Optimizing the Future: Management Innovation for a Sustainable World

Eds. Gabriela Proştean
Budapest: Trivent, 2026
eISBN 978-615-7058-33-0
Available online at http://trivent-publishing.eu/

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DOI: 10.22618/TP.SIM2025.005

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Abstract
Industrial Symbiosis (IS) has become a cornerstone of circular economy strategies, particularly in resource- and energy-intensive industries such as pulp and paper. This paper explores how IS contributes to sustainability transitions by analysing European flagship examples and Slovenian case studies. The analysis demonstrates that symbiotic exchanges in the sector are dominated by energy recovery, by-product valorisation, and increasingly, water reuse. Large-scale ecosystems such as Metsä Group's Äänekoski bioproduct mill, which produces 1.3 million tonnes of pulp annually and generates about 240% of its own energy needs, showcase the systemic integration of side streams into bio-industrial hubs. In contrast, smaller-scale Slovenian initiatives highlight innovative municipal–industrial linkages, such as district heating in Sladki Vrh or wastewater reuse in Ljubljana. The study finds that geographic proximity, shared infrastructure, and supportive EU policy frameworks are consistent enablers, while regulatory hurdles and market volatility remain key barriers. Taken together, the cases confirm that pulp and paper mills can act as central anchors in regional symbiosis networks, positioning the sector as a driver of Europe's green transition.

Keywords
Industrial Symbiosis, Circular Economy, Pulp and Paper Industry, By-product Valorisation, Wastewater Reuse, EU Green Deal

I. Introduction

A. Introduction to Industrial Symbiosis

Industrial Symbiosis is a key practice within industrial ecology that seeks to emulate the closed-loop efficiency of natural ecosystems in industrial systems. In essence, IS involves the synergistic exchange of resources – such as waste materials, by-products, energy, and water - between different companies, so that the "waste" from one becomes a resource for another. [1, 2] This collaborative approach shifts industries away from the traditional linear "take-make-dispose" model toward a circular model where the outputs of one process serve as inputs for others. According to Chertow [3, 4], IS engages traditionally separate industries in a collective strategy for competitive advantage by physically exchanging materials, energy, water and/or by-products.

The purpose of this article is to build on that conceptual foundation and explore how IS can be applied in the pulp and paper industry. The article first introduces IS and its conceptual background, then considers how IS can be implemented, reviews case studies, and reflects on both the enabling conditions and barriers that shape these practices. It concludes with lessons for industry, policymakers, and the broader community. In terms of the research question, this article focuses on how pulp and paper mills can act as anchor points of industrial symbiosis, what enabling conditions and barriers shape these practices, and how lessons from flagship international cases can inform smaller-scale national contexts such as Slovenia.

B. Aspects of IS Implementation

For industrial symbiosis to be effective in practice, cooperation and proximity often play a crucial role. When companies operate in the same area, it becomes much easier to exchange resources and set up practical synergies. The role of IS in sustainable industrial ecosystems is, therefore, to close material loops, reduce the use of virgin resources and waste generation, and create an integrated industrial network that enhances both environmental and economic performance. In practice, IS can occur in various configurations – among co-located firms in an eco-industrial park, among companies in a region, or even virtually across wider distances via facilitated exchanges. By turning one firm's waste into another's input, industrial symbiosis helps to transform waste into valuable commodities, contributing directly to a more circular and sustainable economy. [2] This collaborative approach fosters innovation and resource efficiency and strengthens community ties. Local businesses work together to optimise their operations and share the benefits of reduced costs and environmental impact. [2, 5–7]

At its core, industrial symbiosis operates on the principle that "everything has its use", meaning one entity's residual outputs are another's raw materials. Several fundamental principles guide the implementation of IS: resource synergy, mutual benefit, and collaboration. [8] Participating firms identify opportunities where the waste or by-product of one process (such as excess heat, steam, sludge, or chemical by-products) can replace a resource in another process. Establishing these synergies often requires building trust and information-sharing among companies, sometimes facilitated by a third-party broker or through formal networks. Key aspects of implementing IS include mapping resource flows, negotiating exchange agreements, and often making technical or logistical adjustments to enable the reuse of materials or energy streams. [1, 2]

Effective IS can emerge through both self-organised processes and deliberate facilitation. A famous example of a spontaneously developed symbiosis is the Kalundborg Symbiosis in Denmark [9, 10], which is widely regarded as the first full realisation of IS. Beginning in the 1960s and 1970s, through informal conversations among local managers, the Kalundborg network evolved to link an oil refinery, a power plant, a gypsum board facility, a pharmaceutical plant, and the city municipality in a web of exchanges. By the 1980s, these partners were regularly trading by-products and sharing utilities: for instance, the power plant's surplus steam is piped to the pharmaceutical and refinery operations, sludge from a biotech facility is used as fertiliser by nearby farms, fly ash from the power station is used in cement production, and residual yeast from insulin production becomes pig feed. This synergy evolved over decades based on economic logic and trust, without the need for top-down planning, and it was only later, in 1989, that the term "industrial symbiosis" was applied to describe it [11].

