Industrial Symbiosis in Kalundborg, Denmark

A Quantitative Assessment of Economic and Environmental Aspects

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Keywords

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Summary

As a subdiscipline of industrial ecology, industrial symbiosis is concerned with resource optimization among colocated companies. The industrial symbiosis complex in Kalundborg, Denmark is the seminal example of industrial symbiosis in the industrial ecology literature. In spite of this, there has been no in-depth quantitative analysis enabling more comprehensive understanding of economic and environmental performances connected to this case. In this article some of the central industrial symbiotic exchanges, involving water and steam, in Kalundborg are analyzed, using detailed economic and environmental data. It is found that both substantial and minor environmental benefits accrue from these industrial symbiosis exchanges and that economic motivation often is connected to upstream or downstream operational performance and not directly associated with the value of the exchanged by-product or waste itself. It is concluded that industrial symbiosis, as viewed from a company perspective, has to be understood both in terms of individual economic and environmental performance, and as a more collective approach to industrial sustainability.

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Introduction

Industrial ecology operates at three different levels, ranging from the global level through the interfirm level to the level of the individual facility (Chertow 2000). The level directly examined here—the interfirm level—has been viewed in terms of various models and terminologies, ranging from eco-industrial parks (Côte and Cohen-Rosenthal 1998), industrial symbiosis (Chertow 2004) and industrial ecosystems (Côte and Hall 1995), to islands of sustainability (Wallner and Narodoslawsky 1996), industrial recycling networks (Schwarz and Steininger 1997), and by-product-synergies (Forward and Mangan 1999). Within this framework of interfirm relationships, industrial symbiosis (IS) can be categorized as a concept of collective resource optimization based on by-product exchanges and utility sharing among different colocated facilities. The explicit definition of IS is given by Chertow (2004): "Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchanges of materials, energy, water and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity" (Chertow 2004, 2).

Within the debate about IS, a very large number of references have been made to one particular case: the IS complex in Kalundborg, Denmark (Ehrenfeld and Gertler 1997; Côte and Cohen-Rosenthal 1998; Esty and Porter 1998; Hardy and Graedel 2002; Ehrenfeld and Chertow 2002; Chertow and Portlock 2002; Brings Jacobsen and Anderberg 2004). This case has been seen either as a paradigmatic role model for IS or—on the contrary—as an isolated phenomenon where a number of companies have coincidentally been locked into a web of waste, water, and energy exchanges based on contractual dependency.

In spite of the fact that the Kalundborg IS complex has played a central role in the discussion of how to put the theoretical principles of IS and industrial ecology into practice (Sterr and Ott 2004), no detailed quantitative analysis of the case has ever been conducted.[1] A literature review shows an immense number of references to the case over the past few years, but none goes much beyond mere description of the exchange relationships between the companies in question. The identifiable quantitative data on the case differ in scale and scope (see table A of the electronic supplement [e-supplement], available on the *JIE* Web site); in particular, data on the economic aspects of the IS exchanges are very limited in the current literature.

The narrow objective of this article is to remedy these factual inadequacies by describing and analyzing some of the central quantitative economic and environmental parameters related to the Kalundborg IS complex. The focus is on water- and steam-related IS exchanges, with a view to evaluating the economic and environmental implications of these exchanges. The evaluation is based on a quantitative data record spanning the period 1990–2002.

The evaluation shows that some substantial and some minor environmental benefits are generated by these IS relationships, and that the various water- and steam-related exchanges are closely interconnected in a system based on water/energy cascading, substitution, diversification, and utility-sharing.[2] The question of economic viability is discussed in relation to these findings, and it is argued that IS relationships imply some basic direct and indirect economic benefits that make IS a reasonable approach to interindustrial collaboration, with a built-in environmental effect.

When the economic and environmental significance of the water-related IS exchanges is evaluated, a clearer picture appears of the decision-making parameters and the reasons behind the operationalization of these IS exchanges.[3] The implied broader objective of this article is thus to understand the operational raison d'être of IS from the company perspective and thereby to contribute to the discussion of how to optimize material flows at the interfirm level, as advocated by industrial ecology.

Methodology for Estimation of IS Environmental and Economic Significance

The principles of industrial ecology and industrial symbiosis predict that turning waste output from one facility into raw material for another facility will lead to environmental benefits caused by a reduced intake of virgin material and/or reduced emissions (Graedel and Allenby 1995; Chertow 2004). The environmental effects of the selected water-related IS exchanges are therefore analyzed in terms of their ability to reduce the intake of high-quality water by means of water substitution and water cascading. The theoretical principle of cascading is extensively described by Côte and Hall (1995), and Sirkin and Houten (1994) and is discussed by Connelly and Koshland (1997, 2001). It is used here in a simplified outline version as proposed by Fraanje (1997) where cascading involves starting with high resource quality increasing lifetime per application, overall lifetime, and minimizing quality loss per application. On the basis of these principles, the selected water-related IS exchanges are generally described as a number of downward water-cascading sequences and the resulting amount of water saved is estimated and discussed.

The steam/heat-related IS exchanges are analyzed in terms of the cogeneration effect[4] and the net reduction of emissions of carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO_x) are illustrated in a hypothetical comparison with stand-alone production. The engineering calculations of the cogeneration effects have not been done by the author, but are based on data and calculations from the companies involved, and as such are based on appropriate engineering methodology and references (see table F of the e-supplement and acknowledgments).

The economic aspects of the same exchange relationships are estimated and discussed as a combination of investments at the time of initiation, and direct and indirect economic savings related to upstream or downstream production-related issues. The direct economic savings are usually caused by avoided discharge fees or disposal costs or by reduced prices achieved by substitution. The indirect economic benefits are related to avoided investments, increased flexibility, or supply security. Thus the economic aspects of the IS projects are estimated and discussed as a combination of direct cost reductions, real investments in relation to alternative avoided investment scenarios, and estimated payback times for the different exchange projects at the time of project initiation.

The data for this article are based on qualitative key-informant interviews, internal and external documents from the companies involved, and public statistical material. Data references are given in tables A-F in the e-supplement.

