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Review Article

Industrial symbiosis practices: A case study of Türkiye and Denmark

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ABSTRACT

Industrial symbiosis (IS) is a collaborative strategy where companies share services and physical resources. This promotes resource efficiency and reduces the environmental impact of industrial activities within a network. IS offers numerous benefits, including: (1) reduced greenhouse gas emissions through energy savings, process improvements, and fuel substitution, (2) lower energy costs, (3) less waste sent to landfills, (4) decreased use of virgin materials, (5) minimized transport and logistics costs, (6) lower environmental impact, (7) reduced pollution, (8) decreased water consumption, (9) reduced hazardous waste, (10) economic benefits from waste valorization (adding value), (11) easier compliance with environmental regulations. Consuming large amounts of resources (raw materials, water, electricity, etc.) and generating significant solid, liquid, and gaseous waste, industries in Türkiye and Denmark have increasingly adopted IS to optimize their systems and address sustainability concerns. Concerted efforts over the last decade have advanced IS practices, particularly in process sectors such as chemicals and manufacturing. This study aims to shed light on the current implementation of sustainable practices within the industrial landscapes of these two countries, focusing on key IS initiatives.

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INTRODUCTION

Driven by the use of, among others, conventional energy sources, our planet's health has gradually deteriorated. The modern world now faces many problems arising from past unsustainable practices. One major challenge is the energy crisis, where non-renewable energy sources will be depleted in the coming decades. This will lead to rising energy prices, disrupting the global market and making it difficult for low-income populations to afford it. These are just a few of the challenges facing the modern world [1]. The current situation was the reason for concluding the 2030 Agenda for Sustainable Development (2015) by United Nations (UN). The document presents the 17 Sustainable Development Goals (SDGs) (Fig. 1) and 169 targets to be met by 2030 by the Member States. Agenda is a plan that implements actions for people, planet, and prosperity. It also focuses on cooperation between countries and spreading peace efforts around the world. UN adds that by following the three pillars of sustainable development (social, economic, environmental), human life and the health of our planet will significantly improve [2]. Industrial symbiosis (IS), which focuses on the flows and networks among industrial organizations and aims to build synergistic solutions among resource users and contribute to responsible production and consumption, is an integral part of Sustainable Development Goal 12 under the heading "Responsible Production and Consumption" that promotes resource efficiency and sustainable industrial infrastructure [3].

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Figure 1. The SDGs [4].

IS is a collaborative and sustainable methodology that brings together multiple sectors and businesses to maximise resource use, minimise waste and improve overall economic and environmental outcomes. The idea emphasises the interconnectedness of industrial processes, the partnership here being biologically derived from the term 'symbiosis', creating a system where the by-products of one entity become useful inputs for another, reducing environmental impact and advancing circular economy ideas.

IS could be defined as a situation when the waste or residuals of one entity are transferred to another for utilization in production processes. It is achieved through collaboration between entities for mutual economic and environmental benefits through the exchange of by-products [5]. IS, which is a well-known process, attempts to minimize energy losses by establishing an interconnected network in which materials are constantly circulated. The primary goal is to reduce the negative environmental impact while limiting raw material extraction. It also reduces the growing need for landfill waste disposal. The key principle of IS (Fig. 2) is the physical exchange of materials, energy, and water between two or more companies, turning what is normally seen as waste into a resource.

Ehrenfeld and Gertler [6] have described the Kalundborg IS in Denmark as one of the most prominent cases. This case study illustrates how symbiotic relationships can lead to the effective use of resources and the elimination of waste by examining the growing interdependence between companies in the Kalundborg region. Around the world, efforts of a similar nature have been modeled after the Kalundborg IS.

Boons and Roome [7] look at the link between learning and sustainable development within the broader framework of sustainable development. Although not exclusively focused on IS, their research provides a conceptual structure for understanding the role of education in cultivating sustainable behavior—an idea essential for the implementation of IS projects.