Industrial Symbiosis is a key enabler of the European Green Deal's goal of achieving climate neutrality by 2050 through a circular economy, where growth is decoupled from resource use and environmental harm (European Commission, 2021a; Haines & Scheelbeek, 2020). By reusing materials, energy, and by-products across industries, IS contributes directly to waste reduction, resource efficiency, materials security, greenhouse gas reduction, green growth, and innovation (Ashton, Chertow, & Althaf, 2022; Rungruang et al., 2023). The EU actively supports IS through its Circular Economy Action Plan and New Industrial Strategy (European Commission, 2020, 2021b), as well as funding programs such as Horizon 2020 and Horizon Europe, which foster digital platforms, cross-sectoral collaboration, and eco-innovation (Posselt, Haugk, & Bourayou, 2020). Policy measures, including clarifications in waste legislation, aim to facilitate symbiotic exchanges, while stricter landfill bans and rising waste costs are expected further to incentivise adoption (European Commission, 2015). Looking ahead, IS is set to play a central role in industrial decarbonisation, boosting Europe's competitiveness, creating new business opportunities and jobs, and building resilient, sustainable industrial ecosystems aligned with the EU's green and innovation-driven future (Domenech et al., 2019; Baldassarre et al., 2019; de Selliers & Spataru, 2019).

C. Positive and Negative Aspects of Industrial Symbiosis

The positive impacts of industrial symbiosis are significant for the environment, economy, and innovation. By treating waste as a resource, IS significantly reduces the amount of waste sent to landfills and overall pollution. [12, 13] Materials and energy that would otherwise be discarded are continually recycled, thereby lowering the environmental footprint of industrial activities. For example, exchanges of excess energy or materials directly lead to waste diversion and less extraction of virgin resources, contributing to pollution prevention and resource conservation. IS also significantly improves resource efficiency, meaning industries can produce the same output with fewer inputs by harnessing each other's by-products. This increased resource productivity effectively decouples economic growth from resource consumption, a core goal of sustainability. One EU analysis estimated that scaling up industrial symbiosis could save €1.4 billion per year across the EU in raw material and waste management costs and generate an additional €1.6 billion in sales of new products and services. [14] Such economic gains result from reduced disposal costs, savings on raw materials, and sometimes the emergence of new revenue streams (by selling what was once considered waste). Indeed, industrial symbiosis is often touted as a "win-win" strategy that yields both cost savings and environmental benefits for participating firms.

Companies in symbiotic networks can realise direct financial benefits (e.g. cheaper feedstocks, avoided waste fees) while also cutting emissions and energy use by sharing resources. Moreover, the collaborative process of IS can spur innovation: firms must develop creative technical and logistical solutions to utilise unconventional inputs, which can lead to new technologies or products. As firms collaborate (even with competitors), the "coopetition" dynamic can drive them to innovate and improve their processes. [15] IS networks thus often become hotbeds of eco-innovation and knowledge exchange, finding novel ways to repurpose materials. Wider benefits include job creation in the circular economy (through new recycling or reuse enterprises) and enhanced materials security for industries (relying more on recovered materials reduces exposure to volatile raw material markets). [13]

Despite these benefits, several challenges and drawbacks are associated with implementing industrial symbiosis. One major challenge is regulatory barriers. Environmental regulations, while essential for safety and health, can inadvertently hinder IS when, for instance, a valuable by-product is legally classified as "waste" and thus cannot be easily transported or reused without special permits. Complex or unclear waste-handling rules have historically paralysed some resource exchanges. Recognising this, the EU has moved to clarify definitions of by-products and waste regulations to facilitate industrial symbiosis better [16]. Still, navigating compliance remains a hurdle: Companies must ensure that using another's waste meets all safety, quality, and legal standards, which can involve time-consuming approvals. Another set of barriers is economic feasibility. Not all potential synergies are financially viable; the costs of cleaning, processing, or transporting a by-product may outweigh the savings from using it. For IS exchanges to make sense, there must be a net economic benefit or strategic gain.

