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A preliminary assessment of industrial symbiosis in Sodankylä

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ABSTRACT

This study focuses on developing a possible architecture of planned industrial symbiosis in Sodankylä, Finland. The municipality of Sodankylä is considering the establishment of new businesses to boost the region's local economy. The preliminary assessment presented here evaluates some new markets, including combined heat and power plants, a biogas reactor, greenhouse farm, fish farm and several insect farms. These businesses should be able to fulfil the criteria of sustainability and circular economy. This study proposes an architecture where companies can quantify the value and the cost of material exchange. The combined life cycle cost and the net present value of symbiosis are estimated at €93 and €43 million respectively. The combined life cycle cost of waste management is calculated to be €6.40 million. The study's novelty is its projection of the quantified cost of bio-waste and recyclable waste of industries, highlighting the monetary value of industrial symbiosis where waste products can turn into industries' raw material. The value gained and cost reduced by such symbiosis is forecast at 14.65% and 6.8% respectively.

1. Introduction

Moving from business as usual to sustainability is a paradigm shift. Using waste as a by-product compels industries to cooperate and recycle their waste. Sustainability and value creation are significant challenges for businesses. A sustainable business model must demonstrate three essential characteristics. The first is its value proposition, meaning the product or services provided by the business and the cooperation it forges. The second is an ability to create value from its business activities and to leverage the technology it holds. The final characteristic is to capture value from the product costs and the revenue stream (Bocken et al., 2014). Sustainable businesses consider factors affecting environmental performance, economic contribution and their social responsibility (Azapagic, 2003). This requires businesses to display their environmental impact by strategic mapping and graphical interpretation (De Benedetto and Klemes, 2009). They need to encourage community engagement (Benoît et al., 2010; Benoît-Norris et al., 2011) and agreement on economic benefits from industrial experts (Domenech et al., 2019). Businesses that have successfully shifted to sustainability have encouraged participation in industrial symbiosis (Domenech and Davies, 2011). Industrial symbiosis allows businesses to maximise use of resources by recycling (Angren et al., 2012). It involves opening a mutually beneficial communication forum (Allard et al., 2012; Albertsson and Jónsson, 2010), evaluating the dominant factors in sustainability (Baas, 2008), making matches between customers and practitioners (Cecelja et al., 2015) and sharing the lessons learned (Aparisi, 2010). The key enabling factors of industrial symbiosis are environmental impact and social responsibility of industries. Industrial symbiosis also presents challenges in terms of knowledge-sharing and having a proper platform for monitoring activities.

The European Commission has been monitoring industrial symbiosis in Europe, considering a variety of aspects such as the economic benefits of reducing cost by processing waste, reducing landfill materials and penalties for environmental non-compliance, new sales generated, demolition and waste management (European Commission, 2011; European Commission, EU Construction, and Demolition Waste Management Protocol, 2016). Finland keeps records of symbiosis activities in the Finnish industrial symbiosis system (FISS) (Hirschnitz-Garbers et al., 2015). Business models are transitioning towards sustainability in Nordic countries. Eco-innovative models are encouraged to identify customer behaviour (OECD, 2012), economic benefits (Joyce and Paquin, 2016) and the products' environmental and social benefits (Daddi et al., 2017; Jørgensen et al., 2008). Other key factors to be considered are the environmental impact of products in

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industrial cluster (Daddi et al., 2015), the outcome of the symbiosis (Cutaia et al., 2015), legal aspect of cooperation (Cutaia et al., 2014), the role of public and government institutions (Costa and Ferrão, 2010) and specific features of sustainability (Chun and Lee, 2013). Sustainable business practices are built on a foundation of an accurate evaluation of an industry's waste and an estimation of the energy throughput (Schwarz and Steininger, 1997; Posch, 2010). Quantitative methods should be applied to show the performance of industrial symbiosis (Paquin et al., 2015; Jacobsen, 2006).

The literature reveals methods to estimate the economic, environmental and social benefits of industrial symbiosis, coupled with sustainable business models. It is currently unable to quantify the monetary value created by cooperation among participants. It is normal for businesses to pay least attention to ideas and innovations that fail to show an economic gain. However, quantifying the value of waste products gives an economic incentive for industries to move their business strategy towards the circular economy. A core part of this study is to evaluate the economic value of by-products (waste) so that businesses are likely to consider innovative methods that take them towards the circular economy and industrial cooperation. The next section presents an architecture of industrial symbiosis in Sodankylä. Section 3 postulates methodology to estimate the value of this symbiosis. Section 4 reveals the potential value gained by the symbiosis, and finally, Section 5 presents the conclusion.

2. The architecture of industrial symbiosis in Sodankylä, Finland

Sodankylä is in the Lapland region of northern Finland. The Sodankylä municipality covers an area of over 12,000 km^2 and has a population of 8300. It is colder than most other cities in Finland: Sodankylä's annual average temperature is just -0.4 °C. Fig. 1 shows Sodankylä's position in relation to the rest of Finland. The municipality is attempting to boost its local economy by encouraging the establishment of new industries and farms. These businesses have to fulfil the criteria of sustainability by cooperation and be able to accomplish circular economy in the area. The planned industrial symbiosis consists of six companies. Of these, one business – the main power plant - is currently operational. The municipality is investigating the possibility of constructing several combined heat and power (CHP) plants, a greenhouse farm, fish farm, insect farms and a biogas reactor.

Industrial symbiosis can be defined as material exchange among cooperative actors through turning waste from one industry into the raw material of another. This study investigates and evaluates the waste products from the cooperating companies in this proposed architecture of industrial symbiosis. Fig. 2 identifies the material flow. Sodankylä's municipal authority is responsible for maintaining the cooperation among the participating businesses. The city has two relevant departments, one each for waste management and wastewater treatment businesses. The six companies participating in the symbiosis are as follows:

Fig. 3 illustrates the circularity of the regional economy. The illustration is merely a representation of this regional business approach towards the circular economy. It highlights how the majority of the waste products from the participating industries will serve as the raw material to feed the biogas reactor. The insect farm will provide feedstock to the fish farm. The by-product generated in the biogas reactor is likely to be used in the greenhouse farm. This architecture shows a perfect circular economy scenario where waste products from industries are utilised in the symbiosis, reducing the combined life cycle cost of waste products, as anticipated with the presented architecture. Participating in the symbiosis will result in value creation by monetizing waste products.

2.1. Main power plant

The main power plant is the source of heat production in the region expands over 30 km^2. The plant's capacity is 34 MW. Its input fuels are woodchips, peat and heavy oil which are burnt to produce an annual average of 9.92 MW heat. The primary electricity consumption of the plant is 0.21 MW per year. This electricity and all the input fuels are provided by external industries. The power plant takes freshwater from the municipal

Fig. 1. Map of Finland. The location of Sodankylä pinned on the map. (https://www.google.com/maps).

