Modelling CO_2 savings and economic benefits for the Kalundborg Symbiosis

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Abstract

For more than 40 years something special has been going on in Kalundborg: manufacturing companies have worked together with the municipality and the local utility in order to save resources. An industrial ecosystem has been developed, named Kalundborg Symbiosis and organized as a private association[1]. No doubt, the industrial symbiosis created local growth and an increased competitiveness in the companies over the years, but it was difficult to answer exactly how big the environmental and economic savings were, since symbiosis was just "usual business". Therefore Kalundborg Symbiosis in partnership with Symbiosis Center Denmark has commissioned an analysis of the Symbiosis' effect on CO_2 emissions and resource savings. This paper also describes an economic analysis of the savings generated by Kalundborg Symbiosis compared with a hypothetical situation where it did not exist.

Introduction

The circular economy is a paradigm with sub-categories including industrial ecology and industrial symbiosis. In 2015 the EU issued an Action Plan for the Circular Economy, the intention of which is to better integrate countries' economic activities into their environmental activities by regarding waste resources as having value, and changing from a linear "buy, use, throw away" culture to a more circular mindset, where everything can be reused and increased in value. The concept of industrial symbiosis is part of the circular economy and can be viewed from various angles within a cooperation, with two or more industrial enterprises collaborating on shared solutions.

The most general approach is where the enterprises exchange resource flows in the form of materials, water and energy, such that one enterprise's by-product/side-product becomes another's input in its direct (core operations) or indirect production. The ambition is often to achieve full utilisation of the waste flows, ideally in a cascade – i.e. where (downcycled[2]) flows of lower value are "reused" and enter locations in production where the quality satisfies the need. Examples include deionised cooling water that can be used directly as additional water, or steam (at a higher temperature) which, following a process, becomes useful district heating (at a lower temperature), as well as organic wastewater whose energy can be utilised in various ways before it is treated in the normal

[1] Today the association consists of Novo Nordiske, Novozymes, Equinor Refining Denmark, Gyproc Saint-Gobain, Argo, Ørsted/Asnæs Power Station, Kalundborg Utility and Kalundborg Municipality.
[2] The term upcycling is also in use, where an otherwise low-value flow is converted into a high-value product or output.

manner. In this way, both parties can help to improve the efficiency of resource utilisation and thereby leverage various economic and environmental benefits, including positive marketing/PR.

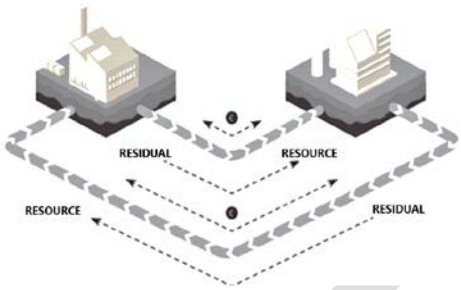

Figure 1: Conceptual sketch of a two-way trade of industrial by-products.

In addition, a symbiosis can also be viewed as a partnership, where the partners invest together in shared projects for their mutual benefit. An example might be two neighbouring enterprises that set up a shared wastewater treatment plant together rather than doing so individually twice, thereby benefiting from economies of scale. Another form of symbiotic partnership could be sharing a site or facilities – or even a workforce.

Objective

The objective of the present analysis is to obtain a calculated CO_2 saving for the Symbiosis. The socio-economic and commercial saving will also be calculated. The methods used for the environmental and economic calculations are analogous and are based on the same principles. The assumptions used in the two calculations are discussed in detail later in this memorandum. *"How much has the Symbiosis saved in 2015*[3] *in comparison with the assumption that the partners operated independently and maintained primary production?"*

Method

The present CO_2 calculation for the Symbiosis uses a new method. The procedure is based on developing a model of the Symbiosis that involves the latest methods in LCA and MFA science[4].

