Based on the collected data, no IS examples work.

5.4. Review of worldwide Industrial Symbiosis cases

Interest in IS has grown significantly in recent years, and numerous case studies published in various scientific publications prove this (Chertow, Kanaoka & Park, 2021; Neves et al., 2020). Although the most cited case in the literature is Kalundborg in Denmark, there have been IS cases worldwide. Therefore, four of the best-known examples of IS worldwide have been included in our report:

- Ulsan, South Korea
- Kwinana, Australia
- Kawasaki, Japan
- Tianjin, China

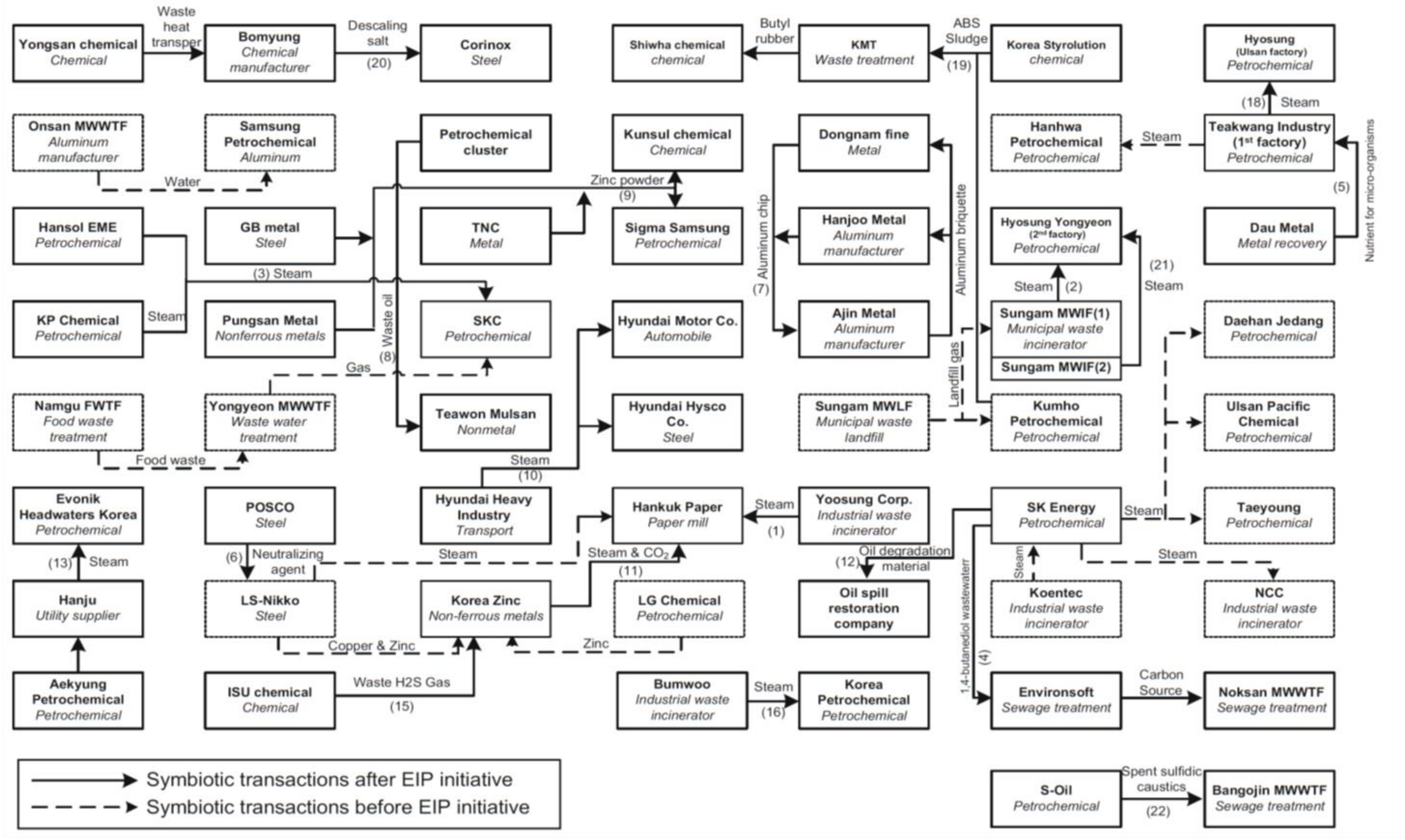
5.4.1. Ulsan, South Korea

The Ulsan Industrial Park in South Korea is a well-known example of IS. Established in 1962, it is the largest industrial complex in South Korea, with more than 1000 companies, whose primary industries are automobiles, oil refineries, shipbuilding and petrochemicals (Park & Behera, 2015; Park, Park & Park, 2016).

Ulsan Mipo-Onsan was one of the first demonstration regions to be covered by an Eco-Industrial Parks (EIP) project, which began in 2005 and ran in three phases over 15 years under the leadership of the Korea National Cleaner Production Centre (Behera et al., 2012). Transferred in 2006 to the Korea Industrial Complex Corporation (KICOX) under the Korean Ministry of Knowledge Economy, the main objectives of this project were to transform industrial complexes into Eco-Industrial Parks, foster industrial ecology through the application of Industrial Symbiosis (Park, Park & Park, 2019) and improve the business, environmental and social performance of the industry (Won et al., 2006). In addition to KICOX, the Ulsan city government, companies, research and development centres, and the Ulsan EIP centre (Behera et al., 2012) were involved in this project. The latter was crucial for creating links between companies, developing trust relationships, identifying new synergies, assessing their viability, and developing suitable business models (Behera et al., 2012).