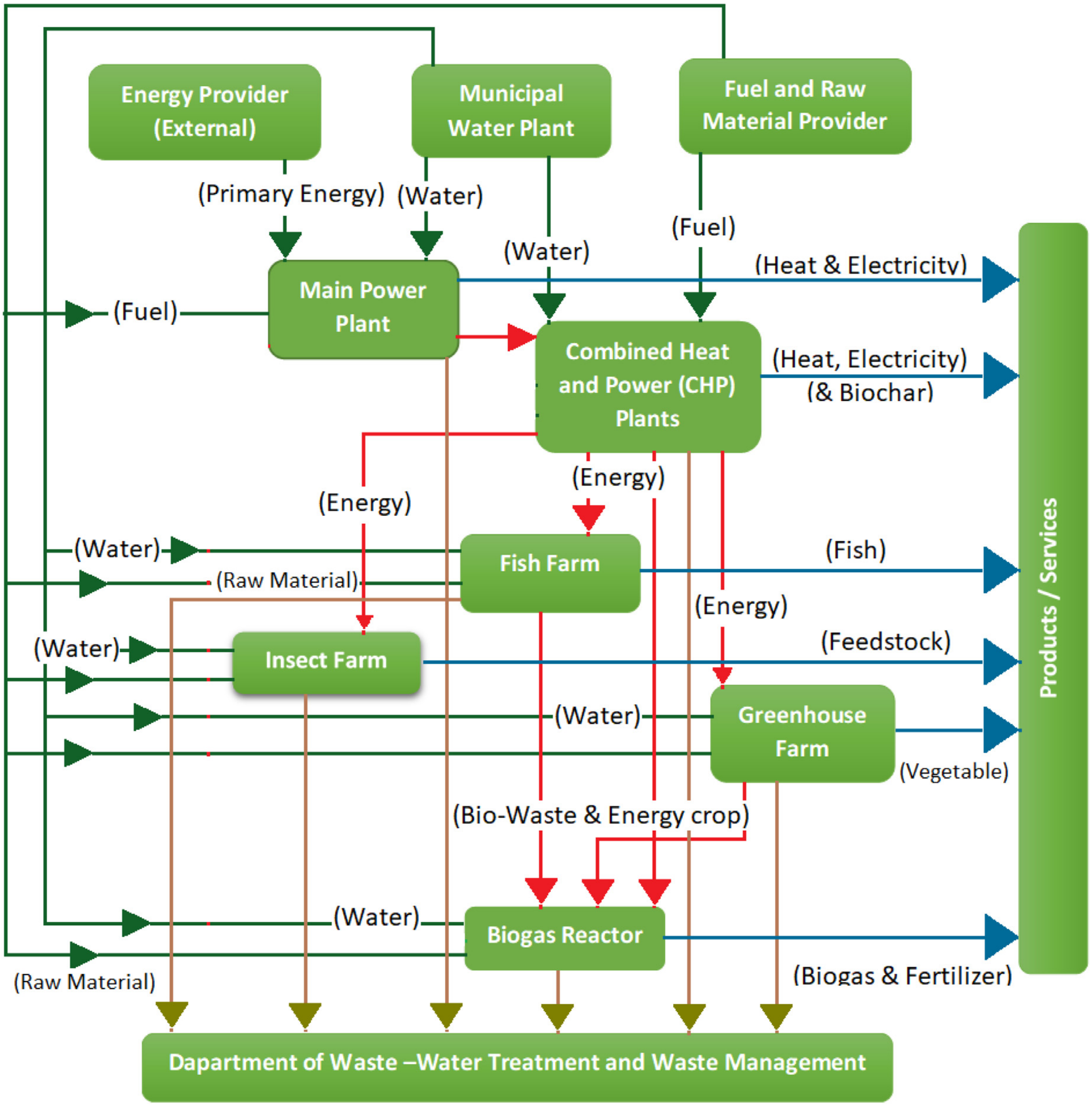

Fig. 2. The architecture of industrial symbiosis in Sodankylä, Finland. Material flow shows inputs and outputs of the nodes, identified with various colours. Green represents the input; blue depicts the output and red reflects the material exchange. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

water plant and releases wastewater to the municipal wastewater treatment department. The plant also releases residue waste, which is sent to the department of waste management.

The plant is capable of supplying primary energy to the planned CHP plants. The costs of the fuels (woodchip, peat and heavy oil) are €0.69, €0.72 and €0.38 million per year respectively. The operation and maintenance costs are assessed at €0.2 million per year. The revenue from the heat sold by the plant is estimated at €3.51 million per year. Table 1 presents the parameters used in the calculation. The plant's capital value debt obligation is assumed at €4 million, with an interest rate of 3%.

2.2. Combined Heat and Power (CHP) plants

The proposal envisages six combined heat and power (CHP) plants to be constructed in Sodankylä. These plants are woodchip fuel-based, capable of producing 4.3 MW of heat for the region. They have a 29% efficiency for electricity production and 55% efficiency for heat production. The plants will also produce biochar as a remnant of the burnt woodchip. This is to be used as a soil improver in the greenhouse farm and also can be sold on the global market. Biochar can be used in filtration and purification systems for drinking water. Wastewater from the CHP plants will go to the department of wastewater treatment. The plants will supply heat and electricity to all the companies in the symbiosis. The price of electricity in the area is assumed at 46 €/MWh. The operation and maintenance costs for all six plants are assumed at €0.2 million per year. Their total cost of energy production is estimated at €1.9 million per year, and the revenue of the product is calculated at €3.2 million per year. Table 2 shows the parameters used in the calculation, including the investment cost of the six CHP plants, which is expected to be €10.5 million. The investment cost includes a 30% subsidy on the original investment estimate.

2.3. Greenhouse farm

The municipality plans to construct an improved greenhouse farm in Sodankylä. The concept of this farm comes from the integrated rooftop greenhouse presented in (Manríquez-Altamirano et al., 2020). In

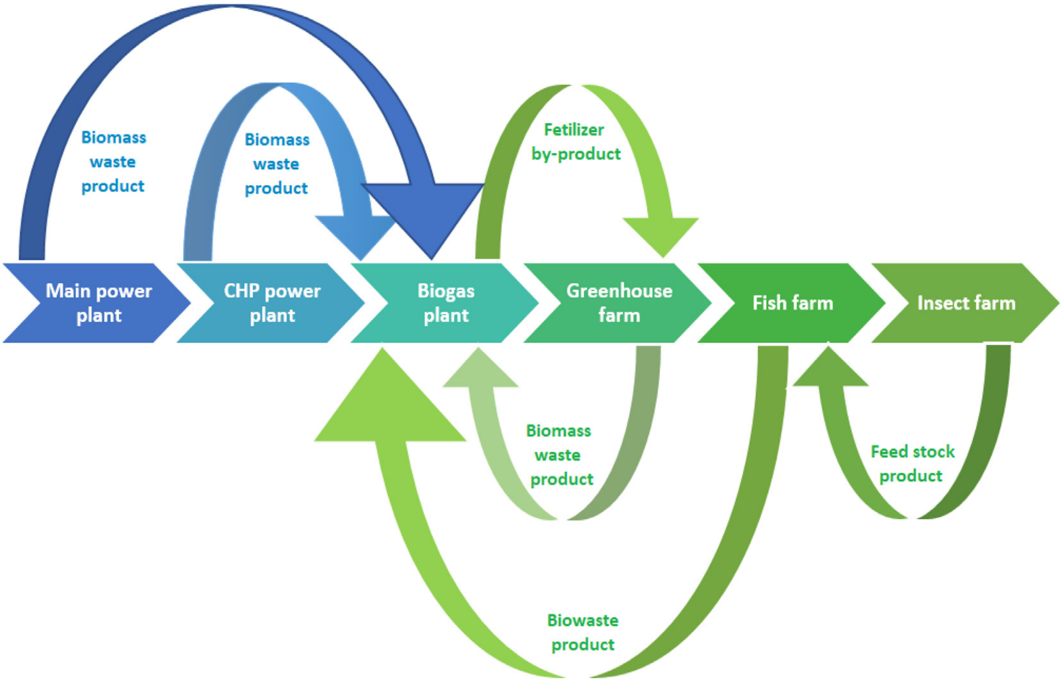

Fig. 3. Representation of circular economy in industrial symbiosis.