Status and Scope of the IS Complex in Kalundborg

The development of industrial symbiosis in Kalundborg, Denmark has been described as an evolutionary process in which a number of independent by-product exchanges have gradually evolved into a complex web of symbiotic interactions among five colocated companies and the local municipality (Ehrenfeld and Gertler 1997; Ehrenfeld and Chertow 2002). The companies involved in industrial symbiosis include a 1,300-MW (2002) power plant (Asnæs),[5] an oil refinery (Statoil A/S), a biotech and pharmaceutical company (Novo Group), a producer of plasterboard (Gyproc Nordic East), and a soil remediation company (Soilrem A/S).

As illustrated in figure 1, the various material flows among the companies are based either on water, solid waste, or energy exchanges. In this system, wastewater and cooling water from the refinery are reused at the power plant: the wastewater for secondary purposes, the cooling water as feeder water for the boilers producing steam and electricity, and also as input water for the desulfurization process. The desulfurization process in turn produces industrial gypsum used in the production of plasterboard at the colocated Gyproc factory, thereby partly replacing the use of natural gypsum. The cogenerating power plant also produces heat for the town of Kalundborg and steam for the Novo facility and the Statoil refinery. The Novo facility is only supplied with steam from the power plant, whereas the refinery has production-related in-house steam generation capacity, partly supplied by preheated boiler water from the power plant in a total-supply-security system. In addition, heated cooling water from the condensation process at the power plant is piped off to a nearby fish farm, thereby increasing the efficiency in the farm, as the heated cooling water ensures full-scale production of the fish

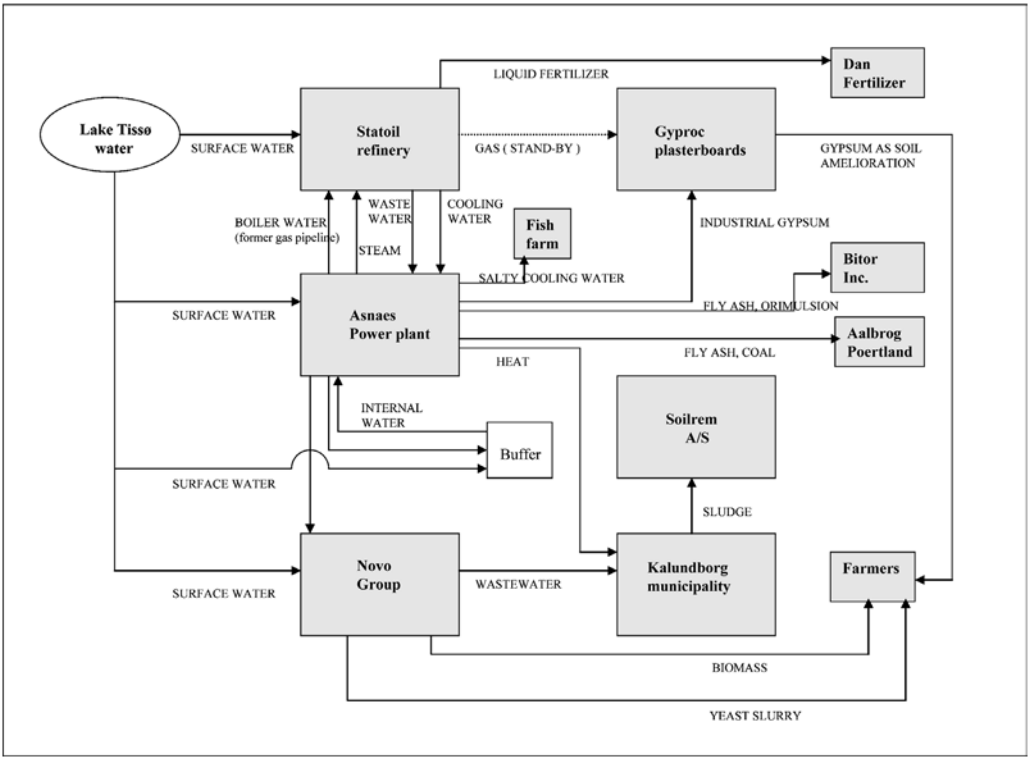

Figure 1 The industrial symbiosis, Kalundborg (in 2002). *Source:* The Center for Industrial Symbiosis, Kalundborg (Hansen 2003).

throughout the year. Finally, solid by-products such as fly ash from coal combustion, sludge from public wastewater treatment, and biomass from biogenetic fermentation at the Novo facility are recycled in various ways, both locally and nonlocally.

In total, industrial symbiosis in Kalundborg counts—depending on the definition—approximately 20 different by-product exchanges in operation, a number of potential projects, and a number of projects closed down as markets and technological innovations have developed.

Following the definition of IS as proposed by Chertow (2004), the symbiotic relationships concerned with water and steam have been chosen for a dedicated in-depth study, because these exchanges illustrate a clear IS business practice based on geographical proximity, by-product reuse and business-to-business resource optimization.

The Water and Steam Exchanges in the Kalundborg IS Complex

The Kalundborg region has a large groundwater deficit, and groundwater supplies have gradually dwindled over a period of 20 years as the local water-consuming industries have expanded in size and consumption. As a result of these developments a number of public/private initiatives for saving groundwater have been initiated over the last few decades. These public/private initiatives can be categorized into three overall strategies by which a number of water/steam-related industrial symbiosis projects can be identified. One strategy has been to replace groundwater with surface water in the most water-consuming industries (1961-). A second strategy has been to optimize internal water use and diversify external water sources in the water-consuming industries (c. 1975-). A third strategy has been to upgrade