Chertow's [8] research, which provides a thorough overview of IS and insights into its literature and taxonomy, is a seminal work on the subject. The study highlights the essential components of symbiotic relationships, emphasizing the sharing of resources and energy between industries to create partnerships that benefit all parties. The author emphasizes how IS can reduce resource depletion and environmental degradation, which can support sustainable growth.

Symeou and Rossos [9] conducted a thorough literature analysis to analyze the incorporation of IS into planning frameworks and to understand its formation in urban and regional planning. Their study highlights the importance of government support and strategic planning while shedding light on the opportunities and difficulties of integrating IS concepts into broader sustainability initiatives.

These references offer a comprehensive overview of IS, including theoretical foundations, real-world applications, and contributions to sustainable development.

Over the last few decades, the negative environmental impacts of increased urbanisation and industrialization, as well as the intensive use of land and natural resources, have led to a growing interest in the concepts of IS and energy efficiency

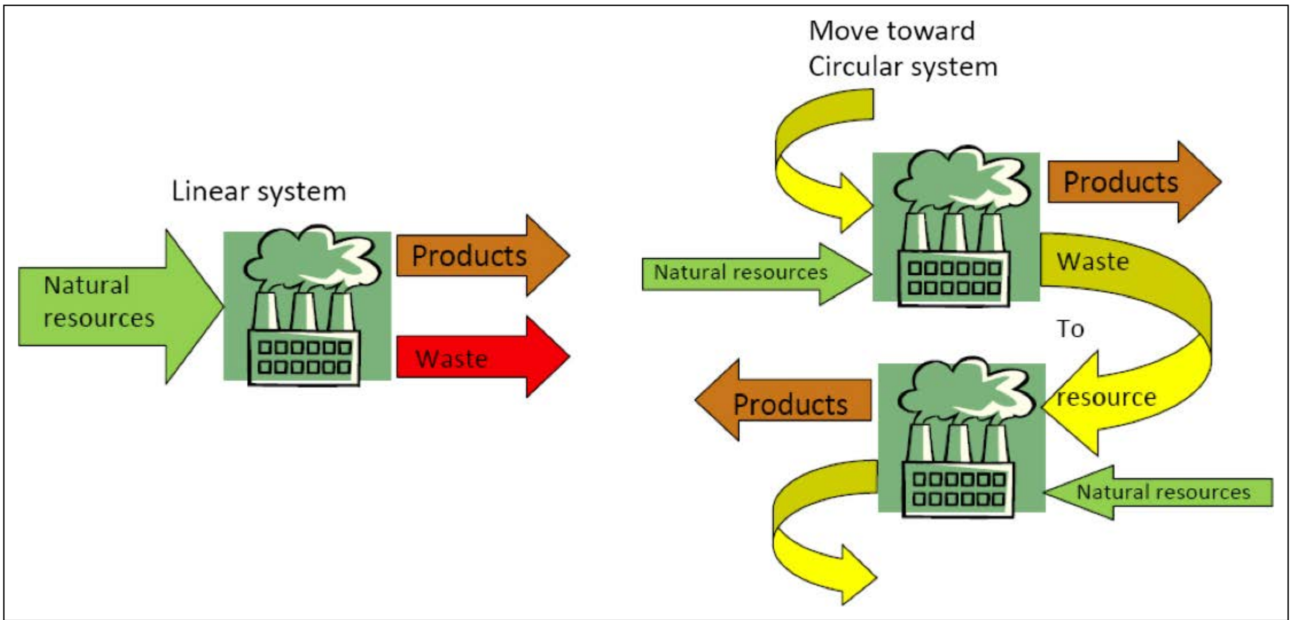

Figure 2. The scheme of IS [11].

and their potential in terms of environmental, economic, and social aspects. Energy-intensive industries are eager to introduce measures to reduce their energy and resource consumption. Smart waste management and efficient water recycling are important complementary measures to improve the efficiency and reduce the environmental impact of production processes. Although IS and energy efficiency case studies have increased over the past decades [10], this trend has only recently increased due to the attention and commitment to sustainability regarding energy consumption. high quality and increasing waste/by-product production [1].

