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Industrial Symbiosis in Taiwan: Case Study on Linhai Industrial Park

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Abstract: Eco-industrial parks (EIP) are a community of manufacturing businesses which seek better environmental and economic performance by using the principles of Industrial Ecology (IE). In Taiwan, government-designated EIPs have operated since 1995, with 23 industrial parks currently in operation. This study presents a case from Taiwan, the Linhai Industrial park, and analyzes the park's transition towards industrial symbiosis and resource sharing. Resource sharing modifications resulted in reduced carbon emissions, millions of liters of fuel saved, and thousands of tons of industrial waste recycled. This successful transition was possible because of coordinated government support. Key factors include technological subsidies, policy support, and willing manufacturers. Additional explanations for Linhai's current success are explored and future areas of research are identified.

Keywords: industrial ecology; eco-industrial park; sustainability; industrial symbiosis; Linhai industrial park; Taiwan

1. Introduction

Due to increasing world population and living standards, alongside the accumulation of greenhouse gases in the atmosphere, the visibility of sustainability has increased [1]. Sustainable development is defined as "Development that meets the need of the present without compromising the ability of future generations to meet their own needs" [2]. At the same time, industry produces unprecedented levels of greenhouse gas emissions, along with air and water pollution [3]. The largest source of greenhouse gas emissions is the industrial sector and it continues to increase [4]. Therefore, strategies to reduce industrial environmental impact without compromising economic performance remain needed.

Industrial ecology (IE) is a concept that is applicable for environmentally sustainable economic development [5]. Within IE, industry can reduce environmental impacts by sharing waste resources, thereby reducing the need for raw materials and instead keep those materials within a supply chain without decreasing economic performance [6]. IE views all industrial operations as a natural system with linkages between industrial processes mirroring symbiotic relationships in nature. These relationships then support the long-term viability of business and create strong regional links between companies [7].

This paper describes the design and function of resource sharing retrofits within an industrial park in Taiwan. In order to contribute to a global understanding of industrial symbiosis and resource sharing networks, this research explores the largest eco-industrial park (EIP) in Taiwan. It will conclude with a summary of positive and negative incentives with suggestions for future research.

2. Literature Review

2.1. The Taiwan Case

Taiwan is geographically located south of Japan and east of the People's Republic of China (PRC). During the late 1950's, industries in Taiwan experienced rapid growth [8]. The major industries in Taiwan are electronics, communications and information technology products, petroleum refining, chemicals, textiles, iron and steel, machinery, cement, food processing, vehicles, consumer products, and pharmaceuticals. Industry made up 36.1% of GDP in 2018 [9]. Taiwan's rapid and successful industrial development, sometimes referred to as "Taiwan's Economic Miracle" depended on energy imports and global trade [10].

More than 90% of energy in Taiwan depends on imports [11]. Energy supply in Taiwan is extremely vulnerable to changes in the international energy environment. Stabilizing energy supply is a major focus of policymakers, with fossil fuels receiving most government support, while little focus is paid on energy efficiency [12]. For more stability, many manufactures installed their own energy generation or coal boilers to ensure stable heat and power. Concerns grew when manufacturing started having major impacts on local air and water quality [13]. However, Taiwan's overall industrial history demonstrates increasing specification and efficiency.

2.2. History of Industrial Park Development in Taiwan

The Ministry of Economic Affairs (MOEA) and the Industrial Development Bureau (IDB) are the responsible agencies for managing industrial parks in Taiwan. The development of industrial parks is divided into four categories based on the policy revision "Regulation of Encouraging Investment" [14]. During 1960–1969, industrial parks entered into a period of rapid growth. The objective during this period was to increase investment and export. One of the first industrial parks developed by the government during this time was the Liutu industrial zone in Keelung. The Kaohsiung export processing zone, was then established in 1965 and was the nation's first industrial park focused on exports. The Paoan Industrial zone was the first primarily private industrial zone established in 1969 at Tainan.

During 1970–1979 there was another growth phase of industrial parks. This phase of development was mainly focused on the petrochemical industries in Da-Shiou and Linyuan. This period saw the largest increase in new industrial parks (see Figure 1). Policies during this time were designed to create small to medium-sized industrial parks in remote areas.