Existing industrial symbiotic relationships (Figure 20) involve steam exchange, by-product exchange, and utility synergies (shared use of utilities such as water, steam, industrial water, hydrogen gas, and biogas) (Behera et al., 2012; Won et al., 2006). The network has grown organically over time, with new links forming as companies recognize the benefits of collaboration (Kim et al., 2018; Shah, Dong & Park, 2020).

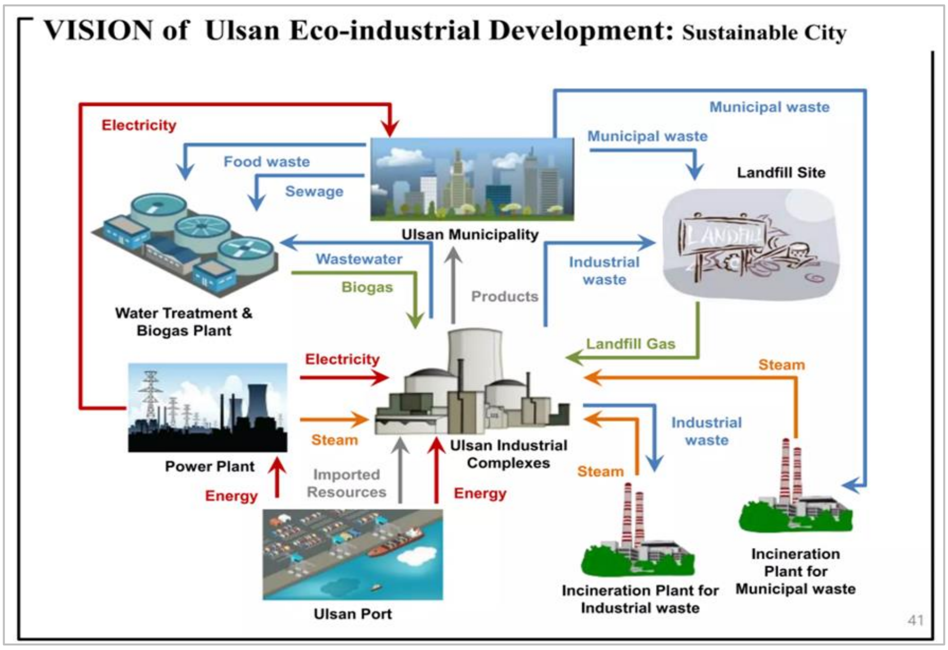
Figure 20. Industrial Symbiosis network in the Ulsan eco-industrial park



Source: Park and Behera, 2015

In addition, industrial and urban symbiosis has also emerged, thus extending the benefits to urban areas with geographical proximity (Figure 21) (Kim et al., 2018). One example is the steam supply to an acid production company by the municipal waste incinerators in Sungam (Shah, Dong & Park, 2020).

Figure 21. Network of industrial and urban symbiosis in Ulsan



Source: Park, 2022

With these industrial symbiotic relationships, it has been possible to obtain numerous economic, environmental and social advantages.

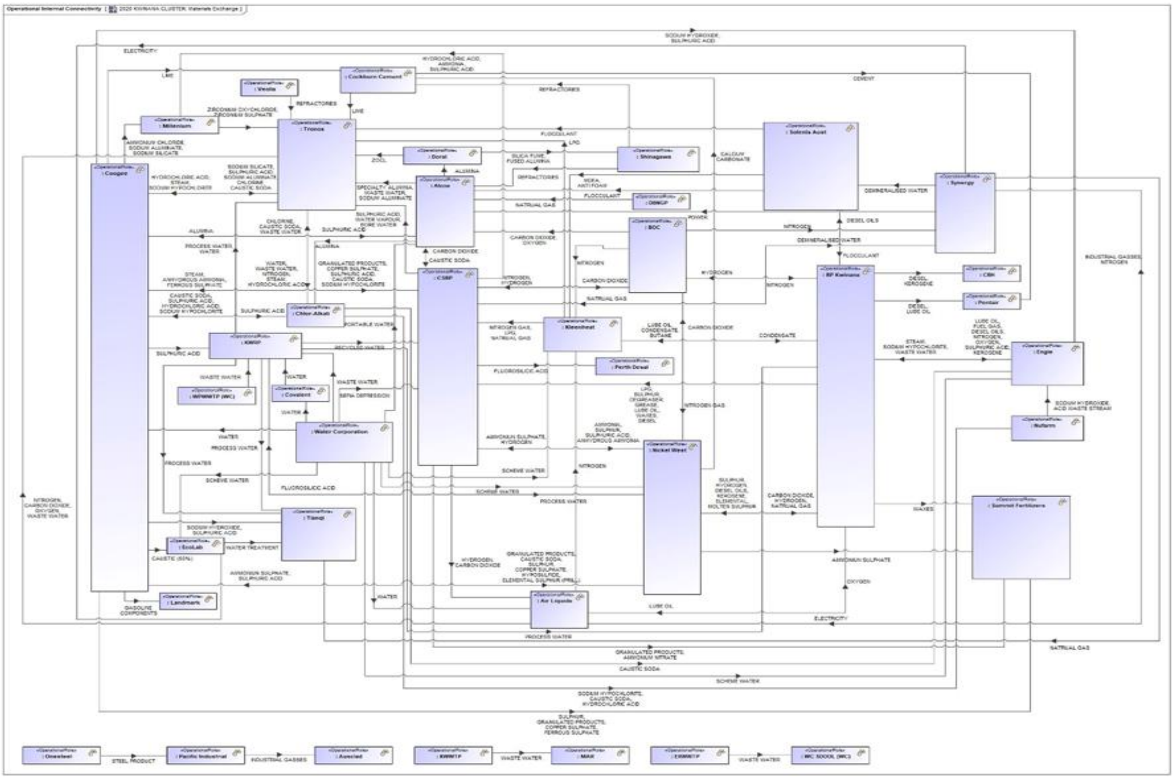
5.4.2. Kwinana, Australia

The Kwinana Industrial Area (KIA) in Western Australia is considered one of the world's best IS, with over 150 documented product and by-product exchanges between companies (Anon, 2024; Oughton et al., 2021). Located 30 km south of Perth, the KIA covers an area of approximately 8 km north-south and 2 km east-west (Oughton et al., 2023b). The KIA is part of the Western Trade Coast (WTC), which includes four primary industrial estates: the KIA, Rockingham Industry Zone, the Australian Marine Complex, and Latitude 32.