IS is a circular economy strategy (Fig. 2) in which the waste and residues of one or more companies become the resource inputs of another company. It is often found in industrial parks that foster innovation and business collaboration. Municipalities can support the growth of IS, thereby contributing to the achievement of carbon reduction goals and reducing resource needs. At the same time, cities can attract businesses, create jobs, increase tax revenue, reduce waste management costs, and promote themselves through IS [5].

The joint sharing of resources such as energy, material by-products, waste, and water is the focus of IS [10]. Economic and environmental benefits have been central concepts of IS [12] since its inception. According to the widely accepted definition of IS, the economic, environmental, and social benefits arising from the exchange of materials and other shared resource flows between and within industries are numerous [13].

Ensuring prosperity in both developed and developing countries requires a comprehensive approach that integrates social, environmental, and economic development. This integration, exemplified by the concept of sustainable development, is increasingly prioritized, particularly in developed nations. IS is emerging as a crucial approach contributing to sustainable development, highlighting the social and economic impacts of environmental progress. IS not only addresses industry-related environmental issues but also yields economic and social benefits. Through fostering partnerships, IS promotes cooperation and teamwork, enhancing both environmental and economic performance. This collaborative approach, known as co-production, not only improves environmental sustainability but also enhances competitiveness. Thus, IS stands as one of the most effective practices in addressing contemporary issues such as "resource efficiency, conservation of natural resources, and environmental awareness" [14].

The eco-industrial park concept is a novel and sustainable approach to industrial growth, aiming to integrate social, economic, and environmental concerns. These parks are designed to encourage collaboration amongst sectors that share a site in order to reduce waste, improve resource efficiency, and decrease environmental impact. Important features of eco-industrial parks include the formation of circular material flows, shared infrastructure, and the exchange of materials and energy. The concept aligns with the principles of industrial ecology by highlighting the interconnectedness and interdependence of industrial systems.

IS, the subject of important studies in the literature, has been applied in various countries and sectors and social, economic and environmental contributions have been obtained. Studies on the development of IS have been carried out in specific sectors, such as chemicals [15] and energy-intensive production [16], and in various countries, such as Brazil [17], China [18] and Portugal [19]. Most of the IS practices around the world involve (i) reduction of water consumption, (ii) recovery and treatment of wastewater, (iii) reduction of waste and use of waste as raw material, and (iv) waste to energy and use of waste heat from various processes for heating purposes. Examples of important applications in related areas [20–24] are given in Table 1.

Table 1. Some important examples about IS activities

Country	Sector	IS activities	Reference
France	Biorefinery	Energy and material recovery from water, district heating	[20]
Italy	Tannery industries	Establishing shared facilities among similar firms, such as wastewater treatment, energy and material recovery, waste minimization, and biogas plants.	[21]
Mexico	Petrochemical	Major infrastructure (wastewater treatment and material recovery)	[22]
South Korea	Petrochemical, chemical, and metallurgical	Energy and material recovery from water and use of reclaimed water through shared reclamation plant	[23]
Tanzania	Farming, ethanol distillery, energy	Partnership for the production of raw materials from waste, material recovery, waste minimisation and service network sharing and optimisation	[24]

In addition to important examples from around the world, this study aims to compare two countries with different characteristics. These countries are Denmark, which is known for its IS applications, and Türkiye, which has a high potential. The choice of Denmark and Türkiye as focal points for IS in this manuscript stems from a nuanced consideration of various factors that promise a rich and comprehensive exploration. Denmark, known for its advanced sustainability practices and commitment to renewable energy, offers a compelling case study of IS in a highly developed and environmentally conscious context. On the other hand, Türkiye, with its burgeoning economy and diverse industrial landscape, provides a fascinating contrast and an opportunity to examine the applicability and adaptability of symbiotic practices in a dynamic and emerging market. The geographical and economic differences between Denmark and Türkiye provide a unique lens through which to analyze the impact of IS in regions with different challenges and opportunities. Furthermore, the different regulatory frameworks, environmental challenges and cultural contexts in these countries contribute to a holistic understanding of the complex interplay between industry, environment and policy. By selecting Denmark and Türkiye, this manuscript aims to provide insights that are not only locally relevant but also globally significant, contributing to the broader discourse on sustainable industrial practices and circular economies.