It is challenging to use a definitive and robust method because the Symbiosis has developed organically since it came into being in 1972, and there has been no final plan or use of "formulae". Therefore, it is difficult to predict how the Symbiosis would otherwise have turned out. Nevertheless, it was decided to compare the present Symbiosis (SYM) with a hypothetical alternative scenario (REF) that supposes independent operations for the symbiosis partners as a basis for 2015 (Baseline). In other words, it represents a situation where the paths on the symbiosis diagram have been cut, so

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3 The model is designed in such a way as to also test future scenarios, though using 2015 data (which presumably will not change substantially for 2018–19).

4 LCA: life-cycle assessment; MFA: material flow analysis. LCA allows documentation of the environmental impact of products and systems, either as individual units or comparing two units that perform a particular service. MFA maps a system (e.g. a society, industrial park or value chain), where particular flows and storage are tracked with a view to identifying distribution and hence the significance of those flows for a circular economy.

that each individual enterprise would have to supply itself independently. Resource utilisation is classified to the extent necessary to fulfil primary production in 2015 (the functional unit). The design and primary assumptions in REF were determined in discussion with the project partners in the Kalundborg Symbiosis.

The study is based on a life-cycle mindset and consequential LCA that complies with the ISO 14040 standard and that uses marginal (market-sensitive) energy, water and material resources by displacement. Both SYM and REF look at how much CO_2 is saved indirectly by displacement from the two systems, after which the difference between the individual net totals is examined in order to find a total net figure – i.e. a sort of "saving of a saving".

It is modelled as a "black box" so that the factories' internal processes and losses are ignored, even across the SYM and REF systems. In principle all input and output flows associated with a carbon footprint factor are utilised, as stated in the model's (internal Excel file) source list with a detailed explanation of the calculation. The model is based on three resource layers: Materials, Energy and Water, each of which is depicted in an accompanying diagram for SYM and REF. Data are associated with each individual flow, with some of the data for SYM and REF estimated manually. Generally CO_2 is calculated as follows for the three layers:

- **Energy**: based on the emission factors of the various forms of energy, and estimated from the forms of energy in the materials layer
- **Materials**: based on transport emissions and the production and procurement of virgin/conventional materials
- **Water**: based on emissions from electricity used to pump the water around

As explained in "Industrial Symbioses", in an industrial symbiosis there can be a holistic interplay between components categorised as water, energy and materials (see Figure 2), in particular due to the characteristics of the individual flows therein. It is necessary to transversely utilise the qualities of these three types of flow. The section on "Assumptions" describes how the relationship between the flow types as regards CO_2 origin is handled in the model.

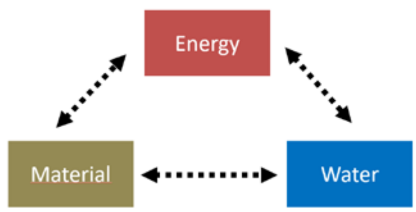

Figure 2: Transverse interaction between the energy, water and materials layers.

Identical processes in the two compared systems offset each other, such as identical utilisation processes or, for example, emissions of N_2O (a powerful greenhouse gas) from wastewater treatment, with no account being taken for these in the comparative (relative) analysis between REF and SYM. When looking specifically at the actual Symbiosis' carbon footprint, that is to say the absolute SYM figures, having as thorough an analysis as possible becomes relevant. In that case, processes cannot simply be immediately ignored. This function is built in to the model as an option, and the results are shown in Table 1. However, they must be taken with some reservations, as such an analysis of the industrial park's emissions and environmental footprint requires more specific data.

The analysis is based on the rationale of resource efficiency, turning lose-lose to win-win. What is understood by this is that by-products that would normally be disposed of and that could be used, for example as agricultural fertiliser, entail an environmental effect both with regards to disposal (transport to waste-disposal site) and to procurement (lost potential by not replacing/displacing production of conventional fertiliser).