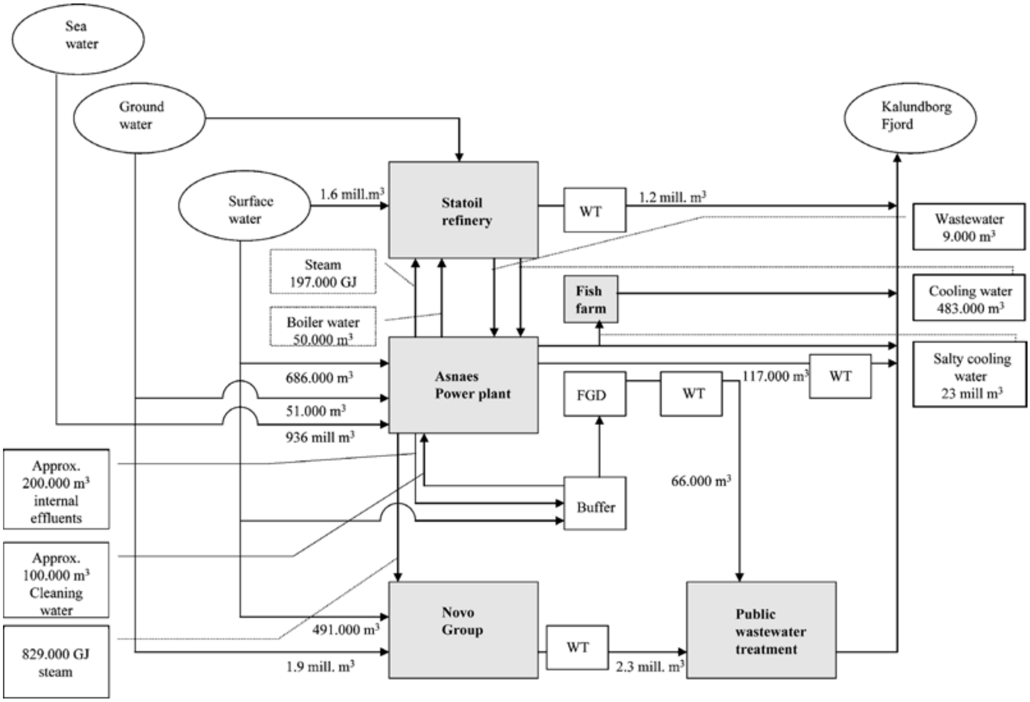

Figure 2 Selected industrial symbiosis water flows in Kalundborg (m^3/yr and GJ/yr) in 2002. *Source:* Green Accounts from Statoil, 2002, Novo Group, 2002, and Asnæs power plant, 2002 and information from the companies obtained through the Kalundborg Center for Industrial Symbiosis (Hansen 2004). WT = wastewater treatment; FGD = fluegas desulfurization; mill. = million. One gigajoule (GJ) = 10^9 joules (J, SI) ≈ 2.39×10^5 kilocalories (kcal) ≈ 9.48×10^5 British thermal units (BTU); one cubic meter (m^3, SI) = 10^3 liters (L) ≈ 264.2 gallons (gal).

surface water to drinking water quality and to import groundwater to the Kalundborg region from adjacent regions (1997-).[6]

These different strategies have created a diversified water supply system in the region, based on close cooperation among the various water-consuming industries. Figure 2 presents a section of this diversified system where the local water flows are related to the water-consuming symbiosis industries. From this, in 2002 a total input of 1.9 million cubic meters (m^3) groundwater[7] and 2.7 million m^3 surface water, and a total industrial discharge of 3.6 million m^3 of water can be observed, excluding salty seawater discharges. During the period 1990–2002, these different flows have undergone some significant quantitative changes, as is shown in table B of the e-supplement. The use of surface water has almost doubled, whereas use of cooling water, wastewater, and boiler water have shown an increase, stabilization, or decrease in amounts exchanged among the different participating companies.

The importance of these water-related symbiotic flows in relation to the total water input in the different symbiotic facilities is considerable, as shown by table C of the e-supplement. More than 95% of the water input at the power plant is part of the symbiotic network, whereas 98% of the water input for the refinery is symbiotic in character, as is approximately 20% for the Novo facility. The steam/heat supply accounts for more than 50% of the energy input at the Novo facility, whereas around 4% of the energy input for the refinery is part of the steam-related symbiotic activities (in 2002). As can be observed from figure 2, the central water- and steam-related IS projects are to a great extent centered on the power plant. Thus an analysis of the water consumption and the historical water prognosis for this facility is a first step toward evaluating the operational raison d'être of the water and steam-related IS projects and their present economic and environmental significance.

Table 1 illustrates how over the last 12 years the power plant has gradually managed to reduce the intake of groundwater by drawing on many different sources, including groundwater, surface water, cooling water, and wastewater, in cooperation with the colocated companies.

The initial cause of this change at the power plant was the installation of a number of water-consuming processes. It was estimated that the installation of a wet flue gas desulfurization plant in 1992 would require approximately 450,000 m^3/yr of water, and the potential installation of another desulfurization plant by 1995/1996 would require another 400,000 m^3/yr. Furthermore, the export of steam to the refinery and the pharmaceutical plant was expected to increase the run-through of process water by 222,000 m^3/yr (in 2000), thereby creating an equivalent need for raw water input.

Table 2 shows the complete forecast for water supply and increased run-through of process water at the power plant (1988–2000). It was estimated that the water intake would increase from the mid-1980s over the next 20 years by a factor of 3 from approximately 1.0 million m^3/yr to approx. 3.0 million m^3/yr. Thus, to secure a steady and cheaper supply of water for the production process, a radical shift was needed from high-quality water to low-quality water where possible. This was further prompted by the increasing intake of water by the colocated companies, especially the pharmaceutical plant, Novo (see table 1).

Five different sources, all of which included a symbiotic element, were to form the basis of the water supply to the power plant. A first source was increased use of surface water jointly with the refinery and the Novo facility. A second source was use of cooling water from the refinery. A third source was use of wastewater from the refinery. The last two proposed sources were reused wastewater from the pharmaceutical company Novo and from the public wastewater treatment plant.