Initiated in the 1950s by the establishment of a large oil refinery, the biggest in Australia at the time, and due to the significant investment by this oil company and the state, the Kwinana Industrial Area became the most important in Western Australia (Harris, 2007; MacLachlan, 2013). As well as smaller companies, this area has attracted numerous multinationals responsible for a large volume of exports and revenue (MacLachlan, 2013). In addition, this area is also characterized by heavy processing industries, such as alumina refinery, nickel refinery, titanium dioxide pigment plant, lime and cement kilns (Van Beers et al., 2007). There are also several chemical companies, utility operations (two power stations, two cogeneration plants), harbour facilities and water and wastewater treatment plants in the area (Van Beers et al., 2007). The intrinsic characteristics of these industries and the existing diversity have played a role in creating industrial symbiotic relationships.

Until 2007, 47 IS relationships were identified, of which 32 are by-products and 15 utilities (Harris, 2007; Oughton et al., 2021), having developed over the years (Figure 22). Examples of the latter include sharing utilities for alternative water supply (Ramin et al., 2024) and a cogeneration plant that produces steam used by the refinery and generates electricity for the latter and the grid (Harris, 2007).

Figure 22. Synergies of existing by-products and utilities between industries in the Kwinana industrial zone



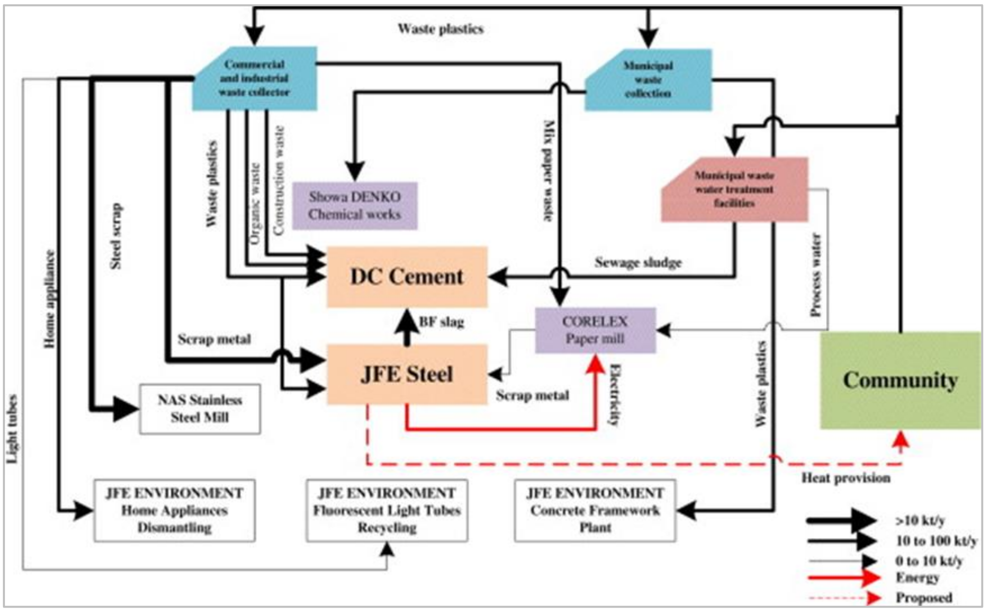
Source: Oughton et al., 2021

The IS model in the Kwinana Industrial Area comprises four dimensions: product/by-product exchanges, skilled workforce, support industries, and governance (Oughton et al., 2023a). Grey literature referred to in academic papers such as internal reports commissioned by the Kwinana Industries Council reveals some analysis of symbioses and mapping of same (Kwinana Industrial Council, 2023) outlining that there are currently over 170 exchanges operating between 34 companies. However, in academic literature, little quantitative data on numbers, types of linkages and elemental quantification of material flows have advanced since the publication of Van Beers et al. (2007) and a tabular descriptive list of synergies published in Van Berkel et al. (2006).

5.4.3. Kawasaki, Japan

Japan was one of the countries that invested in IS and recognized its importance in resolving economic and environmental issues. Thus, starting in 1997, Japan created the Eco-Town Program through a national initiative applied in 26 cities designated as National Eco-Towns (Dong et al., 2014). This program arose from the need to boost the economy, revitalize local industries, and reduce waste disposal due to the limited space (Van Berkel et al., 2009). The city of Kawasaki was one of the first to officially obtain Eco-Town status (Van Berkel et al., 2009). In addition to the industrial area, synergistic relationships have been extended to the city, promoting both industrial and urban symbiosis (Sun et al., 2024). Thus, industrial and commercial waste management companies, municipal waste collection and wastewater treatment centres, and nine companies have made it possible to incorporate waste generated by industries and communities into the processes of different sectors, either as a raw material or as alternative fuels (Figure 23) (Dong et al., 2013, 2014).