Delimitation

The analysis is delimited to the resources exchanged between the enterprises involved in the Symbiosis. This particularly concerns the fertiliser from the materials layer and the materials used internally to produce biomethane in the 2018 scenario (the Kalundborg Bioenergi project). Here the figures for biogas (CH_4 and CO_2, which is then cleaned to produce biomethane) will be rather conservative, as use of external feed material from agriculture in Kalundborg Bioenergi is also planned. The complete figures can be found in the published environmental impact assessment.

Data collection

Data for the amounts of the energy, materials and water flows were collected from the Symbiosis partners by means of interviews (e-mail, telephone and in person) carried out between spring 2016 and spring 2017. Similarly, throughout the process there have been regular discussion and quality-assurance, as well as final approval of the model in its entirety, by the Board of the Symbiosis and experts from Novo Nordisk.

The collected data are commercially sensitive, and only Symbiosis Center Denmark has access to them as part of its partnership agreement with the Kalundborg Symbiosis. Hence, only the total CO_2 and resource-savings figures will be published in the present memorandum, as the other figures are subject to a confidentiality agreement.

Other specific and generic data for use in the model, such as CO_2 factors and transport distances, have been obtained from relevant sources and are stated in the model's source list together with detailed explanations.

Assumptions and assignments

In the model, the diagrams are divided into three "layers" to illustrate the symbiosis flows. The qualities of the various flows are considered in order to create value/perform a service for the functional unit. Here a distinction is made between substance flows and physical flows, divided into water, materials and energy. These characteristics cannot be considered separately, isolated from each other, and there will always be a certain amount of overlap (see description in connection with Figure 2).

When assigning the CO_2 figure to the three individual layers, it is important to understand the background. For example, CO_2 originating from water is presently assigned to the energy layer, as electricity is used to supply the water. In the same way, assignments will be made to the energy layer in connection with material flows (that otherwise contain water), if organic parts of those flows are converted to energy in the form of biogas. The water part will then be disregarded, as the CO_2 impact will be associated with the *water* as energy carrier in steam/district heating if it was originally wasted or cooled.

As previously mentioned, the layers have a reciprocal relationship and should therefore be compared in order for the mass balance (illustrated by the flow diagram's arrows) to make sense. In particular this concerns the material flows, which are often energy carriers (biomass to biogas in the form of electricity and heat or biomethane production). The same is the case for wastewater, for example, which is rich in organic materials as it contains nutrients that are ultimately used in agriculture. For instance, the Biomass/SBM flow in the materials layer is calculated as wet weight; the water is drained off in Environmental Engineering to produce NovoGro30. Therefore, the mass balance should be seen in the context of the flow in the water layer[5]. Another example can be found in the biogas process, where displacement of nutrients is expressed in the materials layer, whereas displacement of energy by use of biogas is expressed in the energy layer for the same material flow and process. To avoid double-counting, the three-layer system should therefore be considered as a whole. The model builds on the following selected systemic assumptions[6].

[5] It is possible to calculate the flows as elementary flows (e.g. the material's energy value and nutrients), but this would be too time-consuming, as the masses of the actual flows of by-products are already stated.

[6] Energy:

- Takes Ørsted Asnæs Power Station as the heart of the Symbiosis. In REF, Ørsted Asnæs Power Station is assumed not to operate within the Symbiosis
- Indirect effects from procurement of energy resources (cradle-to-gate) are implicit in data
- Electricity consumption for upgrading biogas etc. is ignored
- Heat loss through single pipes is not considered further (the stated figures are used directly)

Water:

- Ørsted Asnæs Power Station is assumed to be absent from REF, so Equinor and Kalundborg Utility's drain on Lake Tissø will be greater
- Cooling water is used for the individual energy production plants in REF
- In REF all of the water is obtained from the groundwater reserve instead of Lake Tissø
- NovoZymes' Environmental Engineering is not shared with Novo Nordisk

Materials:

- Marginal ash is displaced at Ålborg Portland instead of virgin material
- The sand is used for road construction instead of being disposed of
- The distribution of the energy masses between Novo Nordisk and Novozymes takes place in accordance with COD mass distribution
- Surplus sludge and SBM for NovoGro20* has the same water content and N:P ratio
- The nutrient distribution of sludge from Novo Nordisk to Novozymes' Environmental Engineering or Kalundborg Forsyning is secondary, as both types of sludge are ultimately spread on the soil
- All material flows are viewed as energy carriers and/or nutrient carriers
- The handling practice for all other material flows remains the same in both scenarios (no net difference in CO_2)
- The difference in N_2O emissions between fertilisation with raw biomass or biomass that has been converted to biogas is ignored.