Today, the first three of these original IS exchanges are in operation, in close conjunction with the downstream steam-related IS exchanges. These IS arrangements have made it possible to replace and diversify the intake of water to the power plant and to optimize the energy efficiency of the facility. By means of these IS relationships, the power plant has managed to replace groundwater with surface water, surface water with cooling water, and cooling water with wastewater. Parallel with this gradual substitution/cascading, the energy content in the water is used at different levels ranging from high-energy steam exchanges to low-energy exchanges of salty cooling water. In conjunction with these arrangements, utility sharing is a third factor used to further optimize economic and environmental performance (see the next section).

The forecast need for 3.0 million m^3 of high-quality water at the power plant by the year 2000 has been turned into consumption of approximately 1.2 million m^3 of low-quality water (in 2002) as a consequence of these IS exchanges among the companies, combined with reduced production capacity at the power plant.[8]

Thus the various IS exchanges in current operation help to optimize the water/energy flows and economic performance at the power plant, and the operational raison d'être of the IS exchanges seems to be primarily based on this fact. To acquire a clear quantitative picture of these IS optimization processes, each water/steam IS exchange is analyzed further below in terms of economic and environmental significance and performance.

Analysis of Water/Steam IS Exchanges Involving the Asnæs Power Plant

As indicated by figure 2, the core water/steam IS exchanges associated with the power plant involve exchanges of surface water, cooling water, wastewater, steam/heat, pretreated boiler water, and salty cooling water. Table D of the e-supplement summarizes the environmental and economic significance of these exchanges, each of which is evaluated in the following sections. Table D also includes the performance of a number of other IS exchanges in the Kalundborg IS complex.

Table 1 Water consumption at Asnæs power plant, Novo plant, and Statoil plant, 1990–2002, in thousand cubic meters (1,000 m^3)

	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*	*2002*
Asnæs Power Plant in Kalundborg													
Groundwater	335	412	356	313	119	73	61	51	39	36	52	37	51
Surface water	105	87	167	407	791	733	522	433	926	827	623	578	686
Cooling/waste water	715	705	802	847	849	820	753	634	580	518	315	647	492
Novo Group in Kalundborg													
Total water intake	1,400	1,600	1,700	1,900	1,900	2,200	2,500	2,500	2,200	2,300	2,300	2,600	2,700
Statoil Plant in Kalundborg													
Total water intake	(*)	(*)	(*)	1,200	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,600	1,600

Source: Green Accounts from Statoil refinery (covering 1997–2002), Novo Group (covering 1994–2002), Asnæs power plant (covering 1996–2002) and internal publication from Asnæs power plant: "Asnæs power plant—Recycling of wastewater (1992/93)." Novo Group water intake includes water imported as steam.
Notes: (*) = Not available. One cubic meter (m^3, SI) = 10^3 liters (L) ≈ 264.2 gallons (gal).

Table 2 Water consumption (1988) and water prognoses (2000) for Asnæs power plant

	1988 (consumption) m^3	*2000 (prognosis)* m^3
Boiler water Unit 1–5	—	390,000
Boiler water Novo	192,000	400,000
Boiler water Statoil	136,000	150,000
Boiler water district heating	5,000	10,000
Sluice water unit 1–5	—	340,000
Granulation/dust	—	830,000
Desulfurization unit 3–5	—	850,000
Sanitary water	—	30,000
Total internal use	736,000	2,400,000
TOTAL consumption including water loss to IS activities	1,069,000	3,000,000

Source: Future water supply for Asnæs power plant, internal document, Asnæs power plant, June 1989.
Notes: (—) = Consumption not explicated in this category, but accumulated as part of the total consumption.

Replacement of Fresh Groundwater with Surface Water

The power plant takes in surface water jointly with the other symbiosis industries from a nearby lake. The surface water is upgraded and thereby made viable as boiler water for steam production. Thus, the intake of surface water at the power plant has had a direct effect on the intake of fresh groundwater, amounting to an annual saving of 686,000 m^3 in 2002, or more than 6.9 million m^3 for the period 1990–2002 (table 1). In the same period all of the symbiosis industries saved more than 30 million m^3 of groundwater, as seen in table B of the e-supplement, as a result of the replacement of groundwater with surface water. Table E of the e-supplement shows the publicly available price difference between surface water and groundwater in the period 1990–2002. Based on this, the replacement of groundwater with surface water led to an annual saving of approximately 7.6 million Danish Kroner (DKK) or $960,000 U.S. for 2002[9] by the power plant, or more than 35 million DKK for the selected period. A joint private investment of 32 million DKK in utility sharing in the present pipeline system has meant a reasonable payback time for the individual symbiosis industries involved.

Replacement of Surface Water with Cooling Water

The intake of surface water is based on utility sharing among the various symbiosis industries, whereas the delivery of cooling water from the refinery to the power plant is based on water substitution and cascading. In this symbiotic relationship, the power plant replaces surface water with cooling water piped from the refinery. Thus the refinery takes in surface water (which replaces groundwater) and uses the surface water as cooling water; then the cooling water is piped to the power plant. The power plant treats and upgrades the cooling water to boiler-water quality in an annual amount of approximately 500,000 m^3 and uses the water in steam production. This IS exchange has meant a saving of more than 7.6 million m^3 of surface water for the selected period 1990–2002 in terms of reduced power plant surface water intake. The cooling water exchange required an investment of approximately 2.0 million DKK for technical installations and piping, shared by the partners at the time of project initiation. An additional investment of 40 million DKK was required for a pretreatment facility to treat both the surface water and the cooling water to boiler-water quality at the power plant. The price of cooling water from the refinery is linked to the price of surface water by a 50% discount. This means that the refinery gained a direct saving of approximately 1.8 million DKK or approximately $228,000 U.S. (in 2002) by trading the cooling water with the power plant, whereas the power plant achieved an equivalent saving caused by a corresponding reduced intake of surface water. Furthermore, the power plant achieves an indirect economic savings due to an energy-cascading effect of the 30°C heated cooling water, which is approximately the temperature required for the boiler-water pretreatment facility. The power plant has thereby avoided an investment of approximately 100,000 DKK[10] for preheating installations for the pretreatment facility. In the same way the refinery gains an extraordinary indirect saving, because the piping of used cooling water to the power plant has meant a postponed 8–10 million DKK investment in an extended wastewater treatment facility at the refinery, which would otherwise have had to treat the cooling water before discharge. Additionally, the cooling water exchange has postponed a collective upstream investment by extending the life of the current-capacity joint pipeline system for surface water intake and at the same time keeping the intake of surface water below the carrying capacity of the surface water donor lake, which is 5.0 million/m^3/yr (in 2004).