Figure 23. Material flows of Industrial Symbiosis in Kawasaki eco-town



Source: Dong et al., 2013

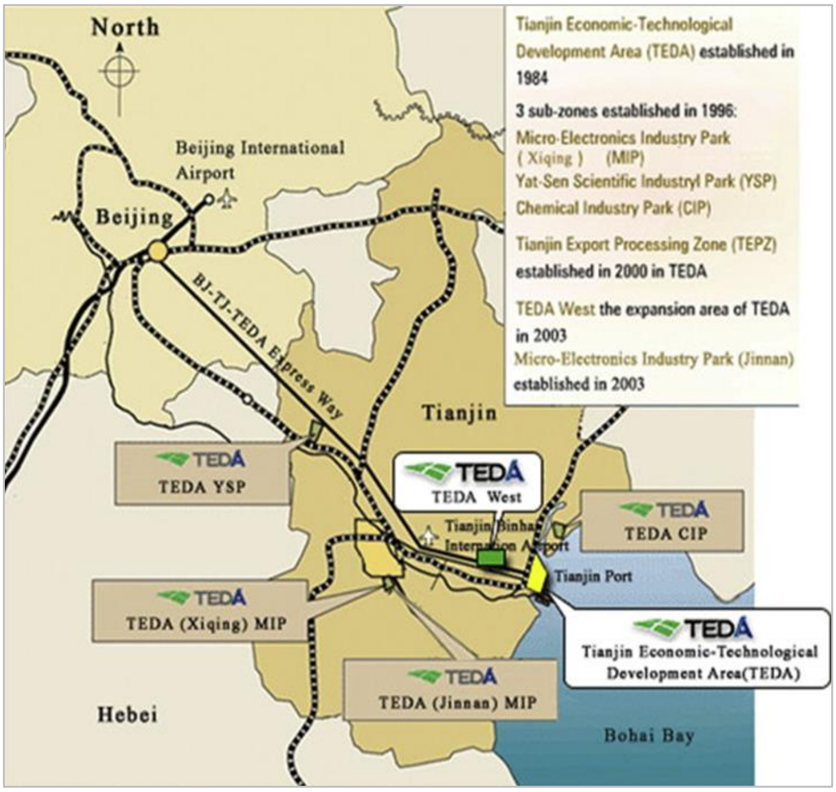
The Kawasaki IS case study findings reveal that this model presents an innovative approach to mitigating carbon emissions at the industrial park level. Two key aspects contributing to this are the reuse of carbon-intensive scrap steel and the reuse of substantial quantities of blast furnace slag (Dong et al., 2014). The Kawasaki case also highlights the role of government programs in facilitating Industrial Symbiosis, as the exchanges were part of Japan's Eco-Town program (Hashimoto et al., 2010). This provides insights into the policy frameworks and governance models that can support the development of urban IS.

The Kawasaki case also demonstrates the potential for realising societal benefits through IS, including enhanced public awareness through promoting IS and better public health by reducing solid and hazardous wastes. This framework fosters collaboration not only among diverse companies but also between companies and municipal authorities, as well as with the local community (Dong et al., 2014; Ohnishi et al., 2017).

5.4.4. Tianjin, China

Tianjin Economic-Technological Development Area (TEDA) in Tianjin was one of the first three National Demonstration Eco-Industrial Parks (Yu, Dijkema & De Jong, 2015) and one of China's leading national eco-industrial parks (Shi, Chertow & Song, 2010). This designation, along with the National Trial Eco-Industrial Parks, is part of a program launched by the State Environmental Protection Administration in 2000 called the China National Eco-Industrial Park Demonstration Program, which developed the largest network of eco-industrial parks (Shi, Chertow & Song, 2010).

Figure 24. Tianjin Economic-Technological Development Area industrial activities map