In some cases, fluctuations in market prices (for raw materials or waste) can suddenly make a previously attractive exchange uneconomical. This ties into the challenge of long-term stability: if one partner in a symbiotic network shuts down or changes its output, the other partners may lose a key resource or outlet, potentially disrupting multiple linked processes. This dependency risk means companies can be hesitant to invest in modifications for symbiosis unless they are confident in their partners' reliability. [16–18]

There are also organisational and social challenges. [2, 17] Establishing symbiosis often requires a high degree of coordination and trust among entities that have no prior collaboration. Information barriers can prevent symbiosis opportunities from even being recognised – companies might simply not know that another nearby facility could use their waste. Overcoming this requires active networking and, sometimes, a facilitator to identify potential matches. Culturally, firms may be reluctant to rely on external partners for critical inputs due to fear of supply disruption, or they may guard proprietary information about their waste streams. Additionally, aligning the timing and quantity of exchanges can be complex: production processes must be synchronised to supply and receive the materials or energy in question consistently. Technical barriers can arise if waste material is not immediately suitable as an input and requires research and development (R&D) to repurpose it. Indeed, researchers categorise IS barriers as technical, economic, informational, regulatory, organisational, and even motivational. [17] For example, a lack of internal management support or the "not-invented-here" mentality can stymie cooperative efforts. Investment costs for necessary infrastructure (like pipelines for steam or water, storage facilities for materials) can be high upfront, posing a barrier, especially for small and medium enterprises. Finally, there may be cases of uneven benefit distribution – if one company gains significantly more than another from the exchange, it could lead to tensions in maintaining the collaboration. Thus, while industrial symbiosis carries tremendous upside, realising those gains requires overcoming a suite of regulatory, economic, and social challenges. Addressing these through supportive policies, facilitation, and good business planning is crucial to unlocking IS's full potential. [2, 19]

D. Industrial Symbiosis in the Papermaking Industry

Industrial Symbiosis has significant potential to enhance sustainability and improve resource efficiency in the paper and board industries. These industries are increasingly adopting IS practices, as demonstrated by specific examples of successful collaboration and resource maximisation. For instance, many paper mills have established networks with nearby companies to reuse cellulose fibres that were previously considered waste by reintegrating those fibres back into their production processes. This cycle of resource recovery supports a circular approach to manufacturing, enhancing overall sustainability [20].

Another notable implementation of industrial symbiosis is the diversion of sludge produced during the papermaking process. Research indicates that sludge can often be repurposed or processed into alternative materials, such as bioenergy or compost, through partnerships with firms in different sectors, including agriculture and energy production [21]. The ability to convert waste into valuable products helps mitigate reliance on landfills, improve economic performance, and foster collaboration across industries.

The packaging sector within the paper industry is also witnessing the adoption of industrial symbiosis practices. Companies in this sector are increasingly collaborating with waste management firms to develop closed-loop systems that collect, recycle, and reintegrate discarded packaging materials into new production cycles. Through these practices, companies minimise their environmental impact and leverage the economic benefits of resource recovery [22, 23]. The European Union's push towards recycling and sustainability initiatives has further accelerated this trend, promoting the establishment of networks among various stakeholders.

Additionally, IS in the paper and board sectors benefits from technological advancements that facilitate data-sharing and optimise resource flow management. Digital platforms enable firms to monitor waste streams and connect with potential partners for resource exchange, streamlining the processes inherent in IS practices [24]. This technological integration supports more effective collaboration and enhances the efficiency of industrial symbiosis initiatives within the industry. [25]

However, challenges remain in promoting greater adoption of industrial symbiosis across the paper and board industries. Despite the recognised benefits, knowledge gaps persist, particularly among small and medium-sized enterprises (SMEs) that may lack the resources or expertise to engage in symbiotic practices. Furthermore, regulatory frameworks may not always encourage collaborative efforts, suggesting the need for more supportive policies to enhance IS initiatives [26].