Replacement of Surface Water and Cooling Water with Wastewater

Wastewater from the refinery is piped to the power plant, where it partly replaces the intake of surface water and cooling water. Approximately 9,000 m^3 of wastewater was delivered from the refinery to the power plant in 2002, and more than 1.1 million m^3 in the period 1992–2002, thereby replacing the same amount of recycled cooling water or surface water for various secondary purposes at the power plant. The wastewater exchange between the refinery and the power plant required a total investment of approximately 2 million DKK at the time of initiation. The wastewater is a giveaway and a contractual evergreen, in the sense that the wastewater is not priced by the refinery and the contract has no time limitation. The economic benefit is, for the refinery, primarily related to the observance of discharge permissions and improved upstream availability of surface water due to a reduced intake by the power plant. The direct economic gains for the power plant are achieved by the replacement of surface water with wastewater and amount to approximately 58,000 DKK for 2002 and about 4.5 million DKK for the period 1992–2002.

As can be observed from table B of the e-supplement, the amount of exchanged wastewater has decreased during the selected period 1992–2002, which is explained by a parallel internal recycling program at the power plant, where a 200,000 m^3 buffer basin has made it possible to pool and recycle wastewater from the power plant, wastewater from the refinery, and drain water from the surrounding fields in order to extend the time frame between water intake and final discharge. This allows the reuse of the same secondary water several times, thereby reducing the intake of water of differing levels of quality. As mentioned above, one of the triggers for operationalizing the three symbiotic water projects was the installation of a water-consuming desulfurization plant at the power plant. The adjustment of these three symbiotic exchange projects and the internal buffer capacity at the power plant in relation to one another made it possible to run the desulfurization plant on low-quality water alone (see figure 2), thereby reducing the intake of an equivalent amount of high-quality water. Reducing the intake of high-quality water for the desulfurization plant made an equivalent amount of high-quality water available as feeder water for the boilers producing steam for the refinery and the pharmaceutical facility.

Steam and Heat Cogeneration at the Asnæs Power Plant

The symbiotic projects concerned with surface water, cooling water, and wastewater are to a great extent interconnected in an integrated circuit. Further down the supply chain the water types are converted into steam and delivered as a high-energy (by-)product to the neighboring facilities or as heat for the district heating system. Following this process flow, it can be noted that the contractual delivery of steam pushed the initiation or expansion of the three water-related IS exchanges as a result of the increased run-though of process water, whereas the steam supply itself arose for a number of different reasons. Among these, the economic and environmental arguments for cogeneration of steam, heat, and electricity compared with stand-alone production turned out to be the most important, in combination with the right timing for boiler renovation and increased steam consumption at the colocated facilities.

A detailed engineering calculation of the full-scale cogeneration effect of the IS relationships is beyond the scope of this article, partly because conditions (e.g., fuels and boilers) have changed over the years, and partly because access to relevant technical data and decision scenarios (e.g., alternatives to IS solutions) is difficult in the longer historical perspective. More current data have therefore been chosen to illustrate the emission savings from the IS steam/heat exchanges, but still based on a number of hypothetical assumptions. Table 3 illustrates a hypothetical emission-reduction scenario achieved by delivering steam and heat from the Asnæs power plant compared with production of the same number of gigajoules per year (GJ/yr)[11] from a hypothetical stand-alone facility fueled with natural gas (see table F of the e-supplement for data reference and assumptions).[12] Thus, for the selected period (1997–2002), an emission reduction of 154,000 tons[13] of CO_2 and 389 tons of NO_x has been achieved by the delivery of steam and heat from the power plant compared with the production of the same number of GJ/yr from a hypothetical stand-alone facility fueled with natural gas.

The calculations in table 3 can only be seen as a partial indication of the environmental benefits of the steam/heat IS relationships because the calculation is based only on production from Asnæs unit 5, fueled with Orimulsion.[14] Therefore, the steam/heat production from Asnæs units 2–4 (fueled by coal in 2002) is excluded, and so are the effect of fuel switching among the units and the adjustment to the grid in general. A more detailed engineered calculation of the full cogeneration effect is beyond the scope of the article, but table 3 gives a qualified picture based on a comparison with a theoretical alternative.

Turning to the economic performance of the steam/heat exchanges, the same complexity can be observed. Following the hypothetical setup above, the central question narrows down to the price of steam/heat produced by a stand-alone facility fueled with natural gas compared to the price of imported power plant steam/heat (DKK/ton).[15] This economic profile can by illustrated in more detail by examining the present-day steam exchange between the power plant and the Novo facility. In 1982 the first steam pipeline was established between the power plant and the Novo facility (maximum capacity 55 tons/hr), but in the late 1990s further capacity was needed due to production expansion at the Novo facility. Thus, the steam prognosis for the period 1999–2005 showed drastic increases in steam demand, as documented in figure A of the e-supplement.

On the basis of these prognoses, the Novo Group investigated three different cost scenarios for producing steam at a level above 55 tons/hr. The first scenario outlined an extension of the existing pipeline system to the power plant; a second scenario projected a company-based stand-alone facility operated by an independent utility supplier; and the third scenario was based on a company-based stand-alone facility operated by the Novo Group. Table 4 indicates comparative cost profiles for the three different scenarios.