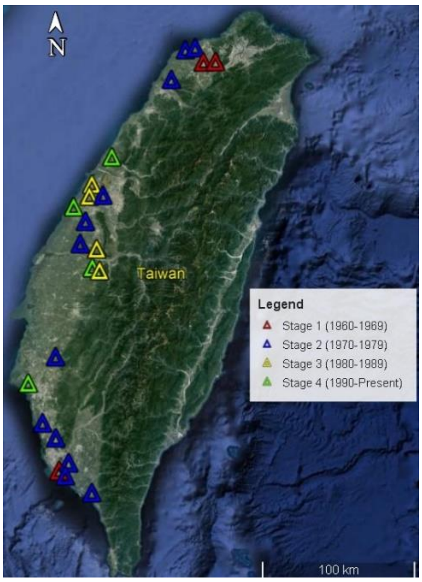

Figure 1. Map of Taiwan with different industrial development periods.

Table 1 lists all of what are now called "eco-industrial parks" by development period. At the time of their creation these industrial clusters had little emphasis on environmental impacts or sustainability.

Table 1. Development period as of Industrial Development Bureau (IDB) policy classification [14].

Period	Industrial Park
1960–1969	Zhongli Industrial Park Guishan Industrial Park Linhai Industrial Park
1970–1979	Renda Industrial Park Taichung Industrial Park Fuxing Industrial Park Yongan Industrial Park Shantou Industrial Park Guanyin Industrial Park Linyuan Industrial Park Hsinchu Industrial Park Guantian Industrial Park Dafa Industrial Park Dayuan industrial Park Pingnan Industrial Park
1980–1989	Taichung Port Guanlin Industrial Park Tanka Industrial Park Douliu Industrial Park Quanxing Industrial Park
1990–Present	Tainan Industrial Park Yunlin Industrial Park Changhua Binhai Industrial Park Daija Youth Industrial Park

The third phase of development was the start of an industrial cluster slowdown, between 1981–1990. International investments increased in Taiwan, while profitable industrial lands declined, and government policy focused more on developing the next generation of industrial parks. Hsinchu Science-Based Park was developed to attract modern technological industries such as semiconductors and ICT technology production. This park laid the foundation for Taiwan's transformation from traditional industries to high-tech industries. Overall, during this period Taiwan focused on higher value-added industries, primarily electronics, instead of traditional manufacturing and textiles.

The final phase of development was after the 1990's. During this period, which was also the end of the martial law period, free elections and protests became legal. Citizens began to protest industrial parks which they saw as polluting. The creation of new industrial clusters slowed down significantly as new industrial spaces frequently clashed with existing residential or agricultural communities, especially in the south of Taiwan [15,16]. Under public pressure and being unable to relocate, existing industrial areas under government control began to implement environmental controls to restore trust with local communities. This initiated a gradual process to reform existing industry using IS principles.

In part due to public pressure, Linhai and Linyuan industrial park in Kaohsiung, Dayuan industrial park in Taoyuan, Yunlin industrial park started to utilize new technologies to increase material and energy efficiency. These retrofits started reducing GHGs, water, waste, and air pollutants. This was the first step in their EIP transition.

Today, there are 61 industrial parks under the IDB's management, over half of which were established more than 30 years ago. Of these, 23 are classified by the government as eco-industrial parks. They do not necessarily meet certain air, water quality, or waste-reuse standards. Rather these industrial parks were retroactively selected to be a part of the "Eco-Industrial Park Program" and receive government support to make resource-sharing modifications.

Limited peer-reviewed English content exists describing any of these parks [17]. A more recent paper describes the overall economic performance of the parks, but does not go into detail on the resource-sharing networks [18]. Data collection is further hampered by Taiwan's absence in many international forums which discourages English reporting on IS. Since Taiwan cannot participate in the United Nations, Taiwanese government agencies have little incentive to publish data internationally or as part of multi-lateral commitments [19]. To increase the availability of information about Taiwan's EIPs and policies, thereby providing global researchers with more cases, this paper collected qualitative and quantitative information from the IDB and major companies operating in Taiwan's largest EIP.