Public awareness and education play crucial roles in overcoming these barriers. Engaging stakeholders in educational initiatives that emphasise the importance and benefits of IS can help inspire action and collaboration. This can include workshops, training programs, and partnerships with academic institutions focused on fostering innovation within IS frameworks. [27]

E. Current Implementation of Industrial Symbiosis in the Slovenian Papermaking Industry

In Slovenia, the paper and board industry is beginning to recognise the benefits of industrial symbiosis as a strategy for enhancing sustainability and resource efficiency. Various initiatives and collaborations among companies indicate a positive shift toward implementing IS principles, yet significant potential for further development remains.

One notable implementation of industrial symbiosis in Slovenia can be found within the framework of local forestry and paper production. Slovenia, being one of the most forested countries in the European Union, has an abundance of biomass resources that can be utilised to produce paper and board products. Companies in the paper sector have collaborated with local sawmills and forestry companies to repurpose wood residues and by-products as raw materials for paper production. This collaboration reduces waste and enhances the sustainability of the supply chain by minimising the reliance on virgin fibres. The effective integration of waste from wood processing industries promotes a circular economy approach, where materials are reused rather than discarded. [28]

Moreover, the Slovenian government has initiated several programs to promote sustainable practices in the paper industry. These initiatives have encouraged the establishment of eco-industrial parks, where businesses can engage in symbiotic relationships. For example, cooperation between paper mills and recycling facilities enables the recycling of old paper and cardboard products, which are then transformed into pulp for new paper production. This practice reflects the core IS principle of turning waste from one process into a resource for another, thereby minimising environmental impacts and fostering resource recovery. [29]

The city of Celje has also emerged as a hub for industrial symbiosis within the paper industry, with several firms collaborating to share resources such as water and energy. Local paper mills have begun using treated wastewater from municipal treatment plants in their production processes. This exchange not only conserves fresh water resources but also highlights the potential for municipal-industrial collaborations that enhance sustainability in local economies. [30]

Nevertheless, several obstacles still impede the broader application of industrial symbiosis in Slovenia's paper and board industry. One significant barrier is the limited awareness of IS benefits among small and medium-sized enterprises (SMEs) in the industry. Many SMEs may lack the necessary knowledge and resources to explore collaborative opportunities [31]. Encouraging educational initiatives and providing guidance on implementing IS practices can empower these businesses to engage more actively in symbiotic relationships.

Moreover, regulatory and infrastructural challenges may hinder the establishment of efficient Industrial Symbiosis networks. For industrial symbiosis to flourish, comprehensive policies that incentivise resource sharing and collaboration among enterprises are essential. This necessitates a supportive framework that encourages organisations to minimise waste and optimise resource use while effectively addressing the complexities of forming partnerships. [32]

II. Case-Based Evidence of Industrial Symbiosis in the Pulp and Paper Sector

The pulp and paper industry is among Europe's most resource-intensive sectors, with high water and energy demands, and significant by-product streams, including sludge, bark, and ash. [33] These very features make it fertile ground for Industrial Symbiosis. By transforming unavoidable residues into new resources and linking mills to municipal or cross-sectoral partners, the sector has produced some of the most notable examples of symbiosis worldwide. [34]

This section draws on international flagship cases and a series of Slovenian examples. The aim is not to compile an exhaustive catalogue but to highlight characteristic modes of collaboration and to identify enabling conditions as well as persistent barriers. The exchanges were analysed across materials, energy, water, chemicals, and utilities, with each case mapped by governance, partner composition, and maturity level. While the majority of IS case studies originate in Europe, forest-based clusters in South America also demonstrate strong potential for circular integration. [35]

A. Large-Scale Industrial Ecosystems

In Northern and Western Europe, large pulp and paper companies have leveraged scale, infrastructure, and policy support to build extensive industrial ecosystems.

Metsä Group – Äänekoski Bioproduct Mill (Finland): A flagship bio-industrial hub where pulp production anchors a wider network of energy generation, chemical recovery, textile fibres, biogas, and fertilisers. The mill produces 1.3 million tonnes of pulp annually and generates about 240% of its own electricity needs, exporting roughly 1,000 GWh of electricity and 600 GWh of steam to external users. By-products include 46,000 tonnes of tall oil, 3,200 tonnes of turpentine, and 500 GWh of biofuels annually, and attracts on-site partners that valorise side streams. [7, 23, 36, 37]

UPM – Kaukas Integrated Site (Finland): A cluster combining a pulp and paper mill, sawmill, biorefinery, and CHP plant. Shared steam, electricity, bark, and black liquor flows illustrate deep resource integration, reinforced by UPM's corporate diversification into bio-based products. [7, 23, 38]