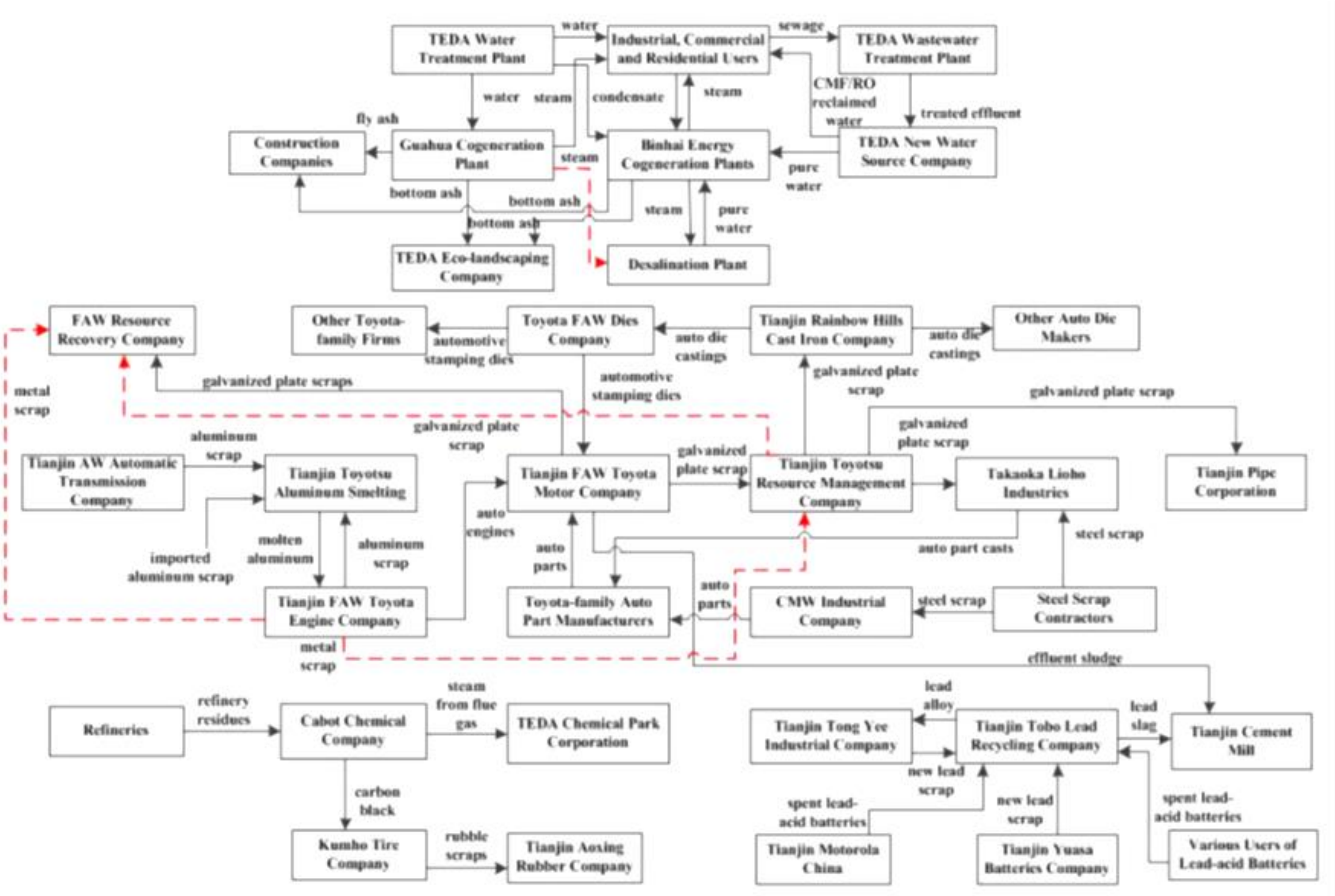
Source: Shi et al., 2010

The main objectives of this program were to promote IS, encourage cleaner industrial practices and boost environmental management (Yu, Dijkema & De Jong, 2015; Yu et al., 2015). However, this was not the only measure taken to boost sustainability. In 2000, it obtained ISO 14001 certification for the entire industrial zone. It was designated as one of SEPA's National ISO 14001 Demonstration Zones, and in 2005, it was selected as a Circular Economy Pilot Park (Shi, Chertow & Song, 2010).

Since its creation in 1984, TEDA has grown significantly, attracting numerous companies from different sectors, mainly automobile and machinery, electronics and telecommunications, food and beverage, aerospace industry, biotechnology and pharmaceutical (Yu, Dijkema & De Jong, 2015). The nature and diversity of the existing companies have facilitated the introduction of Industrial Symbiosis practices. Since the mid-1990s, numerous synergies have emerged involving the exchange of water, energy and solid waste (Shi, Chertow & Song, 2010).

Figure 25 illustrates some industrial symbiotic relationships between the primary industries and others where diversity is notorious. Paper mills and cement mills; coal briquette factories; chemical companies, rubber companies, batteries companies, public utilities and environmental infrastructures, public works companies; commercial and residential users, and port-based industrial complexes are some of these examples (Zheng et al., 2013; Cerceau et al., 2014; Liu et al., 2018).

Figure 25. Tianjin TEDA Industrial Symbiosis network



Source: Zheng et al., 2013

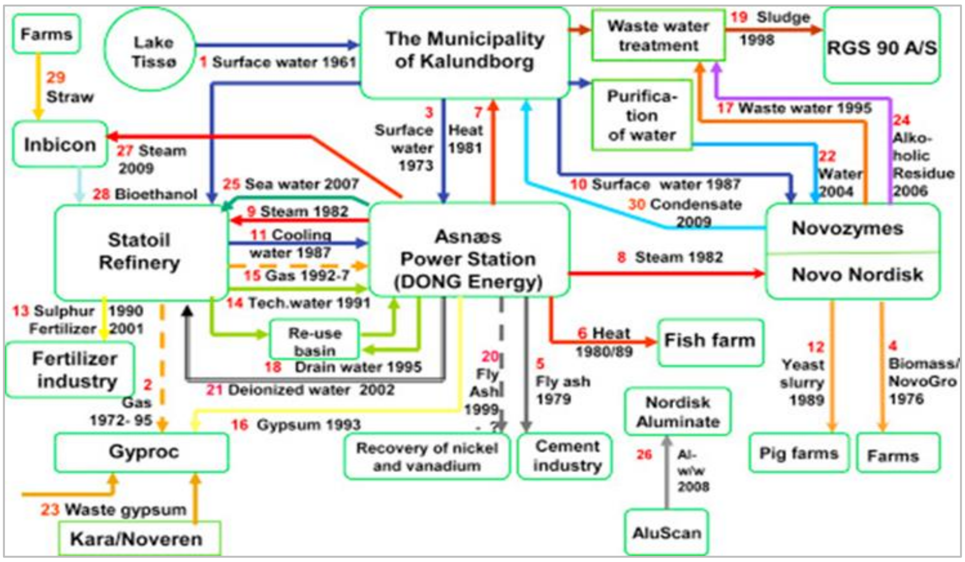
5.5. Overview of Industrial Symbiosis Case studies measurable synergies

To review any recent quantification of the IS synergies effort, it was focused on some of the most reported case studies in academic and professional literature. As a result, this section reviews the existence or absence of any data on the quantification of IS. To demonstrate the challenges faced in comparing IS cases in quantifying synergies, selected case studies (more about cases in chapters 5.2 and 5.4.) are analysed here regarding the quantification methods used in each case.

5.5.1. Kalundborg, Denmark

The Kalundborg is the most well-known paradigm setting and is envisioned as a standard model for the sustainable development of EIPs, realizing the theory of IS. Today, the Kalunborg Symbiosis Park has approximately 30 waste streams, while more are pending to be tested and used as streams. This type of symbiosis is estimated to lead to CO2 savings of 635,000 tons/y, translated to 14 M€ in a variety of benefits for society and economy as well as the much wanted ~24M € in financial savings for the businesses (Transition Aps, 2021).