INDUSTRIAL SYMBIOSIS PRACTICES IN TÜRKİYE

Türkiye's industrial sectors are becoming increasingly aware of the value of IS in improving resource efficiency and sustainability. The nation has shown a growing interest in promoting symbiotic practices.

The development of eco-industrial parks, where different sectors co-locate to share resources, reduce waste, and reap benefits, is a notable project. The Turkish government has been exploring frameworks and regulations to promote the adoption of IS techniques, although these are not project specific.

An important project in Türkiye that aims to create synergies between sectors in the thrace region is the TR21 Thrace Region IS Project. The initiative aims to improve overall sustainability, minimise waste, and maximise resource utilisation by promoting IS. This initiative is expected to involve cooperation between regional companies, governmental organisations, and possibly even foreign partners.

Similarly, the Antalya Organized Industrial Zone IS and Eco-Efficiency Project focuses on promoting IS and eco-efficient practices within the Antalya region. The project strives to optimise resource utilisation, minimise waste, and improve the environmental performance of industries in the region.

Some of the main IS practices in Türkiye are presented in the subtitles of this section.

Çukurova Region

A feasibility study was carried out for biogas and energy production from corn, chicken, and cattle wastes in the Çukurova region. Waste characterization analyses and biochemical methane potential tests were carried out on the wastes collected from the region and the alternative mixtures of these wastes at different rates. It has been shown that, based on the scenario of establishing a facility with an installed capacity of 1 MW, approximately 5.500 tons of high-added-value organic fertilizer can be obtained annually, as well as approximately 9 million kilowatt-hours of energy from a total of 41.000 tons of agricultural and animal waste [25].

Sütaş Group

One of the most important IS practices in Türkiye is carried out by Sütaş. Animal and vegetable wastes are collected and converted into electrical energy at Enfaş's biogas facilities before being transferred to the grid and used in production facilities. The procedure does not end with the processing and utilization of this waste. Hot water and steam, which are wastes generated by energy plants during waste processing, are also evaluated and used in Sütaş factories. In addition to farm animal waste, Enfaş uses returned products, feed, and organic waste from factories in the production of electricity, hot water, and steam. Furthermore, solid, and liquid fermented products produced in biogas plants are reused as solid and liquid fermented fertilizers for agricultural use. There are three facilities (İzmir-Tire, Aksaray, and Bursa) where the IS project is implemented. Within the scope of the related project, it is stated that 584.205 tons of organic waste were disposed of, 1.8 million kWh of energy savings were achieved, and 98% of waste was recycled. One of the project's major accomplishments is that the energy obtained corresponds to 69% of Sütaş Group's electricity needs, 92% of dairy factory needs, and 21% of dairy factory thermal energy needs [26].

FISSAC Project

The project, in which Türkçimento and Ekodenge are among the partners, was supported by the European Union. Within the scope of the project completed in 2020, calcium sulfoaluminate cement (CSA) was produced using glass waste (Şişecam), ceramic waste (Çanakkale Seramik), and aluminium waste (BEFESA). The produced cement was used in road construction in Adana [27].

MAY & EVSU - Biyorem

The performance of the bioremediation product "Biyorem," which is obtained by the pilot-scale processing of lint waste generated during cottonseed production at the May-Agro production facility by EVSU, was studied. In this context, field trials and laboratory analyses were conducted within 8 months to determine the bioremediation and adsorption potential of the product, which is predicted to clean oil-contaminated soils by the bioremediation method and prevent oil spread by trapping oil in the soil, and successful results were obtained [25].

Ekinciler Inc. - Electric Arc Furnace

Within the scope of the project, it is planned to use the slag obtained in the Electric Arc Furnace (EAF) facilities, where 75% of the iron and steel production in the country is realized, as a by-product in highway construction. It is known that slag falls within the scope of waste in Türkiye and is generally stored. The excess waste volume brings with it space occupation, and environmental, and health problems. In the context of IS, the inclusion of this material in the reproduction cycle will add value to the national economy. Within the scope of the project, the possibilities of using the slag samples taken from Ekinciler Inc. in highway construction were examined across the field of the relevant standards. As a result of the experiments, it was determined that the material gave better results than most natural aggregates [28].