Table 1
Parameters used in main power plant evaluation.

Name	Value
Cost of heavy oil	[1]1000 (€/1000 l)
Cost of peat	[1]13 (€/m^3)
Cost of woodchip	[1]18 (€/m^3)
Total cost of fuel	[2]2.0 (€ million/year)
Price of heat	[1]59 (€/MWh)
Revenue of sold heat	[2]3.5 (€ million/year)
Interest rate	[2]3%
Debt	[2]4 (€ million)

[1] Natural Resource Institute Finland (LUKE) estimation.
[2] Author's estimation.

Table 3
Parameters used in greenhouse farm evaluation.

Name	Value
Greenhouse farm area	[1]5000 (m^2)
Tomato yield	[1]70 (kg/m^2)
Yearly production	[4]350 (tonnes/year)
Price of tomatoes	[2]3.05 (€/kg)
Cost of tomato production	[3]1.72 (€/kg)
Interest rate	[4]3%
Investment cost	[4]1 (€ million)

[1] Natural Resource Institute Finland (LUKE) estimation.
[2] Statistics Finland (Prices and Costs, 2020).
[3] Luke report (Niemi and Väre, 2018).
[4] Author's estimation.

Sodankylä's case, the preliminary assessment is based on a greenhouse farm with an area of 5000 m^2, producing a yield of 70 kg/m^2. The study assumes the production of tomatoes, but potted plants and salad leaves are possible products to be added to the assessment in the future. Wastewater and inorganic waste released from the farm will be handled by the departments of wastewater treatment and waste management. The farm will also produce a significant amount of bio-waste to be used in the biogas reactor. Table 3 shows the parameters used in the calculations for the evaluation of the greenhouse farm. The revenue from the produce is €1.0675 million per year, derived from the price of tomatoes in 2018, which is recorded at 3.05 €/kg. The operation and maintenance costs of the farm are assumed at €0.2 million per year. The cost of production is estimated at €0.802 million per year.

Table 2
Parameters used in combined heat and power plants evaluation.

Name	Value
Produced heat	[1]24120 (MWh)
Produced electricity	[1]16560 (MWh)
Income from biochar product	[2]1.10 (€ million/year)
Cost of the product	[3]1.90 (€ million/year)
Revenue from the products	[3]3.2 0(€ million/year)
Interest rate	[3]3%
Investment cost	[3]10.50 (€ million)

[1] Natural Resource Institute Finland (LUKE) estimation.
[2] University of Vaasa estimation.
[3] Author's estimation.

2.4. Fish farm

A fish farm is also one of the businesses under consideration to improve the industrial ecology of the region. The farm investigated has a production capacity of 70 t per year. Fish farms in this region would typically produce either rainbow trout or whitefish. This study considers the production of whitefish only. The municipality is responsible for delivering fresh water and feedstock to the fish farm. Fish farms release bio-waste (sludge) and wastewater. The municipality's wastewater treatment department will collect the wastewater, while the anticipated 438 t per year of sludge from the farm will go to the biogas reactor. Table 4 presents the parameters used in the fish farm calculation, including an assumed fish price of 10 €/kg.

Table 4
Parameters used in fish farm evaluation.

Name	Value
Heat consumption	[1]29 (MW)
Electricity consumption	[1]472 (MW)
Cost of heating	[2]31393 (€/year)
Cost electricity	[2]15286 (€/year)
Cost of fish production	[1]67403 (€/year)
Amount of fish production	[1]70 (tonnes/year)
Price of fish	[1]10 (€/kg)
Cost of feedstock	[1]1.50 (€/kg)
Cost of freshwater	[1]1.17 (€/kg)
Interest rate	[1]3%
Investment cost	[1]0.43 (€ million)

[1] Natural Resource Institute Finland (LUKE) estimation.
[2] University of Vaasa estimation.
[3] Author's estimation.

The operation and maintenance costs are assumed at €0.4 million per year and the revenue from the product calculated at €0.7 million per year. The assumed investment cost is €0.43 million.

2.5. Biogas reactor

The municipality plans to construct a biogas reactor, offering the potential to reduce waste in the region. This reactor will be capable of processing different types of bio-waste coming from various industries. The reactor's capacity is assumed to be 500 m^3, with a digestate flow of 2700 t per year. It has a potential of producing 230 kW of energy. The bio-waste will come from greenhouse farm, fish farm and other bio-waste producers in the region. The waste from the main power plant is burned residue and ash of the input fuels after combustion and gasification. Bio-waste from the greenhouse farm includes stems and leaves. Sludge from the fish farm is the third type of bio-waste. Additional biomass can be collected from other local businesses, including manure from a cattle farm and slaughter waste from a reindeer farm. The challenge is to maintain a steady intake of the raw materials so that the biogas reactor can achieve a constant production rate. The reactor also produces fertilizer as a by-product: this is to be used in the greenhouse farm. Methane production from the reactor is expected to be 203,250 m^3/year, with an estimated density of 0.72 kg/m^3. The cost of the digestate flow is put at €0.135 million per year. The revenue from the reactor's production is likely to be €0.16 million per year. Table 5 lists the parameters used in the calculations. The investment cost of the biogas reactor is €0.4 million, and the interest rate applied is 3%.

2.6. Insect farm

One of the most innovative businesses in Sodankylä's proposed development is insect farming, which is a relatively new concept for Finland. It will produce feedstock for the fish farm. An insect farm requires only stable heat, with very little labour and investment costs. The equipment for insect farming is available in Finland, as is the necessary specific training and education. The study considers the construction of six insect farms, each with an area of 50 m^2. The total output from the six farms is calculated at 4.2 t every year, and the cost of production estimated at €19,384.64 per year. The revenue from the farms' output is assumed at €25,200 per year, and the investment cost of the insect farms is put at €25,000. Table 6 presents the parameters used in the calculation.

Table 5
Parameters used in Biogas reactor evaluation.

Name	Value
Digestate flow	[1]2700 (tonnes/year)
Price of methane	[1]1.22 (€/kg)
Capacity of the reactor	[1]500 (m^3)
Potential energy of the plant	[1]230 (kW)
Potential of methane production	[1]203,250 (m^3/year)
Methane density	[1]0.72 (kg/m^3)
Bio-waste collection fee	[1]50 (€/ton)
Biogas produced	[1]233737.50 (kg/year)
Cost of digestate	[2]135000 (€/year)
Revenue from the product	[2]168291 (€/year)
Interest rate	[2]3%
Investment cost	[2]0.40 (€ million)

[1] Realizing bioeconomy in the north of Finland (Alaraudanjoki, 2016).
[2] Author's estimation.