Stora Enso – Maxau Heat-to-City (Germany): A paper mill that pipes surplus biomass-based heat into Karlsruhe's district heating network, providing renewable energy to homes and public buildings. [7, 23, 39]

SCA Cluster Sites (Sweden): At Munksund, Obbola, and Östrand, SCA links pulp and paper mills with sawmills and cities, exchanging biomass, bark, and steam. Surplus heat supports municipal district heating. [7, 40, 41]

Kuusankoski/Kymijoki District (Finland): A historical eco-industrial network where mills and nearby companies share utilities, infrastructure, and by-products, creating a regional symbiosis model. [7, 42]

Santa Catarina Clusters (Brazil): A forest-based cluster where mills, sawmills, and thermoelectric plants burn wood residues and black liquor to generate renewable electricity for both industrial and municipal use. [35]

These cases show how industrial symbiosis becomes systemic when mills are embedded in wider industrial ecosystems, supported by scale and infrastructure such as CHP and district heating.

B. Mill-Level Circular Innovations

Beyond large ecosystems, several mills have pioneered specific circular practices that demonstrate replicability at smaller scales.

DS Smith – Kemsley (UK): The UK's largest recycled paper mill processes hard-to-recycle rejects, separating plastics and contaminants from fibre to boost recycling rates. CHP provides integrated energy. [43]

DS Smith – Lucca (Italy): Operates a fibre–plastic separation line that recovers usable fibres from mixed rejects while diverting plastics to recycling or energy recovery[44]

International Paper – Closed-Loop Packaging: Collects used corrugated boxes from customers, repulps them, and converts them into new packaging, closing the loop on fibre flows. [45]

Copelme S.A. (Bolivia): A pilot project exploring anaerobic digestion of wastewater sludge to produce renewable biogas for mill operations, cutting both emissions and fuel costs. [46]

These innovations highlight how even single-site mills can advance IS by valorising side streams, closing loops, and investing in recovery technologies.

C. Slovenian Cases

In Slovenia, symbiosis occurs at a smaller scale but provides distinctive models of municipal–industrial integration and cross-sector valorisation.

Paloma (Sladki Vrh): Operates a cogeneration plant that supplies both the mill and local households with heat, reinforcing the role of mills as pillars of community energy security. The district heating for Sladki Vrh and Vranji Vrh is supplied from Paloma’s on-site boiler house with a 626 kW heat / 527 kW power CHP unit and a 1,500 kW peak hot-water boiler. The local DH network shows an average seasonal heat offtake of about 1,890 MWh, with 3,300 m of mains and 3,421 kW of connected capacity. [47–50]

Papirnica Vevče (Ljubljana): Pioneered integration of treated municipal wastewater into its production process, reducing freshwater extraction while easing the burden on public treatment systems. The on-site industrial WWTP treats approximately 800,000 m^3 of process wastewater per year (≈400 Olympic pools), meeting legal discharge parameters before release to the Ljubljanica. [51–53]

Papirnica Goričane (Medvode): Built a biological wastewater treatment plant, creating future opportunities for water reuse and sludge valorisation. In recent years, total freshwater use has been on the order of 1.3–1.4 million m^3/year (e.g., 1.294 million m^3 in 2024), with electricity consumption around 51,000–54,000 MWh/year and paper sludge generation fluctuating between 750 and 1,934 t/year. [54–56]

Radeče Papir Nova: Specialises in recycled paper pulp and has invested in reducing water, energy, and chemical consumption, showing gradual progress toward circular practices. [57]

VIPAP Videm Krško – PaperChain Project: Under the EU-funded PaperChain initiative, tested the use of paper deinking sludge in road construction, linking the pulp and paper sector with civil engineering. At full operation the mill has produced about 210,000 t/year of paper, generating large residue streams typical of deinking lines—approximately 67,000 t/year of deinking paper sludge (DPS) and 25,000 t/year of deinking paper sludge ash (DPSA)—which PaperChain targeted for replacement of virgin backfill in a ~70 m railway section using 15 cm compacted layers. [7, 58–62]

Although modest compared to Nordic flagships, these Slovenian cases illustrate highly replicable pathways, especially in municipal–industrial cooperation and cross-sector material valorisation. [25]

D. Comparative Overview of Industrial Symbiosis Initiatives

Table 1 presents a cross-case comparison of industrial symbiosis initiatives in the pulp and paper sector. The table classifies each case according to its primary exchange dimensions, ranging from raw material supply and processing to energy integration, water reuse, by-product valorisation, and cross-sector linkages. The use of filled (●) and open (○) markers allows for a quick overview of which domains are most actively developed in each case.