Other IS practices in Türkiye are as follows:

Yünsa creates a new eco-fabric collection by recycling the fabric waste generated during production.

Sütaş uses iron powder from a metalworking (laser cutting) project for H_2S removal in biogas production.

Pepsico uses certain types of processed food waste in the production of biogas together with the waste from chip production, optimizing the efficiency of biogas production.

Anadolu Efes studies obtaining value-added products by further conversion of malt pulp, which is a by-product of beer production.

Roteks Inc. evaluates treatment sludge from the denim washing process in the building materials industry.

Procter & Gamble Inc. conducts a feasibility study for obtaining absorbent material, cellulose, and plastic by recycling diaper waste from production.

Eti Krom Inc. evaluates olivine, which is a by-product from chromite enrichment activities, as a refractory raw material.

Eti Krom Inc. produces low-carbon ferrochrome by using fine-grained chromite ore from ore preparation and enrichment activities as a concentrate.

Bilecik Demir Çelik Inc. produces white fused alumina (WFA) as a secondary raw material from alumina-based refractory wastes from iron and steel production furnaces.

Ekinciler Demir Çelik Inc. produces secondary raw materials from dolomite refractory brick waste from iron and steel production furnaces [29].

INDUSTRIAL SYMBIOSIS PRACTICES IN DENMARK

Selected main IS practices in Denmark are presented below.

Baltic Industrial Symbiosis (BIS)

Since the projects and innovations in an IS are about company collaborations, an important role for the facilitator is to be the link between companies that can be a potential match for the symbiotic exchange [30]. The aim of the BIS project is to combine companies' efforts to use the waste of one partner as a resource for others. The project stipulates peer-to-peer exchange practices between IS managers. It develops new business and financial models [31].

Within the Baltic IS (BIS), which promoted IS and helped boost eco-innovation, the partners involved more than 150 enterprises and used a dialogue approach to acquire information regarding the companies' consumption and under-utilized and lost resources within the production process. IS can also benefit municipalities by attracting companies to locate in and/or remain within the municipality, ensuring jobs and tax revenues, drawing in further partners, creating a strong local brand, and perhaps also assisting in reducing waste treatment costs [5]. Denmark's companies, which are named Symbiosis Center Denmark, Kalundborg Municipality, Kalundborg Symbiosis, Næstved Municipality, and Roskilde University, are the partners of BIS.

Ressource City

The Ressource City is at the heart of the circular economy and the green transition in the Næstved metropolis. As a platform for innovation, knowledge and inspiration, the Ressource City contributes to the growth of local businesses by creating value and supporting local sustainable development. The Glass Cluster is a great example of the Ressource City's work and how a municipality can support sustainable business partnerships [30].

The Glass Cluster symbiosis, in the municipality of Næstved, Denmark, recycles 100.000 tons of glass a year and provides heat for 1.250 households. The recycled material makes up 95% of the glass for packaging, while the remaining dust is used to produce insulation. The municipality's circular economy department, "Ressource City," has embraced the cluster and communicated and shared the success story as part of the Næstved brand. Yet, ironically, glass waste from local households in Næstved is collected in such a way that it cannot be used in the Glass Cluster. This highlights a need for clean waste fractions [32, 33].

The Ressource City was responsible for branding the exchange of secondary glass as "the Glass Cluster" and has communicated the success story far and wide to inspire others to work with the circular economy. Næstved municipality and the Glass Cluster were selected as one of C40 and Realdania's "Cities 100": 100 cities with an innovative and ambitious approach to reducing climate footprints [5].

GreenLab Skive

A local goal for carbon neutrality and energy self-sufficiency by 2029 in Skive, central Jutland, and the vision of a transition to a "Green Energy Valley", called for actions out of the ordinary. With a supportive organizational structure, a willingness to take risks, the earmarking of funding, and creativity in solving legislative barriers, the municipality laid the seeds for and nurtured the growth of an innovative IS [34].