Figure 26. Milestones in progress of symbiotic exchanges between industries of common interest

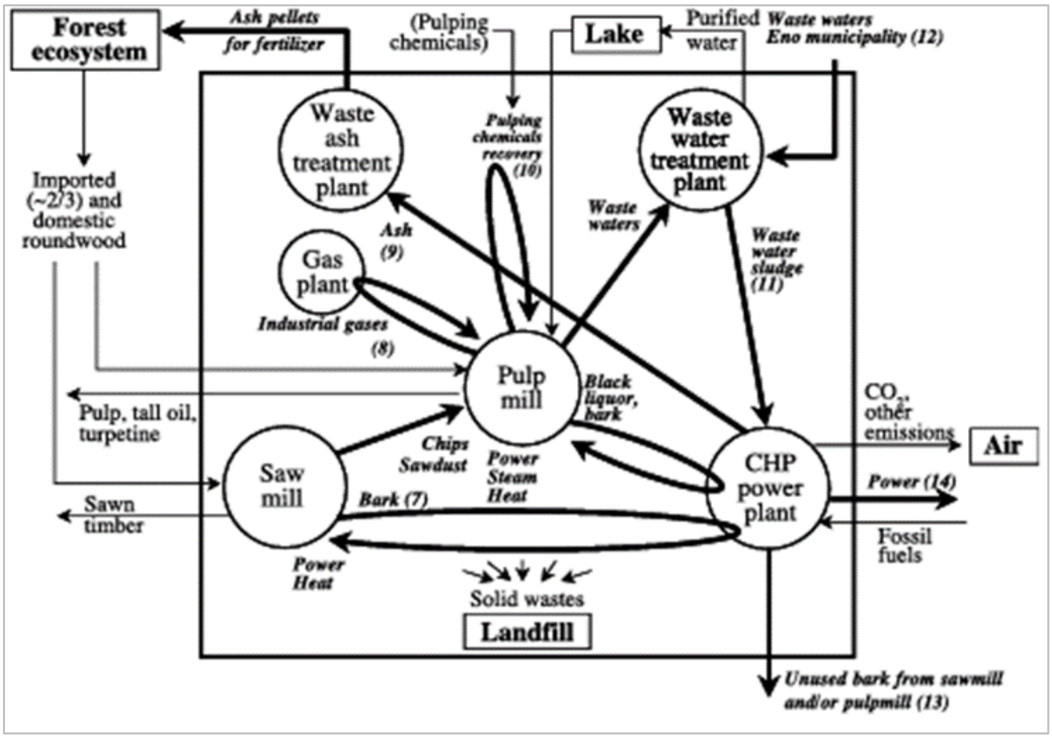


Source: Bradson, 2016

5.5.2. Uimaharju, Finland

Saikku (2006) reported the main challenges for Uimaharju IS Park being its environmental performance, the source of raw materials (imports of pulp reached 40% and timber 85%), the destination of end-materials to parallel markets, e.g., exports of paper 90 %, and once more the definition of the system boundaries.

Figure 27. Schematic representation of energy, water and forestry materials exchanges during early developments of Uimaharju



Source: adapted from Saikku, 2006

Most recent information acquired from grey literature via the snowballing method (Syder, 2009) indicates that in 2019, the Enocell Mill is still producing bleached pulp from softwood and dissolving pulp from birch. The dissolving pulp is used as feedstock to produce speciality products and textiles, for example, for replacing cotton and oil-based materials, such as polyester. More specific information on quantities includes data on Stora Enso Oyj Enocell Mill, which uses 2.7 million m3/y of timber with a production of 470,000 tons/y of bleached softwood and dissolving pulp. The process's most valuable by-products are electricity, pine oil, and turpentine. Similarly, the Stora Enso Wood Products Oy Ltd- Uimaharju Sawmill uses 2.7 million m3/y of timber with a capacity of 240,000 m3/y of sawn timber and 20,000 m3/y of heat-treated wood. The Uimaharju sawmill by-products used for energy generation generate 170 GWh/y, which should be enough to heat nearly a tiny city of 10,000 detached houses. Stora Enso, in 2023, used 1.4 million tons of paper for recycling (PfR) in their products, those being mainly recycled newsprint and container boards (Stora Enso, 2020), while the company started to offer products that are 100% recyclable by 2030 and 100% circular by 2050. Valuable by-products of their process are wood chips, sawdust and bark, and the sawmill's by-products are transported to the Enocell Mill (Uimaharju–Joensuu, N/A).

5.5.3. Ulsan, South Korea

The case of South Korea is interesting as there are 504 industrial parks, which account for almost 33% of the land used (LU). Among all, 34 are of significant industrial scale. The Ulsan IS Industrial Park, now called Eco-Industrial Park (EIP), was in the past one of the most polluting yet, though possibly the most known EIP example in the country. Some of the key industry players of Ulsan EIP are the Hyundai heavy industry, Hyundai automobiles, and Samsung petrochemicals, which are well-known industries around the globe. (Figures 24-25)

Table 5 depicts the synergies and benefits, based on measurable quantities, achieved in the already established symbiotic exchanges of waste, water, CO2 emissions reduction and the numbers of jobs created in Ulsan EIP up to 2013 (Park, 2013). A note is that it seems that Ulsan Industrial Park still relies heavily on fossil-based resources and is mainly concerned about the reduction of CO2 emissions, profits creation for both

Table 6. A summary of some of the Ulsan Eco-Industrial Park (EIP) projects in operation and their associated benefits

