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).

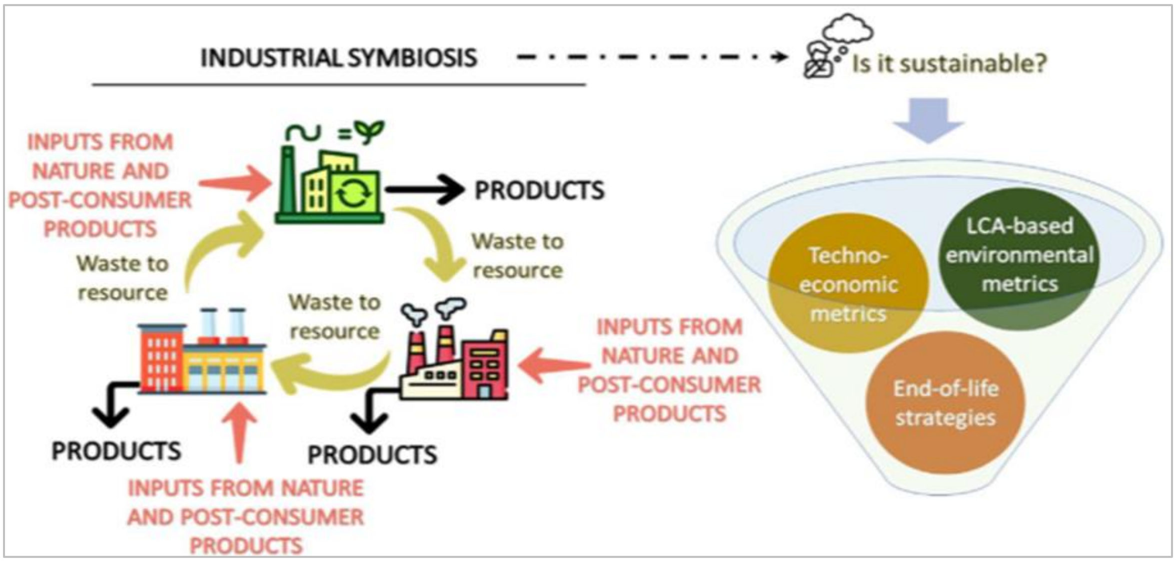
A well-known example of bottom-up synergism is the Kalundborg industrial park in Denmark, which is mainly driven by rational business interests among enterprises. Typical examples of top-down strategic planning are the Kawasaki Ecological Park serving the Keihin Industrial Belt in Japan, the Kokkola 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).

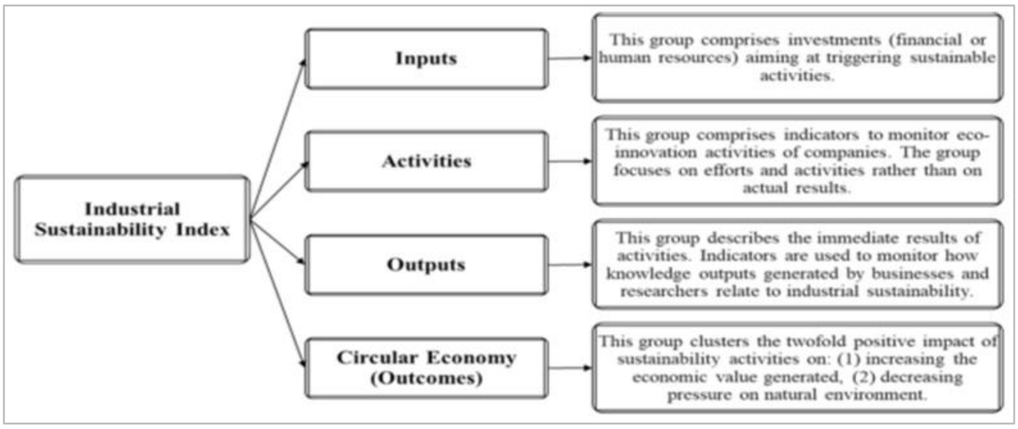
To conclude this section, a brief discussion of IS vulnerability is presented. IS relationships can be vulnerable to disruptive events that reduce the willingness of companies to cooperate in Industrial Symbiosis synergies. Disruptions affecting a given IS relationship may be responsible for creating 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).

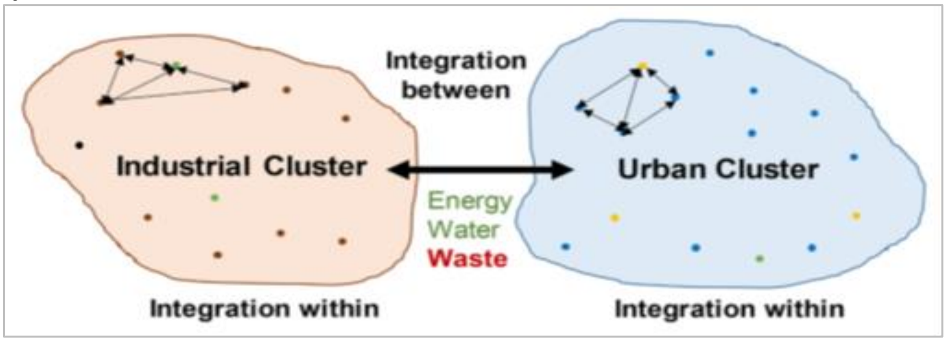
4.2.3. Environmental issues related to the feasibility of Industrial Symbiosis

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.