Table 1. Process Flow of Industrial Symbiosis in the Pulp & Paper Sector

Case Study (Country)	Raw Material Supply & Processing	Energy Integration (CHP, Heat, Power)	Water Reuse / Treatment	By-product Valorisation (Materials, Chemicals)	Cross-sector Linkages (Municipal/ Constructi-on/etc.)
Metsä Äänekoski Bioproduct Mill (Finland)	●	●	●	●	●
UPM Kaukas Integrated Site (Finland)	●	●	○	●	●
Stora Enso Maxau (Germany)	○	●	○	●	●
SCA Sites – Munksund, Obbola, Östrand (Sweden)	○	●	○	●	●
Kuusankoski/Kymijoki Cluster (Finland)	○	●	○	●	●
Santa Catarina Forest Cluster (Brazil)	●	●	○	●	●
DS Smith Kemsley (UK)	○	●	○	●	○
DS Smith Lucca (Italy)	○	●	○	●	○
International Paper (Closed-loop Packaging, USA/Europe)	●	●	○	●	○

Copelme S.A. (Bolivia)	○	● (biogas from sludge)	●	●	○
Paloma (Slovenia)	○	● (district heating)	○	○	●
Papirnica Vevče (Slovenia)	○	● (heat recovery)	● (municipal waste water reuse)	○	●
Papirnica Goričane (Slovenia)	○	○	● (biological wastewate r treatment)	○	○
Radeče Papir Nova (Slovenia)	● (recycled paper)	○	● (water/ energy savings)	○	○
VIPAP PaperChain (Slovenia)	○	○	○	● (sludge to constructi-on)	●
DS Smith Slovenia (Slovenia)	○	●	○	● (fibre recovery, recycling)	○

Legend:

- ● = strong/active contribution
- ○ = limited/indirect contribution

Table 1 shows that energy integration and by-product valorisation are the most consistently developed symbiosis exchanges across cases, particularly in Nordic ecosystems. In contrast, Slovenian mills demonstrate more modest but highly replicable linkages with municipalities, such as district heating and wastewater reuse. For example, Äänekoski exports more than 1,500 GWh of surplus energy each year, whereas Slovenian mills like Paloma focus on district heating at the municipal scale. This contrast illustrates how scale directly influences the type and magnitude of exchanges. On the Slovenian side, Vevče's ~800,000 m^3/year of treated process water and Goričane's ~1.3 million m^3/year of freshwater intake underscore that water management is the primary lever. Paloma's ~1.9 GWh/season district heating demand, by contrast, highlights community-scale heat integration rather than large energy exports.

E. Cross-Case Synthesis: Success Factors and Barriers

Examining the European and Slovenian cases, several success factors consistently emerge that help explain why certain industrial symbiosis initiatives thrive while others falter. The most obvious is geographic proximity. Mills embedded in industrial clusters or situated near cities benefit from the reduced costs and technical feasibility of exchanging energy, water, or materials. This explains why large complexes, such as Äänekoski in Finland or Kaukas in Lappeenranta, can integrate multiple facilities into a single functioning ecosystem, while Slovenian mills like Paloma and Vevče link directly to nearby municipal infrastructures. Without physical closeness, many of these exchanges would be unviable, particularly for heat and wastewater.

Another recurring factor is shared infrastructure and mutual economic benefits. Combined heat and power plants, wastewater treatment facilities, and transport pipelines all create opportunities for collaboration. These infrastructures only generate long-term value when partners see clear financial gains, whether through avoided costs, new revenue streams, or more secure supply chains. Paloma's ability to sell heat, Vevče's reduction of gas purchases, and Metsä's transformation of by-products into marketable products all illustrate that symbiosis succeeds when the economic case is evident for all sides. Projects without a compelling financial rationale, on the other hand, tend to remain pilot studies or collapse once external funding is withdrawn.

A third enabling condition is the role of champions and governance structures. Some of the most ambitious examples, such as Äänekoski or the PaperChain project, were made possible because corporate leaders or EU-funded consortia actively drove the process, reducing uncertainty and aligning diverse interests. In smaller-scale Slovenian cases, this role was often played by municipalities or external project partners who acted as facilitators. Strong governance reduces the "first-mover" risk that typically deters companies from experimenting with new forms of collaboration.