The most cost-effective scenario was found to be the one based on an extended pipeline system between the power plant and the Novo facility—the IS solution. The investment/price ratio of the IS solution showed reasonable advantages compared with stand-alone alternatives, as documented by table 4. A new steam pipeline was therefore constructed and put into operation in 2001 with a considerable excess capacity for further production expansion at the Novo facility. The present steam price is thus based on three interrelated factors: an investment contribution for the new pipeline construction, an energy price, and a price for water pretreatment. The price of steam is constantly fluctuating, but as a general tendency it can observed that the price of steam has changed from the initial project start (1982) to the present date, reflecting the fact that steam is regarded today as a pure commercial product, and no longer as a by-product. Nonetheless, expanded steam capacity between the power plant and the Novo facility in 2001 remains economically feasible for both companies when compared with alternative scenarios, especially when related factors such as supply security, technological insights, and operational expertise are taken into consideration.

Table 3 Hypothetical emission savings from steam and heat generation at Asnæs, Unit 5

	Heat Production		*Emissions*					
			CO_2		SO_2		NO_x	
Year	*Steam Novo+Statoil [GJ/yr]*	*District Heating [GJ/yr]*	*Asnæs [tons/yr]*	*Stand-alone N-gas [tons/yr]*	*Asnæs [tons/yr]*	*Stand-alone N-gas [tons/yr]*	*Asnæs [tons/yr]*	*Stand-alone N-gas [tons/yr]*
1997	346,579	723,099	51,025	74,200	41	0	68	124
1998	384,440	1,088,667	67,789	101,411	54	0	90	169
1999	510,928	731,179	62,148	87,065	49	0	82	145
2000	568,302	730,127	65,880	91,298	52	0	87	152
2001	588,881	730,467	67,247	92,864	54	0	89	155
2002	682,083	569,784	67,102	89,142	53	0	89	149
Total	3,081,213	4,573,323	381,191	535,979	304	0	505	893
Total emissions avoided (tons)			154,788		−304		389	

Notes: N = natural gas; CO_2 = carbon dioxide; SO_2 = sulfur dioxide; NO_x = nitrogen oxides. Tons refers to metric tons; one metric ton (t) = 1 megagram (Mg, SI) = 10^3 kilograms (kg) ≈ 1.102 short tons.

Table 4 Comparative index cost profile for steam production, Novo (Scenario 1 = Index 100)

	Scenario 1 (IS solution with Asnæs power plant)	*Scenario 2 (Stand-alone facility operated by external operator)*	*Scenario 3 (Stand-alone facility operated by Novo)*
Price per ton	100	108	100
Total investment	100	174	120

Source: Tang (2004).

Pretreated Boiler Water from Power Plant to Oil Refinery

The economic complexity of the cogenerated steam exchanges is underlined by the fact that steam has developed gradually into a pure commercial product with a strong conventional market-determined price. Unlike the Novo facility, the refinery had a feasible means of producing its own process-related steam, which is why market price increases meant a decrease in the delivery of steam to the refinery, but an increase in in-house production of process-related steam (see table B of the e-supplement, Row 7). This development, however, has also meant that the cooperation between the refinery and the power plant has evolved into a supplementary cooperative strategy based on exchanges of pretreated boiler water. The increasing in-house production of process-related steam has meant that the refinery has temporary shortages of pretreated boiler water for its own process-related steam facility. On the other hand, the power plant has a permanent excess capacity in the pretreatment facility for boiler water. Piping treated boiler water from the power plant to the refinery has enabled the refinery to shave its peaks and thereby avoid an investment of 10 million DKK in an extension of its own pretreatment facility, whereas the power plant has achieved corresponding increased efficiency of its pretreatment facility. The direct investment in this boiler-water IS project has been small (1.5 million DKK), because existing pipelines and infrastructure have been used to facilitate the IS exchange, which is intended to deliver about 50,000 m^3 of pretreated boiler water per year. Thus the quantitative decline in the high-energy steam exchange between the refinery and the power plant has been counterbalanced by a high-quality water exchange based on the sharing of boiler water, underlining an ongoing adjustment to the economic conditions guiding the IS exchanges.

Salty Cooling Water from Power Plant to Fish Farm

The final step in the total water- and energy-cascading sequence among the companies is a recycling project where salty cooling water from the power plant is used in a colocated fish farm. After producing electricity, steam, and district heating, the boiler water at the power plant is condensed with salty cooling water, causing the temperature of the cooling water to increase by 7–8°C, and thereby rendering the salty cooling water usable by the fish farm. Approximately 23 million m^3 of heated salty cooling water from the power plant was recycled in the fish farm in 2002, whereas the rest of the salty cooling water was discharged directly into the Kalundborg Fjord. The total amount of discharged salty cooling water from Asnæs Power plant is equivalent to 16 million GJ of thermal pollution (2002), so the intake in the fish farm utilizes approximately 2.5% or 39,000 GJ (2002) of this residual heat stream. The exchange is a giveaway and a contractual evergreen requiring a smaller investment of 75,000 DKK and a payback time of less than 2 years, thanks to the 15 percent increase in production capacity in the fish.

Discussion of Economic and Environmental Aspects of IS in Operation

Evaluation of the selected IS exchanges has shown that some significant and some smaller environmental benefits have been achieved as a result of direct substitution, utility-sharing, and water/energy cascading. For example, substantial benefits accrue from exchange of cooling water between the power plant and the refinery, and some minor benefits are achieved by wastewater exchange between the same two companies. In total, the different IS arrangements contributed more than 95% of the total water supply to the power plant in 2002, compared with 70% in 1990, thus demonstrating a gradual development toward a more comprehensive IS supply system and a "system ability" to save groundwater.

A more critical view of the system also reveals some potential for further optimization, because more than 1.2 million m^3 of wastewater is discharged from the refinery, with only 9,000 m^3 reused at the power plant (in 2002) (table C of the e-supplement). Similarly, there seems to be a possibility of reusing some of the 2.3 million m^3 of wastewater from the Novo group beyond the present co-treatment arrangement with the public wastewater facility (see figure 1). Such expansion was investigated in the 1980s and 1990s, but was rejected for economic and technical reasons. The amounts of wastewater discharged from the system, though, still seem to imply possibilities for further IS activity, perhaps primarily in connection with further co-treatment arrangements or utility sharing.