3. Results

Linhai Industrial Park is one of the major heavy industrial parks located in the southwest of Taiwan and was first established in 1960 and completed in 1972. The major industries that makeup Linhai include steel mills, a petrochemical complex, a coal-fired power plant, aluminum manufacturing plants, industrial gas production, and other smaller steel mills. The park covers 15.69 km^2. Among these heavy industries, China Steel Corporation (CSC) is the largest firm in the park.

Interviewing stakeholders within the park, this study aims to expand the literature available on EIPs in Taiwan starting with Linhai. Information comes from government representatives at the MOEA, IDB, along with company representatives from Lee Chang Yung Chemical Industry Corp (LCY), China Steel (CSC), and the China Petroleum Corporation (CPC).

3.1. China Steel Corporation

The China Steel Corporation (CSC), founded in 1971, is one of the largest producers of steel in Taiwan and was a state-owned entity until 1995. Today, it is a private company, with the government owning a majority share. The steel market in Taiwan started with the refining of old ships and scrap. As technology developed, steel mills were integrated with Electric Arc Furnaces (EAF) and production performance increased. During the redevelopment period of industrial parks in Taiwan, the concept of IS was used by policymakers to attract large companies, some formerly government owned, to join resource-sharing networks.

CSC saw the early potential for IS in Linhai Park, because the steel-making process consumes large amounts of energy as well as raw materials. Waste sludge and EAF slag from the steel-making process have value for recycling as commodities outside the park [20]. Within Linhai there are four steel manufacturing companies including CSC, and one aluminum manufacturing company that belongs to the CSC group. Clearly the dominant manufacturer in the park, CSC saw an opportunity to sell its waste materials and energy to other nearby enterprises and reduce emissions from decentralized heat production.

While the MOEA manages overall operations within the industrial clusters, they do not provide thermal energy for industrial processes and do not offer waste collection services. Parks only provided electricity, water, and wastewater treatment. Most factories in the industrial clusters needed steam energy for their processes and had to install their own heat generation, often polluting fuel boilers. Companies must also manage their waste streams separately without a centralized collection system. This approach worked initially, in terms of providing stable heat across the industrial parks, without requiring utility intervention, but began to cause problems as factories and their output increased.

There are four petroleum and petrochemical complexes located within Linhai. In 1992, LCY's petrochemical complex faced a severe water shortage. Even after bringing in additional water via trucks, they were not able to profitably meet their steam or water generation needs. Then in 1993, CSC started supplying waste steam from the steel-making process to LCY, China Petrochemical Development Corporation (CPDC), and China Petroleum Corporation (CPC). After this transfer LCY no longer had difficulties with shortages. This was the first example of IS within an industrial park in Taiwan at an industrial scale. This initial steam transfer was not supported by the IDB, but it inspired policymakers to create new programs through the IDB to formally encourage IS. Alongside these new programs CSC began to develop other IS streams due to the profitability of the network.

3.2. District Enegry Integeration

Prior to establishing the resource exchange network, CSC had large amounts of unutilized steam from combined heat and power generation as well as from the waste heat recovery. Since the steel-making process requires vast amounts of energy, it also creates opportunity for waste, and therefore a way to create IS relationships with other factories in Linhai. The industrial gases produced from the oxygen plant in CSC also shared excess energy with neighboring plants. The process flow diagram below (Figure 2) describes the industries in Linhai and the materials transferred internally and externally in the industrial zone. Waste gases were only transferred within the park while solid materials could find markets outside of Linhai.