2.7. Identifying material exchange in industrial symbiosis

All the businesses mentioned are participating in the symbiosis. The acting and coordinating authority is Sodankylä municipality, which is responsible for a fruitful exchange of materials among industries. An industrial symbiosis network matrix has been constructed, as shown in (European Commission, EU Construction, and Demolition Waste Management Protocol, 2016). Table 7 presents the network connections among the companies. A "1" in the grid denotes possible material exchange among sectors; "0" is used where there is no exchange. The resource flow between industries can be either unidirectional or bidirectional.

The network matrix does not recognize the municipality or its departments of wastewater treatment and waste management. This industrial symbiosis entails three types of material exchange. First, there is energy, namely heat and electricity. Then there is biowaste in the forms of sludge and energy crops. The last type is recyclable waste, comprising fertilizer and biochar. The network identifies two types of waste products: wastewater and non-recyclable waste like ash, inorganic waste and residual waste.

The CHP plants supply energy to all the new businesses. At the same time, the main power plant supplies primary energy to the CHP plants. The primary energy for the main power plant comes from an external supplier, not identified as a cooperative actor in the network. Similarly, another external entity is responsible for supplying fuels for both the main power plant and CHP plants. Freshwater to all industries comes from the municipal water plant, which is also unrecognized in the network. The biogas reactor will be an essential business in the region, responsible for collecting biowaste from four industries. Residual waste coming from the main power plant will be treated by the department of waste management.

2.8. Collecting data and cost of waste management

The assessment of the waste management is based on three criteria. First, is its economic cost, reflecting the cost of waste collection or transport. Then there is its environmental cost, covering carbon tax or waste treatment cost. Finally, there is the societal cost, covering the hard-to-quantify, so-called shadow costs. The method used to calculate the life cycle costs is described in Section 3. The parameters used in estimating life cycle cost are presented in Table 8. The economic waste type refers to the solid waste collected from the industries. The environmental waste type denotes the carbon taxes from the plants and the reactor. The wastewater treatment of the fish farm is also categorised as an environmental waste type in Table 8. The societal costs are the hidden cost of waste products. The cost of waste handling in the fish farms is 2 €/tonne. The amount of

Table 6
Parameters used in insect farm evaluation.

Name	Value
Area of each insect farm	[1]50 (m^2)
Amount of product	[1]4.2 (tonnes/year)
Number of insect farms	[2]6
Price of product	[2]1000 (€/tonne)
Cost of the product	[2]19,384.62 (€/year)
Revenue of the product	[2]25,200 (€/year)
Interest rate	[2]3%
Investment cost	[2]25,000 (€)

[1] Insect farming case study (Entocube, 2020).
[2] Author's estimation.

Table 7
Industrial symbiosis network matrix.

	Main power plant	CHP plants	Greenhouse farm	Fish farm	Insect farms	Biogas reactor
Main power plant	1	1	0	0	0	0
CHP plants	1	1	1	1	1	1
Greenhouse farm	0	1	1	0	0	1
Fish farm	0	1	0	1	1	1
Insect farms	0	1	0	1	1	0
Biogas reactor	0	1	1	1	0	1

sludge produced in the fish farms is 438 t/year. The stem and leaf (energy crop) organic waste generated in the greenhouse farm is estimated at 0.441 kg per kg of tomato production (Manríquez-Altamirano et al., 2020) and the cost of handling that waste is assumed to be 1.5 €/tonne. The greenhouse farm also produces inorganic waste, unaccounted in the preliminary assessment. The residual waste produced by the main power plant is estimated at 8230.69 t/year, with a handling cost assumed at 1.5 €/tonne. The CHP plants do not produce any bio-waste or residual waste. The amount of biochar (fertilizer) produced in the CHP plants is estimated at 2500 t/year (Alaraudanjoki, 2016), with a waste handling cost assumed at 1.5 €/tonne.

Waste product from the fish farm is assessed at 483 t/year, with a handling cost of 2 €/tonne. The cost of handling the farm's wastewater is assumed to be €1000 per year. Waste products coming from the insect farms are not included in the calculation. Currently, there are only two possible waste streams from insect farming: plastic waste and wastewater. These are both in small quantities and considered irrelevant to this study.

2.9. The key drivers and the challenges of industrial symbiosis

According to the latest European green deal, boosting the circular economy requires systemic solutions in the region (Green Deal, 2020). These should be designed to have an impact on specific targets: resource efficiency; reducing greenhouse gas emissions; increasing the circularity in economic sectors; increasing the number of jobs and creating new businesses. Enhancing cooperation among municipal administrators, industries, the scientific community and civil society achieves all the mentioned targets. The critical driving agents of industrial symbiosis are sustainable business development and boosting the circular economy in the region. Utilisation of by-products from industries which otherwise would be waste can provide not only economic benefits but also environmental benefits. The burnt fuel residue from the main power plant makes up 20% of the input fuels. The energy crops from the greenhouse farm make up 40% of the tomato production. The construction of the biogas reactor guarantees that by-products will be used in the creation of environmentally friendly fuel for the vehicles in the region. An external fish food provider could provide feedstock for the fish farm, but instead, the fish food can be locally produced by the insect farms, with minimal labour and investment costs. Fig. 4 illustrates the material exchange. The arrows represent the input and output products. The symbiosis plan includes some exciting developments. For example, the insect farming provides the region with an innovative business proposition which is relatively new for Finland. The greenhouse farm has a creative approach to tomato production, promising the highest volume of tomato production ever recorded in Finland. The planned CHP plants utilise the most sophisticated pyrolysis technology: its manufacturer claims energy losses of less than 6% in the production of heat for the region.

The key challenge for thriving industrial symbiosis is to achieve the economic benefits of material exchange. The business development plans of the CHP plants, biogas reactor and agricultural farms anticipate 15% - 25% subsidies to attract investors. The benefits of all industries are significant in terms of sustainability and circularity. However, the payback time is estimated to be over ten years without government support. Another challenge is wastewater management All businesses release a significant amount of wastewater, unrecognized in the material exchange. A substantial amount of wastewater can be recycled and utilised in the industries. For example, the fish farm will release 31,063 t of processed water every year: the greenhouse farm should be able to use this water. The planned biogas reactor is needed for treating the water coming from the fish farm but it can do this at a significantly lower cost than typical wastewater treatment. There is also a societal challenge where lack of knowledge can lead to opposition to the construction of new CHP plants where there is an existing main power plant with sufficient capacity for the entire region. The main power plant currently consumes peat and heavy oil as input fuel, both of which are environmentally detrimental. CHP plants using woodchip as input fuel would reduce the carbon emissions and contribute to heat production in the region. Sodankylä's relatively small and sparse population is another challenge for industrial symbiosis because the low number of people can make investments unattractive or unjustifiable to investors.