GreenLab Skive is an energy-focused green industrial park that has developed into an IS. As of 2020, nine waste, supply, and private companies are in GreenLab Skive, exchanging energy, excess heat, biomass, and non-recyclable plastic waste. Green-Lab Skive is planned to grow further and attract more energy-demanding companies to take part in the innovative energy symbiosis [5].

Kalundborg Symbiosis

Kalundborg Symbiosis is recognized as the first IS in the world and is considered a best practice example, attracting broad interest from multiple stakeholders [30]. The largest IS facility in Denmark is located in Kalundborg. It is both a city and a municipality, located about 100 km from the capital of Denmark, Copenhagen. The investment in Kalundborg is called the first complete implementation of IS. In this case, it consists of the exchange of goods between participants, which include private and public enterprises. Entities included in the symbiosis are characterized by a high variety of activities [35].

The main entities include, among others:

ARGO is a company responsible for the collection and subsequent processing of waste from the inhabitants of the municipality of Kalundborg. The company's priority is the reuse of a given waste and recycling, which allows for the recovery of raw materials. The final step is to extract thermal energy from the waste, which is converted into electricity.

Avista Green is a company dealing in the processing of waste oils from industrial plants and car workshops. The company has created a permanent loop for the oil by recycling it in a continuous cycle. Avista Green collects used oil and submits it to processes that will enable it to be reused.

Boehringer Ingelheim is a pharmaceutical company focused on improving human and animal health. The plant located in Kalendborg produces feed supplement products with a global reach, exporting its products all over the world.

Kalundborg Rafinery is the largest refinery in Denmark. Thanks to the cooperation between the entities of the symbiosis, the refinery benefits from convenient access to water and biogas. The company is characterized by the fact that residual sulfur from the desulfurization plant is converted into liquid and high-efficiency fertilizer. The result is the production of the cleanest fuel in the world, with a negligible sulfur content.

Saint-Gobain Gyproc is an entity producing gypsum boards made of natural gypsum and recycled gypsum. The company's activities focus on the broadly understood development of the production of recycled gypsum, contributing to the creation of a closed circuit for this material.

Kalundborg Bioenergy is a producer of biogas, from which hydrogen sulfide and carbon dioxide are then removed. The upgraded biogas is sent to participants (IS) and to external recipients throughout the country. The next activity is the recovery of sulfur from hydrogen sulfide, which is then used in fertilizers.

Kalundborg Utility is the main water supply and heat supplier for the residents and local businesses in Kalundborg. The company also deals with innovative wastewater treatment using ozone.

Novo Nordisk is a global manufacturer of pharmaceuticals that are very popular around the world. In Kalundborg, Novo Nordisk produces products for the treatment of severe obesity and diabetes, as well as several biopharmaceutical products.

Novozymes is a company highly associated with the microbiology market, and with enzymes that enable more efficient agriculture, energy savings in production, and washing at lower temperatures. The entity has a positive impact on the environment due to the production of substances that, e.g., allow the use of fewer chemicals while achieving the same result. In addition, the company is an example of the correct creation of a closed loop, benefiting from process steam and treated surface water from Lake Tissø, which is used directly to produce enzymes. The next stage is the processing of biomass obtained from the production of enzymes, which is converted into energy and fertilizers.

Remilk is a company that, thanks to the fermentation process, produces milk proteins. It is a replacement for traditional milk protein derived from animals. The innovative approach of the company allows the creation of any dairy product free from antibiotics, hormones, lactose, and cholesterol. Remilk's breakthrough technology enables the production of a cost-effective dairy alternative on a global scale with negligible environmental impact.

Unibio is a company that produces protein from methane, which is then used as an ingredient in animal feed. The technology used allows for the separation of protein production from agriculture or fishing, thus affecting the natural environment. In addition, the obtained biogas is taken from the entity, which is Kalundborg Bioenergy.