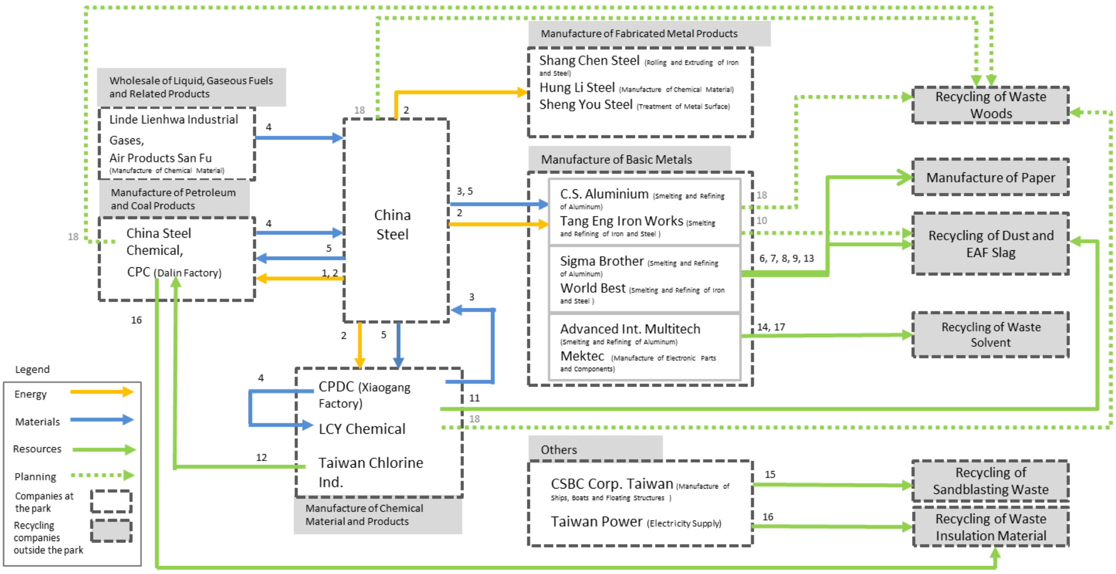

Figure 2. Energy and material exchange of Linhai industrial park [21]. 1—Coke Oven Gas; 2—Steam; 3—Argon; 4—Hydrogen; 5—Nitrogen; 6—Aluminum Slag; 7—EAF * Dust; 8—EAF * Oxidizing Slag; 9—EAF * Reduction Slag; 10—EAF * Slag; 11—Incineration Bottom Ash; 12—Liquid Alkali; 13—Non-hazardous Dust; 14—Non-hazardous Organic Waste Solvent; 15—Sandblasting Waste; 16—Waste Insulation Material; 17—Waste Solvent; 18—Waste Woods; * EAF—Electric Arc Furnace.

3.3. Energy and Material Streams

After first creating an inventory of the available energy and material resources, CSC created a resource-sharing network plan and began to develop material exchanges starting with the most profitable and simple, before moving onto more complex materials. Translated from mandarin-Chinese each resource network was separated into energy, materials, or resources. Energy includes gases and steam which result in energy generation. "Materials" included gases such as argon, hydrogen, and nitrogen. "Resources" included solid waste from industrial processes. Waste wood is a planned resource stream for future development.

In collaboration with the IDB, CSC began to explore other material- and energy-sharing networks. CPC and CPDC were both formerly fully state-owned, and Taipower remains the state-owned electricity utility. Proposed future linkages are represented by a dashed line (Figure 2). Due to privacy concerns on behalf of individual companies, specific amounts of each material stream were unable to be shared.

Common byproducts from CSC include coal tar, light crude oil, blast furnace slag (BF), basic oxygen furnace slag (BOF), iron oxide powder, desulfurization slag, residual iron, gases, and dust. The BF slag is granulated and sold to local businesses outside Linhai (Figure 2), and is commonly used to make cement. Air-cooled BF slag is much harder and dense, which can be used as a construction aggregate. BOF slag is cooled similarly to air-cooled BF slag and also can be used for the same purpose. Gases from coke ovens, BF or BOF, once cleaned, are used for production of steam internally. This process produces electricity which reduces the external demand of electricity. Dust removed from gases will usually contain iron and can be used again in the steel-making process. The recovered iron oxides from gases cannot be reused but can be sold to other industries for various applications. Coal tar and light crude oil are used in the making of electrodes for the aluminum industry [22].

The first resource stream developed at Linhai and the one with the most information available was the steam-sharing network. Unlike other physical material streams, the creation of the steam network had an obvious financial benefit that did not initially require government support although the network was developed between what were primarily state-owned companies.