3. Methodology

The study adopted a conceptual business model framework to articulate the sustainable new businesses (Bocken et al., 2014; Richardson, 2008). The framework entails analysis of the three essential factors of a sustainable business. The first is the value proposition, meaning the product or services provided by the business. The second is the value creation and delivery system, referring to the activities that will create and deliver the products/services to the customers. The final factor is value capture, evaluating the costs and profits. This study evaluates the value capture part of the sustainable business framework by estimating the life cycle cost (LCC_{IS}) and the net present value (NPV_{IS}). The cost and the value are calculated as (Short et al., 1995):

$$LCC_{IS} = \sum_{a=1}^{n} \left(C_p * (1+e)^{-a} \right) \tag{1}$$

$$NPV_{IS} = \sum_{a=1}^{n} \left(CF_a * (1+r)^{-a} \right) \tag{2}$$

Table 8
Parameters used in life cycle cost estimation.

Industry	Waste type	Waste product/by-product (tonnes/year)	Waste handling cost
Fish farm	Economic	438[1]	2[1] (€/tonne)
	Environmental	31063[1]	1000[2] (€)
	Societal	438[1]	1[3] (€/tonne)
Greenhouse farm	Economic	154.35[4]	1.50[3] (€/tonne)
	Environmental	–	–
	Societal	154.35[3]	2[3] (€/tonne)
Main power plant	Economic	8230.69[1]	1.50[3] (€/tonne)
	Environmental	24,682.11[5]	35[7] (€/tonne)
	Societal	8230.69[1]	6[3] (€/tonne)
CHP plant	Economic	0	0
	Environmental	1019[5]	5[3] (€/tonne)
	Societal	0	0
Biogas reactor	Economic	2500[6]	1.50[3] (€/tonne)
	Environmental	402.5[5,6]	5[5] (€/tonne)
	Societal	2500[6]	5[3] (€/tonne)

[1] Natural Resource Institute Finland estimate.
[2] Sodankylä Municipality (Lapeco, 2020).
[3] Assumption based on the case study presented in (Martinez-Sanchez et al., 2015).
[4] Assumption based on the case study of tomato farming in (Manríquez-Altamirano et al., 2020).
[5] Global warming potential of energy sources (Finland, 2020).
[6] A case study of Biogas reactor in Sodankylä (Alaraudanjoki, 2016).
[7] Taxing energy use 2019 (OECD, 2019).

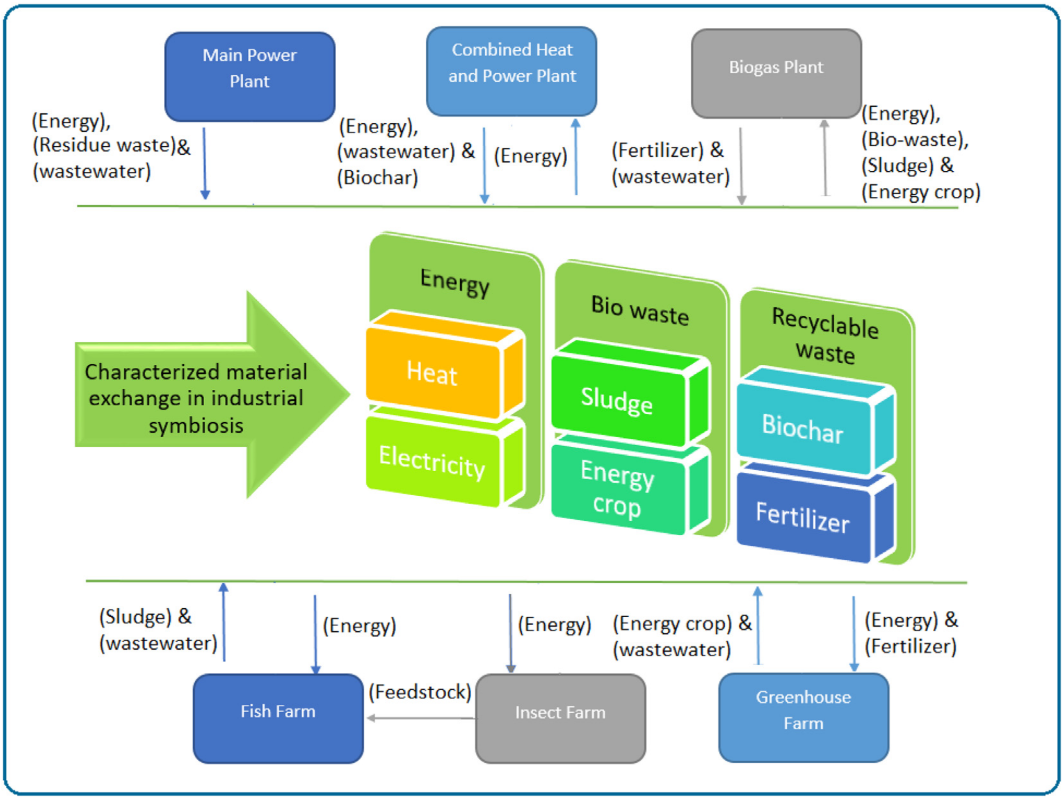

Fig. 4. Material (by-product) characterization in industrial symbiosis. The energy produced in the material exchange is surplus energy, which would otherwise go to waste if not utilised in industrial symbiosis.

where LCC_{IS} is life cycle cost; n is the number of years; C_p is the cost of production (€/tonne); NPV_{IS} is the net present value; CF_a is the yearly cash flow; e is the inflation rate; r is the discount rate.

The cash flow of the businesses is estimated by subtracting production cost from revenue. The prices and costs of products for all industries are presented in Section 2. The value capture of industries depends on the products and services delivered to the customers. Eq. (1) provides a general approach to calculate the total cost of products. The production cost (C_p) of each industry consists of the costs of raw material, energy consumption, input fuel, feedstock and labour. There are three aspects of calculating life cycle cost (LCC) (Martinez-Sanchez et al., 2015): economic LCC (LCC_{eco}); environmental LCC (LCC_{env}); and societal LCC (LCC_{soc}). The cost of waste products is calculated separately to show how they are reduced by industrial symbiosis, thus reducing the life cycle cost (LCC_{IS}) of the industries. The cost of waste products is the value gained in the symbiosis. The cost of the waste products is formulated as (Timonen et al., 2017):

$$LCC_{eco} = \sum_{i=1}^{n} [W_i * (UBC_i + UT_i)] \tag{3}$$

$$LCC_{env} = \sum_{i=1}^{n} [W_i * (UBC_i + UT_i + UAT_i)] \tag{4}$$

$$LCC_{soc} = \sum_{i=1}^{n} [W_i * (UBC_i * NTF + UEC_i)] \tag{5}$$

where i is the unit cost activity; n is the number of years; W_i is the amount of waste input of activity (waste input for waste management); UBC_i is the unit budget cost of the activity (waste management activity); UT_i is the unit transfer of activity (waste collection or transfer cost for waste management). UAT_i is the unit anticipated transfer of activity (anticipated cost increase in future); NTF is the net tax factor (shadow price of marketed goods); UEC_i is the unit externality cost of the activity (unintended cost). The life cycle (n) considered is 20 years.

The industries' costs used in the life cycle cost estimation are presented in Table 8 and further explained in Section 2.8.

4. Results and discussion

This section estimates the life cycle cost (LCC_{IS}) and net present value (NPV_{IS}) of the industries' products. Estimated profits are represented with net present value during a life cycle of 20 years. The total cost of the product includes the costs of heating, electricity, feeding, freshwater and labour.