Ørsted is owner of the Asnæs Power Station in Kalundborg. It produces electricity, steam, and heat. Steam is supplied to Novozymes and Novo Nordisk. The power plant uses steam to produce electricity. The heat generated from this production is transferred to residents and businesses in the Kalundborg area. An important fact is the cooperation between Kalundborg Rafinery and Ørsted. The companies exchange the water produced as a by-product. On a large scale, this reduces the demand for water abstraction from the nearby Tissø lake.

Each of the listed exemplary participants cooperates with others, trying to pass on the goods they need. The goods exchanged between the participants include water, information, energy, and broadly understood material goods [36].

Every year, the IS saves the partners and the environment for:

- 4 million m^3 of groundwater by using surface water instead
- 586.000 tonnes of CO_2
- 62.000 tonnes of recycled residual materials

80% of the CO_2 emissions in the symbiosis have been reduced since 2015. The local energy supply is now CO_2-neutral [37].

IS in the municipality of Kalundborg is constantly developing, becoming a leader under the influence of the scale, quantity, and quality of implemented solutions. The project in Kalundborg is a global example of how IS should work [36].

Aalborg: IS North

Another example is the "IS North" project, which takes place in the north of Denmark. The cooperation is focused on the resources of the limestone lake, which is located near the city of Aalborg. IS has its origins in the 1970s, but a significant intensification took place after 2010, when cooperation between entities located in the north of Denmark allowed the effective use of limestone in many mutually beneficial stages of production. From year to year, the number of companies involved in the IS model increases, including both large and small local enterprises. There are more than 25 streams of resource exchange between participants. The concept of resources has no limits because it includes any material whose reuse brings about the desired effect. For some enterprises, a by-product may be a suitable raw material for another entity.

The IS North project demonstrates significant energy savings. Companies participating in this initiative save an average of 264 MWh each. This corresponds to the annual energy consumption of 8 households. On average, companies can avoid 800 tons of CO_2 emissions. This corresponds to the annual CO_2 emissions of 100 Danish people. A typical value for resource exchange symbiosis is between 30 and 50.000 DKK per year for a small company. The average value of such symbiosis is much higher, two SMEs can expect 1-2 million DKK per year in sustainable synergy [38].

The IS North project brings surprising results, and its main goal is constant development. Therefore, new businesses are encouraged to become participants from the very beginning and positively influence the world. As science advances, new flows of material exchange between existing market partners emerge that revolutionize the economic model of the time. The project introduced in northern Denmark fits perfectly into the climate goals of the 21st century. To achieve climate neutrality, it is necessary to change the strategy of economic development. This requires cooperation between companies and joining forces in the development of a circular economy [37].

Water Symbiosis

The increasing pressure on drinking water resources has led to a focus on replacing drinking water with lower quality secondary water in Denmark. Advanced treatment technologies are making it financially viable to upgrade this secondary water for specific purposes. This project investigates and optimizes the use of such treated secondary water in IS between companies [35].

Green District Heat

The Green District Heat project is developing a generic model for utilizing industrial waste heat as district heating in nearby communities, specifically oil refineries or villages associated with them. In the context of reducing fossil fuel use in the Sealand region, the project investigates the possibility of transferring excess heat from factories to the district heating network in a way that is both socio-economically and environmentally sustainable. A similar application has been implemented in the Kalundborg region, where the Statoil refinery, a partner in the Kalundborg Symbiosis, generates enough excess heat to cover 80% of Kalundborg's heat needs [35].

BENEFITS OF INDUSTRIAL SYMBIOSIS PRACTICES

The implementation of IS practices offers several benefits with social, environmental, and economic aspects. IS promotes a circular economy model by sharing resources, such as energy and raw materials, and recycling waste as inputs for other processes. This reduces the need for new resource extraction and minimises disposal costs. Chertow [8] and Ehrenfeld and Gertler [6] highlight the potential for cost-effective collaboration and increased competitiveness between industries involved in symbiotic relationships, which underlines this economic efficiency.

From an environmental point of view, IS is seen as a major contributor to sustainable development goals. It reduces their negative impact on the environment by encouraging the reuse of by-products and reducing the total amount of waste generated. The exchange of materials and energy between companies can reduce pollution, greenhouse gas emissions, and resource depletion. Gibbs and Deutz [39] highlight the possibility of reduced environmental impacts through symbiotic interactions when they discuss these environmental benefits in the context of industrial ecology and eco-industrial development.