MATERIALS	FROM INDUSTRY	TO INDUSTRY	PROFIT (M€/Y)	REDUCTION OF WASTE (T/Y)	REUSE OF WASTEWATER (TON/Y)	REDUCTION OF CO_2 (T/Y)	REDUCTION OF AIR POLLUTANTS (T/Y)	JOBS
Wastewater and aldehyde	SK Energy	Noksan MWWTF	14.9	-	6,132	-	-	-
Steam	Yoosung Corp.	Hankuk Paper	28.9	-	-	3,893	12,491	-
	Sung-am MWIF	Hyosung	55.3	-	-	18,850	60,476	140
	Hyundai heavy industry	Hyundai motor Hyundai HYsko	24	-	-	6,024	10,188	-
	KP chemical h HaNsol EME	SKC	30	-	-	10,880	34,907	-
	Aekyung petrochemical	Evonik headquarters Korea	18	-	-	8,881	30,094	-
	Bum Woo IF	Korea petrochemical	41.1	-	-	8,278	25,084	-
Steam and CO_2	Korea Zinc	Hankuk paper	49.5	-	-	26,849	63,643	-
Oil degradation material	SK energy	Oil spill restoration company	0.9	200	-	-		-
Nutrients for	Dau metal	Teak wang industry	27.7		30,000	-		-

microorganisms								
Aluminium chip	Dongnam fine Hanjoo metal	Ajim metal	24.7	-1250	-	-		-
Neutralising agent	Posco	LS- Nikko	8.6	29,000	-	-		-
Waste oil	Petrochemical cluster	Teawon Muslan	12.5	300	900	12,120		-
H_2S gas	ISU chemicals	Korea Zink LS Nikko	79.6	2,800	-	-		-
Zink powder	Poongsan metal GB metal TNC	Kunsul chemical industry Sigma Samsung	40.7	1.178			316	

Source: Adapted from Park, 2013

An estimated financial benefit of 84.39 million US$/year resulting from an investment of 78.80 million US$, a reduction of 330,970 tons/year of CO2, a reduction in atmospheric pollutants (SOx, NOx and CO) of 4052.6 tons/year, and an increased community and worker satisfaction due to job creation and improved environmental quality (Park & Behera, 2015). Furthermore, between 2000 and 2015, at the regional level, industrial eco-efficiency in energy use and waste generation improved by 21.4% and 35.0%, respectively (Shah, Dong and Park, 2020). Industrial waste intensity fell by 51.2% between 2000 and 2015 (Shah, Dong and Park, 2020). In addition, it was possible to decouple industrial production from waste and energy intensity since although industrial production increased by 12.7% between 2007 and 2015, waste production and energy intensity decreased (Shah, Dong & Park, 2020).

5.5.4. Kwinana, Australia

Over 150 product and by-product exchanges have been documented at the Kiwana Industrial Area (KIA) (Oughton et al., 2021). Oughton et al. (2021) presented two water Circular Economy case studies; however, no quantification of the exchanges was provided. One discussion was about a failed initiative. Rosano and Schianetz (2014) outlined the collaborative development of a matrix of sustainability indicators selected and ratified by industry and the community (Table 7).

Table 7. Kwinana Industrial Area (KIA) sustainability management matrix

	PRIMARY PERFORMANCE INDICATORS		SECONDARY PERFORMANCE INDICATORS	
Outcome sought	Name	Unit	Name	Unit
Carbon neutral KIA (ENERGY)	Net GHG emissions (CO2-e) per economic output	ktonnes CO_2-e/ $Bn KIA GDP	CO_2 emissions GHG emissions GHG emissions offset	kt CO_2 kt CO_2-e kt CO_2-e

World benchmark in energy conservation (ENERGY)	Total energy consumption per economic output	PJ/$Bn KIA GDP	Total energy use Utility synergies (energy)	PJ TJ
Zero process use water scheme (WATER)	Total water use per economic output	%	Total water use Groundwater use Surface water (total)	GL GL GL
World benchmark in water conservation (WATER)	Fraction scheme water in total water use Fraction of recycled water in total water use	GL/$Bn KIA GDP %	Surface water (low quality) Scheme water use Off-site water recycling (synergies)	GL GL GL
World benchmark in reused byproducts (BYPRODUCTS)	Reused by-products as a fraction of total process residues Number of by-product synergies	% -	Process residues Re-used by-products	Kt Kt
Recognized as the premier industrial estate in Australia (ECONOMY)	Contribution of KIA GDP to WA GSP	%	Total sales (KIA GDP contribution) Direct and indirect wages and salaries Purchase of goods Purchase of imported goods (international and national)	$M $M $M $M
World benchmark on industrial emissions (ECOLOGICAL HEALTH)	Air emissions per economic output • SO_2 • NOx • PM10 Cockburn sound quality measures • Physical/chemical • Direct biological • Toxicants	Tonnes/$Bn KIA GDP Below are guidelines for the selected criteria	Air emissions • SO_2 • NOx • PM10	Tonnes

	Number of incidents of non-compliance with noise regulations in KIA	-		
Welcome neighbour (COMMUNITY)	Contributions to community programs per economic output Fraction community that believes the industry has a positive impact on community wellbeing	$k/$Bn KIA GDP %	Contributions to community programs	k$
Sustainable workforce (WORKFORCE)	Number of direct and indirect employees per economic output Fraction apprentice/traineeships of total direct workforce Fraction employees living locally Lost time injury frequency rate (LTIFR)	employees/$Bn KIA GDP % % No lost time injuries per million hours worked	Employees Apprentice/traineeships Fraction females in the workforce (full-time) Employees > age 55 years Total lost time injury	Direct (indirect) Total (female) % % Days per year

Source: Rosano and Schianetz, 2014

These synergistic relationships have led to numerous environmental, economic and social benefits. Using carbon dioxide from a nearby ammonia plant by Alcoa's Kwinana alumina refinery resulted in a greenhouse gas benefit equivalent to 70.000 tons of CO2-eq per year. The natural gas supply to the cogeneration plant, supplemented by excess gas from the refinery, reduced approximately 170.000 tons of CO2 emissions per year (Beers & Biswas, 2008).