4.1. Estimating the costs and the value of industries

Fig. 5 presents the estimated life cycle cost (LCC_{IS}) of the six industries, both individually and when combined. Adding the cost of all the participating industries gives a combined cost of €93.03 million when working in this symbiotic environment. The life cycle cost of the main power plant is forecast to be €35.68 million, which includes the combined costs of input fuels, operation and maintenance, subjected to an inflation rate of 1.5%. This is the highest life cycle cost of the six industries, primarily because of the cost stemming from the power plant's input fuel consumption for district heat production. The life cycle cost of the CHP plants is estimated at €32.62 million. The CHP plants also consume a significant amount of input fuel to generate heat for the district. The costs of the greenhouse and fish farms are calculated to be €13.76 and €8.31 million respectively. The greenhouse farm's cost is significantly higher than the fish farm's because of the large amount of heat required for tomato production. Nevertheless, the fish farm also uses a controlled heating environment, which increases its cost of production. The life cycle costs of the biogas reactor and the insect farms are relatively low, projected to be €2.31 and €0.33 million respectively.

The combined net present value (NPV_{IS}) in a symbiotic environment is estimated by projecting the cash flow of industries, as shown in eq. (2).

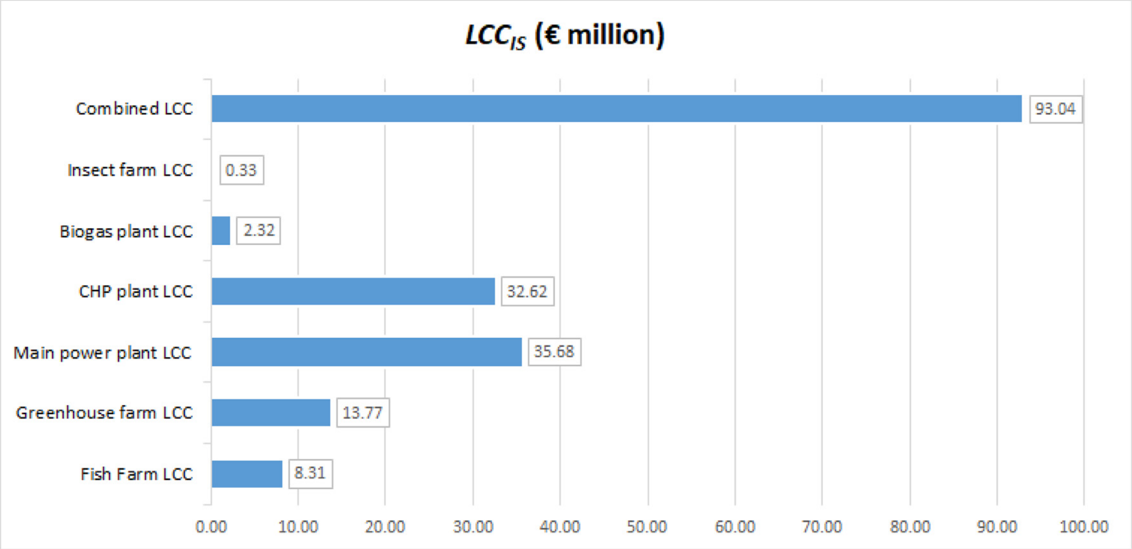

Fig. 5. Life cycle cost (LCC_{IS}) of industries participating in industrial symbiosis.

The cash flow subtracts the cost of production from the revenues. Fig. 6 depicts the NPV_{IS} of the symbiosis participants and shows that the combined total value of the six industries is forecast at €43.68 million. The main power plant attracts the highest valuation, at €21.38 million, even though that calculation includes the debt on the power plant, which results in a lower valuation. The value of the CHP plants is estimated at €13.75 million, somewhat suppressed by the significant construction cost of the six plants, which reduces their value. The values of the greenhouse and fish farms are put at €4.48 and €3.7 million respectively. The fish farm's lower valuation stems mainly from the fact that its operation and maintenance costs considered by the calculation are significantly higher than the greenhouse farm's. The biogas reactor and the insect farms have much lower values than the other industries, projected at €0.35 and €0.09 million respectively.

4.2. Economic, environmental and societal life cycle cost of the waste products

Fig. 7 depicts the combined life cycle costs of the waste products. The economic life cycle cost refers to the waste collection or waste transport cost. The LCC_{eco} of the main power plant is estimated at €0.24 million and refers to the collection and transport costs of ash disposal. The municipality is responsible for disposing and collecting the ash from the main power plant. The CHP plants do not produce reusable wastes, so their LCC_{eco} is considered to be €0. The amount of waste products from the biogas reactor, fish farm and greenhouse farm have minimal impact on the LCC_{eco}, and the projections are €75,000, €17,520 and €4630 respectively. The transportation and collection costs from the reactor include the collection of fertilizers. The waste collection from both greenhouse and fish farms are small, depending on the size of the farms. Turning to the environmental life cycle costs, the main power plant has the highest cost due to carbon taxes on its heavy oil and peat fuels. Its projected LCC_{env} is €3.7 million. This environmental cost could be significantly reduced by using renewable fuel. The LCC_{env} of the six CHP plants is estimated at just over €1 million, followed by the biogas reactor at €40,480. The environmental impact of the agriculture businesses includes wastewater release, which has an annual fee but no taxation. The estimated LCC_{env} of both the greenhouse and fish farms is estimated to be €20,000 each. The societal cost of industries represents their unintended costs to the region. The main power plant again

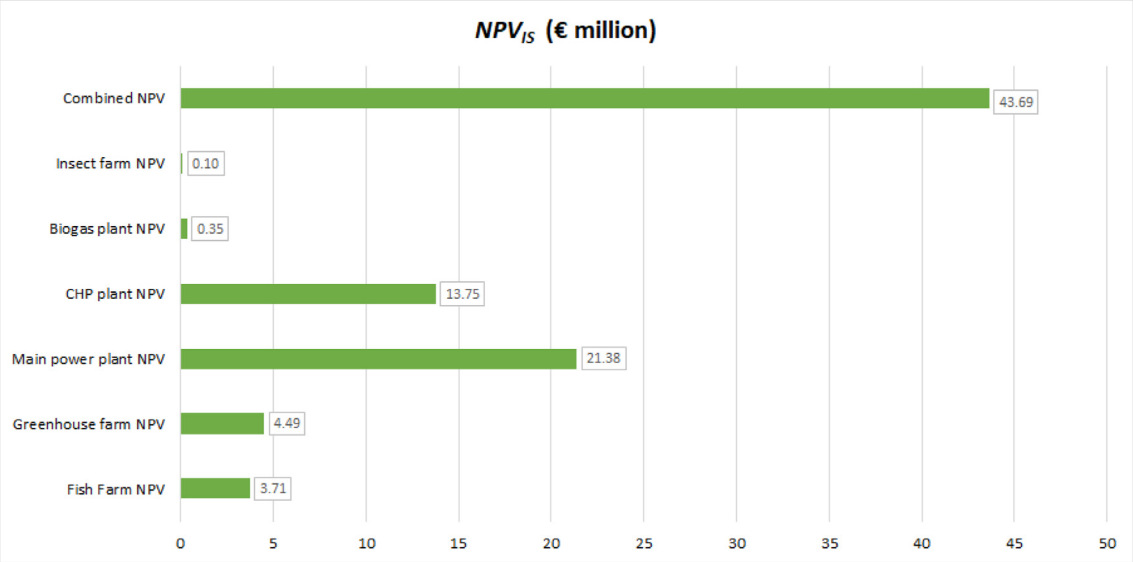

Fig. 6. Net present value (NPV_{IS}) of industries participating in industrial symbiosis.