IS techniques promote community involvement and cooperation, fostering social cohesion at a societal level. This collaborative strategy can build social cohesion, create jobs, and improve the general standard of living in areas surrounding industrial sites. Boons and Roome [7] emphasize the critical role of collaboration in achieving positive social outcomes in sustainable development.

This manuscript compares key IS applications developed in Denmark with similar practices used in Türkiye. Due to its status as a developed country with diverse infrastructure, Denmark has an advantage over Türkiye in implementing these applications. Additionally, Denmark excels in fostering regional partnerships for IS practices. Compared to Türkiye, Danish applications tend to be more collaborative and have more developed components. In similar practices in Türkiye, deficiencies are noticeable in terms of infrastructure and cooperation, particularly in areas like waste heat, wastewater reuse, and establishing industrial raw material exchange infrastructure between public and private sectors. However, Türkiye has great potential, due to its waste volume and geographical area. To promote IS in Türkiye, the first step is to develop new partnerships and spread awareness about IS nationwide. Water symbiosis and green district heating projects are also recommended for implementation in Türkiye, particularly in Organized Industrial Zones and surrounding areas. These projects hold promise for achieving social, economic, and environmental benefits.

Each of these countries attempts, in its own way, to mitigate the negative effects of industrial development and implement sustainable development practices. Nowadays, Denmark stands out for its advanced cooperative structure, technological infrastructure, and current practices. Denmark, which hosts leading sustainable development applications, is a model country, especially with its eco-park and socio-economic benefits. Meanwhile, Türkiye is improving its achievements in existing applications and realizing its potential through partnerships and investments throughout the country.

The application of IS techniques offers three key benefits: social well-being, environmental sustainability, and economic efficiency. A body of the manuscript underlines this point, highlighting the significant contribution of IS to promoting a more sustainable and circular industrial landscape.

CONCLUSION

IS is an environmental management approach within the framework of an industrial ecology. It is a key enabler of the circular economy, supporting the industry in the transition from inefficient and unsustainable production systems to profitable and environmentally friendly manufacturing concepts. Creating IS in an industrial park can be done by discovering IS, that is, seeing opportunities to change materials, energy, products or water. Potential flows of matter and energy can be constructed by seeing possibilities change depending on the raw materials used, waste or products.

The IS practices, which are becoming more preferred all over the world, will increasingly develop and will no longer be limited to the exchanges or flows of matter such as materials, energy, water, and by-products. In Europe, the inclusion of IS as an example of resource efficiency in Commission policy is helping to pave the way for new programs.

This study addresses different IS practices in two countries, Türkiye and Denmark. The main factors for choosing these two countries are as follows: (i) Denmark is one of the leading regions in the world for IS implementation. (ii) Danish IS studies are implemented regionally (Baltic region), suggesting a similar mission/vision might be possible for Türkiye due to its geopolitical position. (iii) Türkiye has high waste generation and recycling potential, with a significant amount of organic waste. (iv) Türkiye's growing population and developing industries create energy needs that IS could help address. (v) This study compares Denmark, with its world-leading Kalundborg case, to Türkiye's high IS potential. It examines the applicability of Danish practices to the Turkish context. By considering these elements, the study explores prominent IS practices in both countries and offers future suggestions, particularly for Türkiye, to evaluate its IS potential.

This study makes a noteworthy contribution to the existing literature by offering a comparative analysis of IS practices in two diverse contexts, Denmark and Türkiye. Comparing these countries provides a novel perspective on the adaptability and effectiveness of IS strategies,considering varying levels of economic development, industrial diversity, and environmental priorities. The findings are expected to provide valuable insights for policymakers, researchers, and industry practitioners. This will aid in the development of tailored IS approaches that consider local nuances. Additionally, the study contributes to the broader discourse on sustainable industrial practices and circular economies,offering a deeper understanding of how IS can be applied and optimized in different global settings.

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DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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