The same picture can be observed in the case of the steam/heat projects, where some significant cumulative CO_2 reduction effects are achieved when one compares the system with hypothetical stand-alone production. Still, the total fuel efficiency of the Asnæs power plant is—among the other factors—dependent on local heat and steam demand. In general, Kalundborg (with only 20,000 inhabitants) is far too small compared to the total capacity of Asnæs (approx. 1,300 MW), again reflecting the fact that Asnæs was located in Kalundborg in a time (1959) before cogeneration was a consideration. A complete picture of the environmental effect of cogeneration is beyond the scope of this article, and it is recognized that such a full-scale analysis would naturally include the life-cycle assessment (LCA) and a system analysis of Danish power generation.[16]

These clarifications raise a number of questions in relation to the environmental benefits of IS exchanges. On the one hand, it can be observed that the IS exchanges involve environmental savings in terms of substitution or energy cascading. On the other hand, it can be questioned whether these savings are substantial, if we compare them with the potential for further IS arrangements and the total flows of waste material, energy, and water. We may further ask whether the downstream IS solutions have become an obstacle to radical upstream environmental improvements (e.g., reduction at source or the application of cleaner technologies) (Oldenburg and Geiser 1997). In the end, these points raise the question of whether IS can be viewed as a comprehensive strategy for environmental improvements.

It seems reasonable to say that the interpretation of the success of IS exchanges depends greatly on the context and the perspective in which these intercompany arrangements are viewed. The findings from the present analysis indicate that the IS exchanges only form a single element in an overall process of improving the environmental performance of a number of companies, each with a significant environmental impact factor. A large number of the IS exchanges are closely connected with the existence of air pollution controls or water purification plants, and the use of these installations has paved the way for the trading of reusable by-products (e.g., industrial gypsum, fly ash, waste, and cooling water). Thus IS exchange is not regarded as an isolated, ultimate environmental solution, but rather as part of a process of improving the total environmental performance of the individual company. As in most other cases, internal environmental improvements specified by annual improvement targets are given first priority by each company in the present case.

The potential for further IS improvements of the total regional material flows thus has to be evaluated in this context, and has to be considered in combination with a number of other in-house environmental initiatives, each of which seems to be central to the understanding of the rationale behind a given IS exchange. The analysis of the water-related IS exchanges has demonstrated the importance of this point, and this contextual understanding of the IS exchanges seems to be important if IS is to be judged as part of a comprehensive strategy for environmental improvements.

The same kind of contextual interpretation is important in the discussion of the economic aspects of the IS exchanges. The present evaluation has shown that the pure water-related exchanges lead to economic benefits because of the scarcity and costliness of groundwater resources. As shown by table E of the e-supplement, direct economic benefits can be achieved by replacing groundwater with other water sources. Nevertheless, from a corporate perspective, the direct economic savings from the use of other water sources are minor, which is why some indirect economic arguments are required to understand the economic motivation of the water-related exchanges.

These indirect economic arguments are, to a great extent, associated with long-term strategic planning based on the desire for increased supply security, operational capability, and the expansion of production without the obstacle of water shortages in the longer term. The direct economic returns related to the value of the exchanged by-product are thus balanced by indirect economic returns related to the operation in general. The latter represent the real economic argument for a number of the water-related IS exchanges, and the same tendency can be seen with a number of other IS exchanges in the case studied here.

This picture of indirect economic arguments changes, however, when one considers by-products with a higher initial value due, for example, to higher energy content or the market value of substances. The indirect economic arguments are of less importance to the steam exchanges presented in this study; it can be observed here that it is the direct value of the steam itself that is the fundamental driving force and focal point for the exchange relationships. Furthermore, the recipient can focus on its core business instead of running utilities. Thus, the steam exchanges differ radically from the water exchanges in terms of direct economic motivation and the commercial setup. This difference is clearly reflected by complex contractual agreements in the case of steam, whereas the water exchanges are based on simpler contracts.

A highly differentiated picture of the economic stimuli for the selected IS exchanges thus appears, stressing the need to understand the context in which the IS exchanges find their relevance and motivation. In general it can be observed that low-value by-product exchanges are often motivated by indirect economic benefits, whereas high-value by-product exchanges are often motivated more by direct economic benefits related to the value of the by-product itself. Between these two extremes there are a number of intermediate stages, which often move from low-value status to high-value status as a result of upgrading, or the gradual creation of a market and thus more direct economic benefits. This sequence is followed by increasing contractual complexity and a tendency toward a redefinition or reconception of the exchanged materials from waste/by-product status to commercial product status. If we take IS as an expression of a business-to-business economic transaction with a built-in environmental effect, it follows that the basic economy of these arrangements is driven by both long-term and short-term direct and indirect economic considerations depending on commercial market status and the production-related importance of the exchanged by-product.

In sum, these findings raise the question of whether IS relationships can be viewed as solely market-driven arrangements that evolve spontaneously, or whether the initiation of IS relationships requires something beyond pure market forces. The primary objective of this article has been to investigate the quantitative aspects and operational raison d'être of a selected number of IS exchanges, and these quantitative aspects do to a certain extent explain the immediate logic of the selected IS exchanges. Nevertheless, these quantitative findings also point to some additional perspectives relevant to a full explanation of the IS exchanges.

On one hand, the economic and environmental parameters listed in table D (e-supplement) seem to support a market-based view that explains the IS exchanges as a combination of operational, environmental, and economic benefits. This explanation seems to be important in the case of high-value by-products such as steam and heat, a picture that also seems to be supported by other studies of high-value IS exchanges (Chertow and Lombardi 2005).

On the other hand, a number of the selected IS exchanges in the present case have to be understood in a wider perspective where the direct economic benefits and market logic are more difficult to grasp. The wastewater exchange between the refinery and the power plant provide one example of this. When the direct short-term economic benefit is minor and the risk is high it often seems to be the case that companies refrain from engaging in IS exchanges unless something else drives the establishment of the IS exchange.