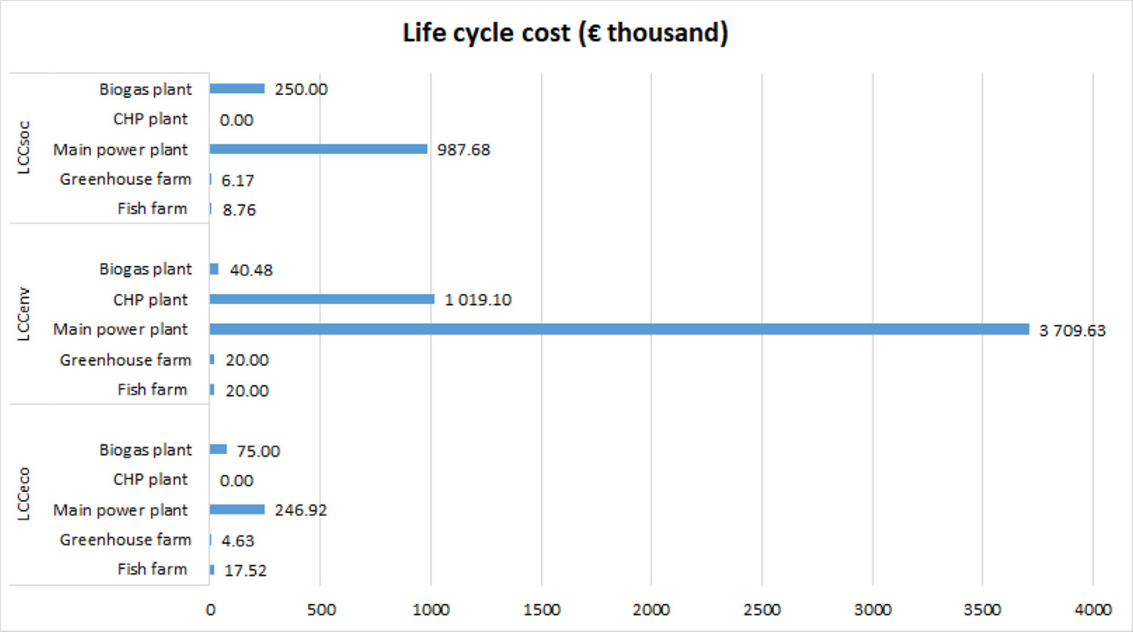

Fig. 7. Life cycle costs of waste products of companies.

dominates this category, with an LCC_{soc} projection of €0.98 million. The LCC_{soc} of the CHP plants is put at €0, and that of the biogas reactor estimated at €0.25 million. The greenhouse and fish farms have LCC_{soc} of €6170 and €8760 respectively. Overall, the majority of all waste management costs comes from the main power plant. This fact reflects the plant's lack of sustainability when compared to the other industries. The newer businesses place far greater importance on sustainability and the circular economy.

Fig. 8 presents the combined life cycle cost of waste management. It is immediately apparent that the environmental costs are dominant, making up 75% of the total cost projection. Then comes the industries' societal costs, accounting for 20% of total LCC. The economical cost has the lowest contribution, at 5%. Replacing fossil fuels with renewable energy sources would reduce or even eliminate carbon emission taxes, which make up 75% of environmental costs from the energy sector. The combined life cycle cost of waste management is a burden to industries in a non-symbiotic environment, but symbiosis provides the companies with opportunities to reduce waste management cost through cooperation.

4.3. Discussion

The life cycle costs of the industries' waste management are illustrated in Fig. 6. They total €6.4 million (Fig. 7) and if working in a non-symbiotic environment these would add to the production cost of the respective industries. This means the combined life cycle cost of the industries, predicted at €93.03 million (Fig. 4), would increase by €6.4 million. On the other hand, industrial symbiosis allows the industries to exchange waste products. This material exchange saves a combined cost of €6.4 million. The monetary gain through industrial symbiosis in Sodankylä is valued at 14.65%, which means the combined valuation of industries is increased by 14.65% in industrial symbiosis compared to the

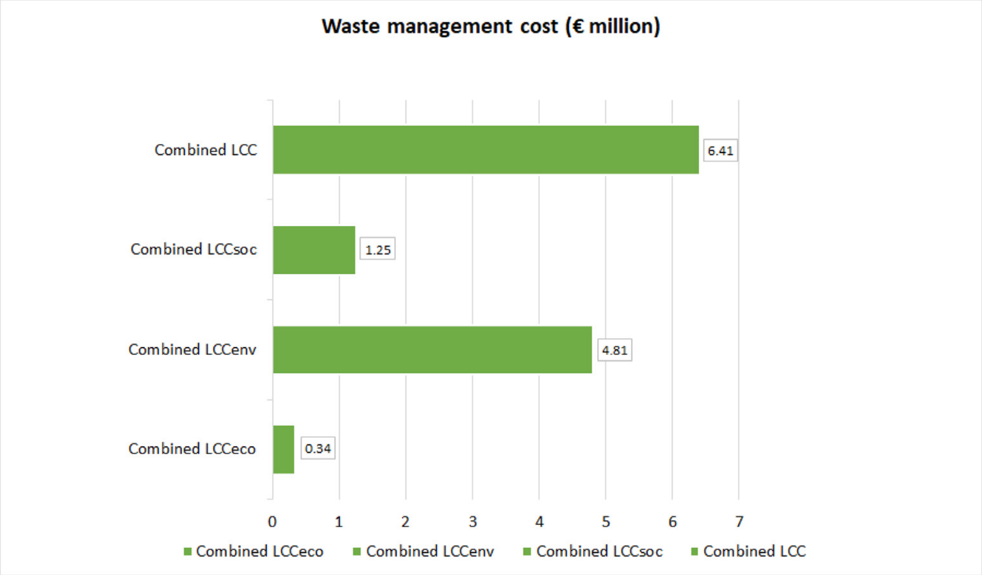

Fig. 8. Combined waste management cost.

non-symbiotic environment. The cost reduction achieved through industrial symbiosis is estimated at 6.8% compared to the non-symbiotic environment. The benefits of industrial symbiosis depend entirely on the waste product exchange. The value of the symbiosis will increase if there are more participants from different sectors.