Environmental results

A number of scenarios and assumptions have been tested to check their significance and sensitivity. The results are summarised in Table 1.

The Baseline scenario for 2015 indicates as follows: Ørsted Asnæs Power Station supplies coal-based steam and district heating to the Symbiosis. This displaces alternative use of natural-gas-based energy. The coal-based electricity to the electricity grid displaces electricity based on an average energy mix and displaces the same type of electricity. The most general form of handling biomass residues in 2015 in the alternative scenario would be conversion to biogas before spreading as fertiliser, and therefore this will be relevant as a baseline in REF[7].

	Scenarios/assumptions	The Symbiosis' emissions (tonnes CO_2)	Difference between scenarios (tonnes CO_2)	Savings in REF – SYM (tonnes CO_2)	Difference between scenarios (tonnes CO_2)
	Baseline scenario 2015: Ørsted/Asnæs Power Station powered by coal	-732,988	–	-443,382	–
SYM	Marginal electricity displaced	-727,838	5,150	-205,608	237,774
SYM	2019: Ørsted/Asnæs Power Station powered by woodchips (+ heat pump)	-47,445	685,543	172,807	**616,189**
SYM	2018: Kalundborg Bioenergi: Novo Yeast Cream, NovoGro20* and sludge are converted to biogas locally before spreading as fertiliser	-714,215	18,773	-424,610	**18,772**[8]
REF	Novo Yeast Cream and NovoGro20* spread directly as fertiliser	–	–	-439,375	-4,007
REF	Kalundborg Forsyning supplies biomass-based district heating instead of natural-gas-based	–	–	-484,453	-41,071
REF	Fuel oil used instead of natural gas	–	–	-419,284	24,098

Table 1: Summary of CO_2 emissions and savings. Negative figures indicate net CO_2 emissions; positive figures indicate savings compared with REF and/or Baseline. The table is divided into emissions from SYM itself and a SYM–REF difference, and a breakdown by measure/assumption that can be varied for SYM and REF.

[7] On the other hand, the Symbiosis' practice up to 2018 (when Kalundborg Bioenergi starts) is to spread most of the bio-residues directly on agricultural land. Therefore the effect of an assumption of *direct* spreading of all biomass in REF has also been tested.

[8] It must be emphasised that the estimated CO_2 saving is much higher in practice, as this analysis is limited to exclusive use of the Symbiosis' resources as feed material for Kalundborg Bioenergi.

Table 1 shows variants of scenarios and assumptions, with their significance tested individually. It is also possible to test combinations of two or more variants simultaneously, depending on the purpose and how realistic they are.

Two CO_2 emissions analyses have been created: the first charts exclusively the amount of emissions the Symbiosis itself creates, and the other compares this with a hypothetical system (REF) to see whether the Symbiosis has produced CO_2 savings. In this case, SYM and REF are calculated in relation to each other, so when an improvement (CO_2 reduction) is assumed in REF it makes the SYM picture look worse, and vice versa.

If the combined CO_2 emissions in the REF system are reduced in relation to the SYM system, it will therefore entail an overall negative net saving compared with Baseline. For example, the difference in emissions is negative when Novo Yeast Cream and NovoGro20 are converted to biogas regionally in REF, as that makes the REF scenario appear better (-4,007 tonnes of CO_2). On the other hand, the figures are positive when the SYM system overall copes better, e.g. in the case of biomass treatment in Kalundborg Bioenergi (18,772 tonnes of CO_2).