5.5.5. Kawasaki, Japan

Kawasaki's IS initiated with an oil refinery, a coal-fired power station, and a pharmaceutical and biotechnology industry as the core of its business, according to Van Berkel et al. (2009). In 2003, 11 companies participated in the initial stage of Kawasaki Industrial Symbiosis, with six by-product exchanges and seven utilities. Some of the initiatives subsidized to strengthen the symbiosis were the recycling of plastics as reductant (for BF) at 50,000 ton/y, plastics for concrete formwork (20,000 ton/y), a recycling plant for unsorted and contaminated paper wastes (73,800 ton/y), recycling of plastics for ammonia production (64,000 ton/y) and polyethene terephthalate (PET) to PET recycling plant with a capacity of 27, 500 ton/y (Van Berkel et al., 2009). The symbiotic exchanges of energy, water and materials are depicted in Figure 23.

Tables 8 and 9 summarize the quantification of materials and their associated vital actors, reduced waste, the benefits of fossil resources saved and substituted, and economic evaluations of some symbiosis examples in Kawasaki IP.

Table 8. Quantification of some materials of some Industrial Symbiosis examples in Kawasaki

MATERIALS	FROM INDUSTRY	TO INDUSTRY	BENEFIT	REDUCTION OF WASTE (1000*T/Y)	BENEFICIAL APPLICATION	QUANTITY SUBSTITUTED (1000*T/Y)
Mixed plastic waste	Commercial waste collectors	DC Cement	Diverted from incineration	-6.75	Coal substitution	-
Paper sludge	Corelex		Diverted from incineration	16.8	Clay substitution	263
Construction soils,	Commercial waste collectors		Diverted from landfill	-	-	-
Blast furnace (BF) slag	JFE steelworks			315	Clinker (on site)	-
Wastewater treatment plant (WWTP)'s sludge	Kawasaki WWTP		Diverted from incineration	20	Limestone substitution	55
Organic waste	-	-		14.86	-	-
Soot and other combustion residues	Commercial waste collectors	-	Diverted from landfill	0.7	-	-
Mixed plastic waste (~50%packaging+ 50% industrial plastics)	Waste collectors	JFE steelworks	Diverted from	66	Coal substitution	~71.3

Mixed plastic waste (containers and wrapping)	Kawasaki municipality	Show Denko	incineration	37	City gas	~13
Mixed paper wastes	Commercial waste collectors	Corelex		69	Virgin fiber pulp	54.3

Source: Adapted from Van Berkel et al., 2009

Table 9. Economic evaluation of some Industrial Symbiosis examples in Kawasaki

MATERIAL SYMBIOSIS	COMPONENT	ANNUAL AMOUNT (1000*T/Y)	ANNUAL BENEFIT (JPY/Y)
Blast Furnace slag as clinger substitute in cement	Buy granulated BF slag	315	-527
	Replacement of cement	315	957
	Clinger		430
Alternative blast furnace-reducing agent	Acceptance fee for waste plastics	66	4,092
	Replacement of coal for production costs	71.3	4,821
Production of ammonia (NH_4) from waste plastics	Acceptance fee for waste plastics	37	-
	Replacement of city gas as raw material for NH_4 production	18,130 Nm^3/y	3419
Production of form-boards from waste plastics	Acceptance fee for waste plastics	18	-
	Sale income from plywood	12	3,432
	Purchase of virgin polypropylene	2.5	-418

Source: Adapted from Van Berkel et al., 2009

With these IS and industrial and urban symbiosis relationships, it has been possible to obtain numerous benefits. Carbon emission efficiency was improved by 13.77% (Dong et al., 2014), with a total reduction in carbon emissions of 4.26 Mt CO2e (Dong et al., 2014), economic gains of more than 54 million dollars resulting from four symbiotic links related to the iron/steel industry, in which the amount of by-products/waste exchanged is around 500 kton/y (Dong et al., 2013), an economic benefit of 430 MJPY/y due to the use of BF slag as a clinker substitute in cement industry (Dong et al., 2013), a reduction of 6.4% in the physical value of material use (Ohnishi et al., 2017), and a diversion of approximately 565,000 tons of waste from landfill or incineration resulting from seven material swaps (Van Berkel et al., 2009).

5.5.6. Tianjin, China

Quantification of material exchanges was outlined by (Shi et al., 2010) in terms of symbiotic exchanges, which numbered 70 at the time of their analysis. Aggregated mass is presented as tons and cubic meters (m3) of materials and water flows dating from 2006. Figures (28-29) schematically represent those symbiotic exchanges (water, energy and iron–metals products and by-products), while Figure 12 depicts the location of actors of symbiosis on the map.

By 2010, 81 Industrial Symbiosis relationships had been identified, with 1.26 million cubic meters of reclaimed water, 23,193 tons of NovoGro used as fertilizer on farms, vegetable gardens and orchards, more than 12,000 tons of recycled galvanized sheet metal scrap used as moulds and raw materials for car manufacturing, more than 3700 tons of food waste used as raw materials in the production of animal feed, among others (Shi, Chertow & Song, 2010). These industrial symbiotic relationships have achieved environmental, economic, and social benefits. It has been possible to reduce waste disposal in landfill by 250,000 tons (Liu et al., 2018), reduce CO2 emissions by 42,000 tons (Liu et al., 2018), reduce energy consumption by industrial added value by 11% (2011 compared to 2008) (Yu, Dijkema & De Jong, 2015), reduce freshwater consumption and wastewater discharge by 29.2% and 40.1% respectively (Yu, Dijkema & De Jong, 2015), and an economic benefit for the companies involved in the synergies of 3212 thousand US dollars (Liu et al., 2018).

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