Supportive policies and regulatory frameworks also play a decisive role. The distinction between waste and by-product is a recurring bottleneck: whether sludge can be used in construction or whether treated wastewater can be reused depends not only on technical feasibility but also on legal classification. Where regulation is flexible and aligned with the objectives of a circular economy, projects move forward more easily. Conversely, rigid or unclear rules remain one of the most cited barriers, particularly in Slovenia, where smaller mills struggle to navigate regulatory requirements.

At the same time, the cases highlight a range of persistent barriers. Economic and market risks are among the most significant. High upfront investment, uncertain payback periods, and volatile secondary material markets all discourage participation, especially among small and medium-sized mills that lack the capital reserves of larger Nordic companies. For small and medium-sized enterprises (SMEs), these constraints are particularly acute. Limited financial capacity, restricted access to expertise, and regulatory burdens mean that many SMEs cannot engage in industrial symbiosis without targeted support. Unlike large Nordic corporations, which can absorb infrastructure costs and risks, SMEs require tailored incentives, cooperative platforms, and technical assistance to make symbiosis viable. Organisational and cultural barriers also surface: companies are often reluctant to share sensitive data or depend on external partners, preferring self-sufficiency over collaboration. This is especially true in continuous processing industries, such as papermaking, where reliability is non-negotiable. If a symbiotic input cannot guarantee consistent quality and supply, mills are unlikely to take the risk. [35]

Finally, logistics and distance remain hard constraints. Heat cannot travel far without major losses, and transporting bulky or wet residues quickly erodes any economic advantage. Successful cases, therefore, tend to be hyper-local, reinforcing the importance of clustering and co-location. [35]

In summary, the comparative analysis reveals that while flagship ecosystems in Northern Europe benefit from scale, infrastructure, and corporate strategy, the Slovenian cases demonstrate the potential of municipal–industrial linkages and cross-sector valorisation in smaller economies. The conditions for success are clear and remarkably consistent across various contexts: proximity, infrastructure, economic benefits, governance, supportive policies, and trust. However, the barriers—regulatory complexity, economic risk, organisational inertia, and logistical limits—remain stubborn obstacles. Overcoming these challenges will require not only technological innovation but also regulatory reform, facilitation platforms, and a cultural shift toward collaboration and teamwork.

Figure 1 provides a comparative overview of the industrial symbiosis cases analysed, showing the distribution of exchange types (materials, energy, water, chemicals) across mills and clusters. The visualisation highlights that energy and material exchanges dominate the pulp and paper sector, with some flagship mills exporting more than 1,000 GWh of surplus energy annually. By contrast, water reuse and chemical recovery remain emerging areas, concentrated in large biorefinery projects such as Äänekoski and often requiring greater technological investment. Slovenian mills, meanwhile, manage water flows on the order of 10^5–10^6 m^3 per year, reflecting their focus on community-scale symbiosis rather than large-scale energy exports.

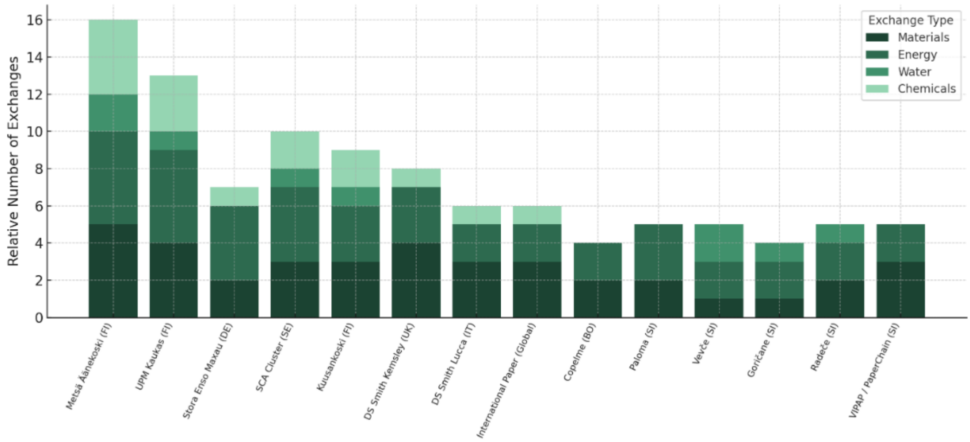

Fig. 1. Case Studies by Exchange Type

F. Recommendations

Drawing on international and Slovenian case studies, several recommendations can guide industry, policymakers, and researchers in strengthening industrial symbiosis, particularly in the pulp and paper sector.