3.4. Overall Network Trends

Generally, steam sales from CSC's steam-sharing network increased gradually from 1994 to 2006 before increasing dramatically. During the 2009 global financial crisis, CSC managed to sell 1.86 million tons (MT) of steam (Figure 3). Later in 2013–2014 there was a decrease in steam utilization because of a global economic recession. While in 2015, steam sales plummeted with a global decline in energy prices [23]. Carbon reduction from CSC steam sales thus directly depends on the amount of steam sold.

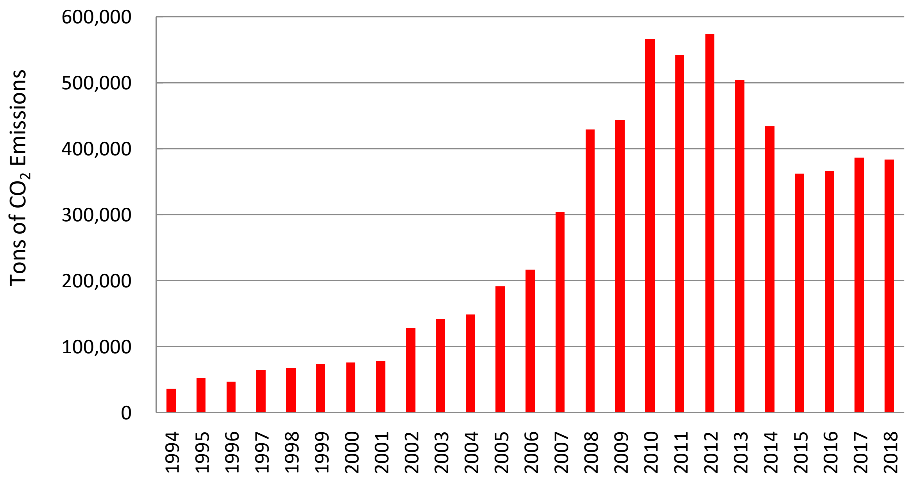

Figure 3. CO_2 reduction from steam sale [23].

In 2018, 1.67 MT of steam sales saved the equivalent of 1.3 kL of low sulfur fuel oil. This resource exchange was equivalent to an annual reduction of 383,000 tons of CO_2, 1222 tons of SO_x, 847 tons of NO_x and 120 tons of particulate matter. Air quality information comes from CSC. Figure 3 shows changes over time in Linhai's carbon performance rather than just a yearly average as reported in another study [17]. Since air pollution benefits match steam sales, carbon reductions depend on total economic output of the park, it is not a constant decrease in carbon emissions. The overall resource-sharing network reuses on average 1.1–1.4 million tons of industrial waste (excluding steam but including other gases) per year and 1.6 million tons of steam per year. Specific levels of re-use between companies could not be obtained for this study but are important to obtain for future research.

3.5. Contextualizing the Network

Since Taiwanese EIP cases are lacking, comparisons to international EIPs (Table 2) are made [24–26]. Comparing types of resource streams Linhai matches with other comparable international examples such as the Altamaria-Tampico Corridor and the Deux Synthe Park, as well as Kalunborg. With energy intensive industries within the parks opportunities for IS exist. Linhai does not contain agricultural or organic waste processing and thus a case like Ulsan Korea focuses instead on biogas. Currently the IDB has plans to add biogas and wood-processing to the resource-sharing network. When compared with other EIPs, Linhai appears to have a larger focus on one central company rather than an evenly distributed network.

Table 2. Comparing international eco-industrial parks (EIPs) with Linhai [24].