A combination of Ørsted/Asnæs Power Station's green conversion and Kalundborg Bioenergi entails a total net saving of just under 635,000 tonnes of CO_2 at overall Symbiosis level (shown in bold), compared with the Symbiosis's Baseline in 2015. It is estimated that this saving would have amounted to approximately 80,000 tonnes of CO_2 more in SYM 2019 if Equinor had not decided to introduce its own natural-gas boiler instead of continuing to take (now green) steam from Ørsted/Asnæs Power Station. In addition it is estimated that by far the greatest share of CO_2 emissions are in the energy area, which indicates good potential for optimisation here.

Almost 99 per cent of the total CO_2 emissions in Baseline come from the energy layer. The reasons for this are that the forms of energy are CO_2-intensive and that the amounts are enormous, seeing as they are supplied to the process industry. A proportion of the carbon footprint can, as previously described, in principle be ascribed to water and materials, but it has been chosen not to do this due to the holistic picture.

Just under 18,000 MWh are saved by mutual utilisation of resources. Nearly 90,000 tonnes of material have been saved from going to landfill and have been given new value. 3.6 million m³ of drinking water have been saved in relation to REF, of which 343,000 m³ is estimated to have been reduced thanks to the Symbiosis' exchange and coproduction, as well as by avoiding mass cooling of individual processes.

Scenarios/assumptions	Energy (MWh)	Water (m^3)	Materials (tonnes)
Baseline scenarios 2015: Ørsted/Asnæs Power Station powered by coal	17,589	3,644,220 drinking water, of which 342,880 from missing symbiosis	87,211
2019: Ørsted/Asnæs Power Station powered by woodchips (+ heat pump)	24,095	See above	7,331
2018: Kalundborg Bioenergi: Novo Yeast Cream, NovoGro20* and sludge converted to biogas locally before spreading as fertiliser	100,477	See above	87,211

Table 2: Savings of energy, water and materials in SYM Baseline compared with REF for individual scenarios.

In both the Baseline 2015 and 2018 scenarios, 87,000 tonnes of materials are saved, including gypsum, fly ash, sulphur, sand and ethanol. There is no difference between these two scenarios and between SYM and REF, as the handling of the different materials (NovoGro, Novo Yeast Cream and wastewater sludge) is assumed to be the same in REF as in SYM. However, only approximately 7,000 tonnes of material will be saved in the 2019 scenario, as Ørsted/Asnæs Power Station will no longer produce fly ash and gypsum. In return the energy saving and the associated reduction in CO_2 emissions will be considerable. The energy saving will be achieved thanks to the heat pump now extracting "free" heat from Kalundborg Forsyning's wastewater. This requires very little electricity, but displaces in return a certain amount of natural gas in REF. Four times as much energy will be saved in addition when Kalundborg Bioenergi starts production, as the biomethane will displace natural gas, which entails a total saving of over 125,000 MWh per year from 2020. The total energy figures indicate a net export of energy (electricity and biomethane) out of the Symbiosis. In this way, the Symbiosis has become a so-called "prosumer" – that is, an association that both consumes *and* produces resources for resale.

It is modelled in the three following resource layers, with by far the largest CO_2 emissions being found in the energy layer (-446,180 tonnes), followed by the water layer, influenced by modest emissions from the difference in electricity consumption for water pumping and treatment (-119 tonnes). The materials layer actually achieves a saving in comparison with REF (2,917 tonnes), but this would have been larger if the contribution from materials-based energy, which is displaced (especially from biogas), had been transferred from the energy layer.

Economic results

A considerable socio-economic and commercial saving has been estimated. This has been calculated only for 2015 and therefore only includes a comparison of Ørsted/Asnæs Power Station as a coal-powered power station. However, the significance of a single assumption has been tested: the assumption that Kalundborg Forsyning supplied woodchip-based district heating instead of natural-gas-based in REF (see Table 3). The figures are immediately consistent with one of the sources, which states an annual saving of EUR 15 million (equivalent to DKK 115 million)[9]. Regrettably, however, it has not been possible to find out how this figure was calculated.