For industry:

Start by mapping what goes in and out of production — from energy and water to waste streams and by-products. Very often, what appears to be "waste" can become a valuable input for a neighbor.

Build closer ties with municipalities and local businesses. District heating, wastewater treatment, or reusing sludge are all areas where cooperation can cut costs and reduce environmental burdens.

Pilot small projects first. Demonstrating exchanges such as water reuse or fiber recovery can work in practice, help to build trust and open the door to larger collaborations.

For policymakers:

- Simplify the rules around waste and by-products. Clear and consistent regulation reduces hesitation and makes companies more confident about trying new exchanges.
- Offer incentives that reward circular practices — for example, tax breaks, lower landfill fees, or dedicated funding for eco-industrial parks.
- Create spaces where companies from various sectors can meet, share information, and explore new opportunities for collaboration.

For researchers and facilitators:

- Develop tools and platforms that make it easier to match companies with complementary resource needs.
- Share good practices from pioneering projects, such as Kalundborg, but adapt them to the realities of local industries and communities.

- Keep track of IS initiatives over time and measure their impact, so that the benefits are visible and can be used to encourage further action.

For Slovenia in particular:

- Use smaller pulp and paper mills as hubs for collaboration. When connected with agriculture, energy providers, or local utilities, they can anchor regional symbiosis networks.
- Encourage clustering of companies in key regions to bring partners physically closer together and reduce the costs of exchange.
- Frame IS as part of Slovenia's larger shift toward a circular bioeconomy, positioning it as both an economic opportunity and an environmental necessity.

Taken together, these recommendations suggest that industrial symbiosis is not just a technical fix but a way of working differently — one that relies on trust, cooperation, and a willingness to see waste as a resource. If these conditions are met, the pulp and paper sector in Slovenia, and elsewhere, can play a leading role in building a more circular and sustainable economy.

III. Conclusion

The evidence from European and Slovenian pulp and paper mills underscores the sector's crucial role in advancing industrial symbiosis as part of the broader circular and low-carbon transition. Traditionally viewed as a resource-intensive industry, pulp and paper is increasingly turning its challenges into opportunities - exchanging energy, reusing water, and finding new value in by-products.

Flagship bioproduct mills in Northern Europe, such as Metsä Äänekoski and UPM Kaukas, demonstrate what can be achieved when scale, corporate strategy, and infrastructure align. The Äänekoski site alone produces over 1.3 million tonnes of pulp per year and exports around 1,600 GWh of surplus energy to regional grids. These sites have evolved into regional innovation hubs, linking pulp production with energy, chemical recovery, textile fibres, and fertilisers. At the same time, Slovenian cases remind us that industrial symbiosis is not limited to large-scale projects. Paloma, Papirnica Vevče, and VIPAP demonstrate that smaller mills, when working closely with municipalities and partners, can also deliver meaningful innovations —such as cogeneration for community heating, water reuse, and road-building materials derived from paper sludge.

Across all these examples, some common threads stand out: proximity and cooperation, strong governance, and the role of pilot projects in lowering financial risks. At the same time, persistent challenges remain, especially around restrictive waste regulations, volatile secondary markets, and the limited resources of smaller mills. These barriers highlight the importance of policy frameworks that can adapt, incentivise collaboration, and provide support for small and medium-sized enterprises.

Looking ahead, the pulp and paper industry has the chance to define itself not only as a producer of fibre, but also as an anchor of local industrial communities and a driver of circular innovation. By embedding IS practices into large bioproduct clusters and smaller regional networks, the sector can make a tangible contribution to the goals of the European Green Deal: improving resource efficiency, achieving carbon neutrality, and building climate resilience.

Ultimately, this study demonstrates that industrial symbiosis in the pulp and paper sector is not an abstract concept, but a practical pathway that is already delivering results. With the right support and wider adoption, it can transform the industry's role in shaping a more sustainable and resilient future for Europe and beyond.

Acknowledgements

This work was supported by the Erasmus+ project FReINDS – Future-ready Industries: Smart, sustainable, and circular resource management through Industrial Symbiosis (Project No. 2024-1-NO01-KA220-HED-000246621, 2024–2026) and the Erasmus+ project SymbioTech – The European Alliance for Advancing Circular Economy via Industrial Digital Symbiosis (Project No. 101186405, 2024–2027).

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