Name of EIP	Facilities Involved	Materials Involved
Kalunborg, Denmark	Coal-fired power plant, pharmaceuticals, gypsum board, oil refining, fish farming	Water, wastewater, sulfur, steam, sludge, fly ash, yeast and organic residuals
Guayama, Puerto Rico	Coal-fired power plant, chemical refining, pharmaceuticals	Wastewater, condensate, steam, ash
Campbell Industrial Park, Hawaii	Coal-fired power plant, oil refining, cement, water reclamation, recycling	Wastewater, waste oil, steam, ash, shredded tires, activated carbon
Shenzhen Huaqing Holdings Ltd.	Sugar reefing, alcohol, pulp and paper mill, cement, alkali recovery, agriculture	Sludge, alcohol, fertilizer, alkali
Ulsan Eco-Industrial Park, Korea	Oil, chemicals, incineration, metal processing, paper mill	Wastewater, biogas, steam, metal
The Deux Synthe Park, France	Coal-fired power plant, central heat power plant, cement, steel slag treatment, steel production, construction, brick manufacture	Steam, blast furnace slag, ground slag, tires, refractory bricks, steel mill dust, scrap
Altamaria-Tampico Corridor, Mexico	Petrochemical production, fertilizer, fiberglass, textiles, waste incineration, cement, water treatment, asphalt	Silica, CO, O_2, residual PET, manganese flakes, plastic byproducts, nitrogen, residual gases, waste solvent
Linhai Industrial Park, Taiwan *	Coal-fired power plant, chemical refining, manufacture of basic metals and advanced metals, petrochemical products, fuel production	Coke oven gas, steam, argon, hydrogen gas, nitrogen gas, aluminum slag, EAF dust, EAF oxidizing slag, EAF reduction slag, EAF slag, incineration bottom ash, liquid alkali, non-hazardous organic waste solvent sandblasting waste, waste insulation material, waste solvent

* Industrial Development Bureau, CSC, 2019.

According to the IDB and CSC, to establish a successful network proximity is a key factor. Stakeholders in the resource sharing network found that the distance between supply and demand must be less than 4 km for exchanges to be economically beneficial. This observation from Taiwan is stricter than other relationships between successful exchange found in the UK [27]. If the exchange is greater than that distance, the cost of building connecting infrastructure and organizing the exchange would exceed the potential savings. Within the network, it must be profitable for both sides to share resources. If one company has a great demand for energy but the other has no excess heat, there is no reason to sell as the exchange is not profitable, even with government support and subsidies. This finding raises questions about the replicability of Linhai's carbon benefits to other EIPs, not every EIP has large energy consuming processes.

Despite potential benefits, a critical challenge was to design and develop the infrastructure to attract new customers. Since CSC was state-owned and is government-backed, smaller companies felt confident that the network would be supported on a long-term basis. With larger companies, such as LCY joining the network first, smaller companies felt confident that the network would be profitable to join. Seeing the success of the network, the IDB later launched a program called "Industrial Park

Energy and Resource Integration" for nationwide EIP development. Since the Linhai Industrial Park's EIP transition generated clear economic and environmental benefits, the next step is to understand the key factors for their transition and determine if they can be applied to other EIPs in Taiwan or globally.

4. Discussion

4.1. Negative Incentives

According to responses from stakeholders at Linhai, some of the most powerful incentives for companies to join an industrial cluster could come from negative incentives. Through conversations with stakeholders across the resource-sharing network three key pressures emerged.

First, pollution abatement costs can be prohibitively high for certain industries. Generally, the industrial park provides water, electricity, and wastewater treatment. The factories themselves are responsible for their own energy needs, which requires building internal boilers. With increasing pressure on carbon and air emissions, some factories found operating individual boilers costly in terms of maintenance, fuel, or pollution abatement costs.

Second, water shortages also put pressure on companies to re-use. According to Taiwan's Water Resource Agency, water shortages across the island will reach 350 million tons by 2031. High risk regions include Taoyuan, Changhua, Yunlin, and Kaohsiung which are also heavy industry regions. A water shortage led to the first resource linkages in Linhai, if shortages continue. more factories might explore IS.

Third, waste disposal can be expensive in Taiwan, and unprofitable for certain types of hard-to-manage waste [28]. Since manufacturers dispose of waste separately, they do not achieve economies of scale and fail to obtain low-cost resource inputs. Finding recycling and disposal solutions for hard-to-manage items is a positive incentive for IS. According to Taiwan's Waste Disposal Act, steep penalties can be levied for companies that do not dispose of waste according to regulations [29]. These penalties create incentives for finding recycling options that lower waste management costs.