2015	Socio-economic (DKK)	Commercial (DKK)
Exclusively natural-gas-based energy in REF	106 million	182 million
Energy	55%	55%
Water	32%	27%
Materials	13%	18%
Natural-gas-based energy in REF, except for district heating, which is woodchip-based	113 million	137 million
Energy	58%	40%
Water	30%	36%
Materials	12%	24%

Table 3: Estimated financial savings for the 2015 scenario, with SYM compared with REF. The financial savings for the two substantial assumptions have been tested. The distribution is stated for the three resource categories.

It is estimated that Ørsted/Asnæs Power Station and the energy pipelines between the enterprises have already paid for themselves. At the same time, the heating price within the Symbiosis is regarded as including the full price of investments etc.

The socio-economic benefit is regarded as a contribution to GNP, partly through reuse of resources and utilisation of cheaper input in production instead of disposal, as well as the best possible energy and water-resource utilisation nationally, and thereby reducing imports. This section considers prices for import goods etc., for instance when raw gypsum is imported from Spain (REF) or when ashes are exported (SYM). As far as possible, government taxes and duties have been deducted from the prices in order to examine the effect of the cash flows that cannot simply be transferred to the state.

It can be seen that the enterprises themselves save more together, as there are also some savings in the taxes and duties that would otherwise be transferred to the state. It is also particularly interesting that the enterprises save less by partly introducing woodchip in REF, as woodchip is exempt from duties. In return, society (the state) saves more, that is to say DKK 7 million, when SYM is compared with a REF where the unit price for heat production is higher (excluding duties). It is generally well known that the prices of heating by natural gas and woodchip are roughly the same: construction costs for natural gas are comparatively higher, and operating costs comparatively lower than those for woodchip[10]. The savings from the green-energy scenarios for 2018–19 have not been calculated.

[9] Orée, "Industrial and Territorial Ecology, a sustainable economic development tool", PDF, on page 1 of 4.
[10] https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger

Conclusion

The Symbiosis contributed a socio-economic saving of DKK 106 million in 2015. The enterprises achieved a combined saving of DKK 182 million, assuming full use of natural gas in REF. On the other hand, in 2015 the Symbiosis generated considerable net emissions (443,000 tonnes of CO_2), explained by the large amounts of CO_2-intensive energy from coal. Coal is more CO_2-intensive than fuel oil, let alone natural gas, which in the REF scenario can compete with the CO_2 emissions for the same energy supply. There will not be any considerable reduction in CO_2 until the years up to 2020, primarily as a result of Asnæs Power Station's green conversion to CO_2-neutral fuel and Kalundborg Bioenergi's biomethane produced within the Symbiosis. SYM will thereby achieve a total saving of 635,000 tonnes of CO_2 annually, if the same REF conditions are assumed. This analysis' environmental accounts are restricted to the most general climate category. A future analysis may be extended to take account of savings in acidification (sulphur utilisation etc.) and similar. However, it appears unlikely that the total environmental saving will change, as CO_2 already comes from 99% of the system.

In REF we have assumed what the equivalent would have done in 2015. The closer we approach optimal use of resources, the more difficult it seems to be to harvest "low-hanging fruit" in a way that is financially reasonable. If it were decided to depart from the methodological norms and consider REF as a system from e.g. the 1980s, it would only help the environmental accounts a little on materials and possibly also water, due to the more CO_2-intensive electricity used for water pumping. Moreover, it would not have a great influence on energy, as coal is traditionally the most polluting energy source.

We now have the technologies – it is simply a question of optimising the interaction between them so that we can achieve more with less, where there is a commercial reason for doing so. The energy layer is well on the way to becoming fully optimised in the Symbiosis thanks to various technologies. On the other hand, we are facing a time when water and materials become scarce resources, including in an international perspective. Therefore it is important in the coming years to carry out a systematic screening of all available streams to fulfil the ambition to be the world´s leading industrial ecosystem with a circular approach to production.