It has often been pointed out that social relations and individual agency at the interfirm level (Cohen-Rosenthal 2000; Korhonen 2004) might be important factors when by-products are pushed "across the factory fence." These factors might also explain why certain IS exchanges are initiated despite only minor short-term economic benefits. The present article does not investigate whether these "soft" social factors have had any influence on the initiation of the selected IS exchanges, but it can be observed that certain of the IS exchanges in the Kalundborg IS complex are such that these factors might provide further important explanations. To judge whether the social factors actually are important for IS initiation and operation would require further research (Brings Jacobsen 2005), and the question seems to be fruitful, because it touches on the discussion of the drivers of and barriers to IS exchanges in particular (Ehrenfeld and Gertler 1997) and industrial ecology in general (Van Berkel et al. 1997).

Conclusion

This study has presented some central economic and environmental facts related to selected IS exchanges in Kalundborg, and in so doing differs in detail and contextual scope from other analyses (see table A of the e-supplement). It has shown that some significant and some smaller environmental savings are related to the individual IS exchanges based on water substitution and cascading. Likewise, it has been shown that the economy of the IS exchanges differs in scale and scope depending on the specific production-related context. It seems clear that each exchange project is justified by an individual economic argument and related environmental considerations. The former argument has a narrow individual focus on economic viability in a wider operational context. The second implies a more collectivist approach to resource efficiency, driven by individual benefits and contexts. The water- and steam-related IS projects thus have to be explained at a variety of levels and from different perspectives. First, the low groundwater availability in the municipality created pressure for a diversified water supply strategy to secure a resource basis for production expansion at the different facilities in the region. Second, the installation of specific water-consuming processes at the power plant triggered the cooling water and wastewater exchanges between the power plant and refinery. Third, the contractual obligations for the export of steam and heat from the power plant to the neighboring industries and the city of Kalundborg created a high flow-through of process water at the power plant, in turn triggering the cooling water and wastewater exchanges and the increased intake of surface water. Fourth, direct and indirect economic arguments based on increased flexibility, capacity extension, technology access, supply security, and water substitution created an economic motivation for both the water and steam exchanges.

On the basis of these clarifications it can be concluded that the water/steam IS exchanges in Kalundborg are driven to a great extent by the search for a diversified water supply and the possibility of optimizing energy efficiency and supply security for economic and operational reasons. Nevertheless, this ongoing search for solutions to the problem of water supply and the extent to which some of the IS exchanges involve only minor and long-term benefits presumably indicate that a purely market-based explanation of the IS exchanges has to be supplemented by an explanation that takes individual agency and social factors during the project development phases into consideration. Especially in the early project development phase of an IS exchange, when exact benefits are unclear and uncertainty is high, individual agency can be assumed to be vital to project development; but how far this assumption is correct must be verified by further research.

The clarification of this latter point is important, because it is relevant to any full explanation of the IS complex in Kalundborg and the degree to which this example can be used as a model for IS initiatives at other locations. The economic, environmental, and operational facts pointed out in this article are all related to a specific context, partly explain why a number of IS exchanges were initiated in the case studied here, and highlight the obvious fact that IS exchanges have to contribute in some way to the bottom line of a given company. Nevertheless, the findings have also indicated that this obvious truth about IS requires a more sophisticated view of the bottom line that considers both short-term economic and long-term environmental and operational aspects that might lower initial entry barriers to engagement in exchanges. Taken together, these elements involve a more universal logic that might be transferable to other agglomerations of companies searching for IS solutions and point to IS as an element in a rational business perspective that takes sustainability into account.

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Notes

1. This assertion is based on a literature review and an evaluation of incoming research requests on IS to the Symbiosis Institute and the Symbiosis Industries, Kalundborg, 1995–2004.
2. See the methodological section for terminological explanations.
3. The question of environmental regulation is not touched upon in this article, but it is recognized that environmental regulations often work as a central precondition for IS implementation.
4. In this context cogeneration refers to power plants that utilize residual heat from electricity production for, for example, industrial purposes or district heating systems.
5. One megawatt (mW) = 10^6 watts (W, SI) ≈ 56.91 × 10^3 British thermal units (BTU)/min.
6. Editor's note: For an optimatization model of water reuse in industrial parks, see the article in this journal by Keckler and Allen (1998).
7. One cubic meter (m^3, SI) = 10^3 liters (L) ≈ 264.2 gallons (gal).
8. The calculation of proportion of the reduction in consumption attributable to IS exchanges versus reduced production capacity is complex and beyond the scope of this article if the result is to be exact. As one example, however, IS exchanges concerned with cooling and waste water reduced *de facto* the intake of surface water to Asnæs by approximately 55% during 1990–2002.
9. Based on an average currency exchange rate of 788 DKK = $100 U.S. in 2002. Obtained from Danish national bank statistics. The same exchange rate and year are used when DKK are converted to U.S. $ in other sections of the article.
10. An approximation referring to the time of the project's initiation (Christensen 2003).
11. One gigajoule (GJ) = 10^9 joules (J, SI) ≈ 2.39 × 10^5 kilocalories (kcal) ≈ 9.48 × 10^5 British thermal units (BTU).
12. At the time of the initiation of the steam exchanges (1982), the fuel for stand-alone production would probably have been fuel oil. In this analysis, natural gas is chosen as a hypothetical fuel for a stand-alone facility because this fuel would probably have been relevant to stand-alone production in a present-day picture, according to the companies.
13. Tons refers to metric tons; one metric ton (t) = 1 megagram (Mg, SI) = 10^3 kilograms (kg) ≈ 1.102 short tons.
14. Orimulsion is a fuel composed of 70% bitumen and 30% water. The fly ash from Orimulsion contains 12.2% vanadium and 2.7% nickel on average, which is extracted for recirculation. Orimulsion was used at Asnæs in the period 1994/1995–2002/2003.
15. The hypothetical stand-alone natural gas facility used in Table 3 is—technically—not identical to either of the two stand-alone facilities used in Scenario 2 or Scenario 3 in Table 4.
16. See work by Energy E2 (2000).

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