4.2. Positive Incentives

There are also positive incentives that can encourage companies to join the resource network: adequate technology, full support from authorities, and the size of the existing network.

Manufacturers face many financial pressures, this means investing in new technology especially outside of their immediate operational control poses high risks. Accessing adequate and proven technology that will not only reduce their costs for energy and waste but also make environmental targets easier to hit is a positive incentive as it severely mitigates risk.

Lastly, a network with large companies participating reduces the risk of joining a resource -haring network. Since large companies could bear the potential investment risk, smaller companies that want to buy energy or materials could be certain that the network would exist long enough for them to benefit from the exchange. Taiwan's successful economic development history relied on the central government to create structural changes that small and medium size enterprises could then exploit for global competitiveness [30]. Thus, the EIP retrofits at Linhai followed a similar model where the government and formerly state-owned companies led network creation, then smaller companies joined to exploit specific niches. If the networks were purely privately led, it was unlikely that many smaller manufacturers would join, and the network could not expand beyond steam or internationally traded recycling commodities. Further research is needed to see if this trend follows other EIPs or it was specific to Linhai given the park's historically close relationship to the MOEA.

While the economic and environmental benefits are clear, these networks would likely not exist, or not grow beyond one or two resource streams, without robust government support. The risks to establishing successful EIPs include environmental liabilities, technology uncertainty, and regulatory uncertainty [31]. These are mitigated by strong government support from the MOEA and IDB. Environmental liabilities are minimized by the regulators themselves through the creation of the network. Technological uncertainty was minimized by large corporate support of the network and regulatory uncertainty was also minimized by strong central government support.

Trust between stakeholders in the resource network is essential for the continued operation of exchanges. Large state-owned or formerly state-owned enterprises support the majority of exchanges in Linhai because there is well-established trust among the government, these large entities, and the industrial park itself. Over time as communication increases trust builds, and the network took on increasingly complex exchanges.

A mix of positive and negative factors incentivized network growth at Linhai Park from a small cluster of connections focusing purely on steam, to a sprawling ecosystem encompassing more than twelve different resource and energy streams with more planned for the future.

5. Conclusions

The Linhai Eco-Industrial Park is one of the largest industrial clusters in Taiwan and was originally not focused on sustainability, instead prioritizing economic returns. In the 1990s, the cluster began to transition away from polluting individual factory fuel boilers towards network steam and material sharing. Now Taiwan's twenty-three EIPs plan further retrofits yet lack sufficiently available public data for discussion. These data gaps make it challenging to extrapolate lessons from Linhai to the rest of Taiwan's EIPs.

Linhai's success in developing a profitable and environmentally impactful resource-sharing network came from the large steel industry which could generate enough steam for other manufacturers in the park thereby reducing their new for self-generated heat. Newer technology-based clusters or even older textile-based clusters may not have the same raw energy potential and would instead rely on material transfers.

With the government playing a strong role in network development, companies receive additional assurance that the network will exist long enough for benefits of the resource exchange to accrue. Taiwan's economy is largely export-based and is therefore vulnerable to international trade shocks. For example, when steam sales fell for CSC it did not collapse the network as by that stage other resource streams had been established and the network did not depend on just one industry. If the network were supported solely by private business without government support, companies would likely not join, as they would have no guarantee on the longevity of the program.

One area of further research would be to explore the role of private companies in network development. The most important area for future research would be to analyze the other 22 EIPs in Taiwan and to better understand if their retrofits have been as successful as Linhai. Since CSC is publicly listed and publishes sustainability reports, they have disclosed adequate data for analysis. Other parks do not have internationally recognized companies inside or an incentive to disclose pollutants beyond standard government reporting.

With waste management becoming increasingly difficult on land-scarce Taiwan and public awareness increasing on climate change and air pollution, EIPs will remain an important tool for decarbonization. The challenge remains, how can Taiwan make sure that the success of one park can scale to the others? More publicly available data is required to fully answer this question. Further research can add more information about the performance of EIPs in Taiwan into the global IS discussion.

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