5. Conclusion

The study presents the possible architecture of industrial symbiosis in Sodankylä, Finland. Preliminary assessment of symbiosis revealed significant benefits of industrial cooperation to reduce waste from businesses. The development of new businesses in Sodankylä shows the potential for cost savings from waste management and promotion of the circular economy in the region. Six industrial participants were considered in the architecture, three from the energy sector and three from the agriculture sector. Quantifying their waste products proved the potential for cost savings through the material exchange identified in the symbiosis. The combined cost (LCC_{IS}) and value (NPV_{IS}) of symbiosis are projected to be €93 and €43 million respectively. The estimated value is highly dependent on the material cost of the products. The cost of the input materials for the industries may vary over time, whereas the valuation of symbiosis is calculated with constant material cost. This issue of future variation in material costs is a limiting factor for this assessment's methodology.

The life cycle cost of waste management is projected at €6.4 million. This waste management cost is the value gained through industrial symbiosis. In the non-symbiotic environment, the waste management cost will simply add to the cost of production of the respective industries. However, industrial symbiosis allows businesses to reduce the combined waste management cost. Industrial symbiosis can significantly reduce costs when the waste products are utilised entirely by transferring them between the respective industries. The environmental cost saving requires a reduction in the use of fossil fuels in the main power plant. The waste management forecast encourages industries to participate in symbiosis, ultimately boosting the circular economy of the region.

This monetary evaluation of industrial symbiosis encourages businesses to initiate this type of cooperation. The method used in the study projected a combined gain in the valuation of the participating industries, which acts as an incentive for the businesses to move towards the circular economy. The presented method will allow municipalities to persuade businesses to cooperate in symbiosis with economic incentives.

Ethics approval and consent to participate

Not applicable.

Availability of data and materials

The manuscript presents all the relevant data in the text and figures.

Consent for publication

The author declares full contribution towards the manuscript. The author edited the manuscript and approved the final manuscript.

Declaration of Competing Interest

The author does not intend to compete and declare no competing interests.

The author declares no conflict of interest.

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References

Alaraudanjoki, Joonas, 2016. Realizing Bioeconomy in the North of Finland: Design of a Co-digester for the Municipality of Sodankylä. Master's thesis. Environmental Engineering, University of Oulu.

Albertsson, Albert, Jónsson, Júlíus, 2010. The Svartsengi Resource Park, Proceedings World Geothermal Congress. , pp. 25–29. https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/3313.pdf.

Allard, Victor, Broberg, Nicklas, Danielsson, Emilia, Elmtoft, Erik, Lindström, Gustav, Nelénius, Maria, Ohlander, Christoffer, Samuelsson, Karl, Torgnysson, Emelie, Wallberg, Robert, Åslund, Petter, Österqvist, Joel, 2012. Industry Park of Sweden, Project in TKMJ38–Industrial Symbiosis, Sweden.

Angren, Jimmy, Arnoldsson, Joel, Arvidsson, Johan, Baumgarten, Sara, Dijkstra, Sjoerd, Högström, Christian, Mårtensson, Cecilia, Nilsson, Matilda, Pettersson, David, Rehn, Sofia, Skoglund, Martin, Willman, Andreas, 2012. Exploring the Industrial Symbiosis in Lidköping. University of Linköping, Sweden.

Aparisi, Teresa Ana Domenech, 2010. Social Aspects of Industrial Symbiosis Networks. Bartlett School of Graduate Studies, University College London.

Azapagic, A., 2003. Systems approach to corporate sustainability. A general management framework. Trans. IChemE 81 (B), 303–316. https://pdfs.semanticscholar.org/31cc/3c9c6ef0b8163b7c9cc0ef91d903d6d83819.pdf.

Baas, Leo, 2008. industrial symbiosis in the Rotterdam harbour and industry complex: reflections on the interconnection of the techno-sphere with the social system, business strategy and the environment. Bus. Strat. Env. 17 (330–340). https://doi.org/10.1002/bse.624.

Benoît, Catherine, Norris, Gregory A., Valdivia, Sonia, Ciroth, Andreas, Moberg, Asa, Prakash, Ulrike Bos Siddharth, Ugaya, Cassia, Beck, Tabea, 2010. The guidelines for social life cycle assessment of products: just in time! Int. J. Life Cycle Assess. 15, 156–163. https://doi.org/10.1007/s11367-009-0147-8.

Benoît-Norris, Catherine, Vickery-Niederman, Gina, Valdivia, Sonia, Franze, Juliane, Traverso, Marzia, Ciroth, Andreas, Mazijn, Bernard, 2011. Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA. Int. J. Life Cycle Assess. 16, 682–690. https://doi.org/10.1007/s11367-011-0301-y.

Bocken, N.M.P., Short, S.W., Rana, P., Evans, S., 2014. A literature and practice review to develop sustainable business model archetypes. J. Clean. Prod. 65, 42–56. https://doi.org/10.1016/j.jclepro.2013.11.039.

Cecelja, F., Raafat, T., Trokanas, N., Innes, S., Smith, M., Yang, A., Zorgios, Y., Korkofygas, A., Kokossis, A., 2015. e-Symbiosis: technology-enabled support for Industrial Symbiosis targeting Small and Medium Enterprises and innovation. J. Clean. Prod. 98, 336–352. https://doi.org/10.1016/j.jclepro.2014.08.051.

Chun, Yoon-Young, Lee, Kun-Mo, 2013. Life cycle-based generic business strategies for sustainable business models. J. Sustain. Dev. 6 (8) (ISSN: 1913-9063).

Costa, Inês, Ferrão, Paulo, 2010. A case study of industrial symbiosis development using a middle-out approach. J. Clean. Prod. 18, 984–992. https://doi.org/10.1016/j.jclepro.2010.03.007.

Cutaia, L., Barberio, G., Luciano, A., Mancuso, E., Sbaffoni, S., La Monica, M., Scagliarino, C., 2014. A Systematic Methodology for Industrial Symbiosis Approach Development at a Regional Scale. Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA).

Cutaia, Laura, Luciano, Antonella, Barberio, Grazia, Sbaffoni, Silvia, Mancuso, Erika, Scagliarino, Claudia, La Monica, Marco, 2015. The experience of the first industrial symbiosis platform in Italy. Environ. Eng. Manag. J. 14 (7), 1521–1533. http://omicron.ch.tuiasi.ro/EEMJ/.

Daddi, Tiberio, Nucci, Benedetta, Iraldo, Fabio, Testa, Francesco, 2015. Enhancing the adoption of life cycle assessment by small and medium enterprises grouped in an industrial cluster a case study of the tanning cluster in Tuscany (Italy). J. Ind. Ecol. 20 (5). https://doi.org/10.1111/jiec.12379.

Daddi, Tiberio, Nucci, Benedetta, Iraldo, Fabio, 2017. Using Life Cycle Assessment (LCA) to measure the environmental benefits of industrial symbiosis in an industrial cluster of SMEs. J. Clean. Product. 147, 157–164. https://doi.org/10.1016/j.jclepro.2017.01.090.

De Benedetto, Luca, Klemes, Jiri, 2009. The Environmental Performance Strategy Map: an integrated LCA approach to support the strategic decision-making process. J. Clean. Product. 17, 900–906. https://doi.org/10.1016/j.jclepro.2009.02.012.

Domenech, Teresa, Davies, Michael, 2011. Structure and morphology of industrial symbiosis networks: the case of Kalundborg. Proc. Soc. Behav. Sci. 10, 79–89. https://doi.org/10.1016/j.sbspro.2011.01.011.

Domenech, Teresa, Bleischwitz, Raimund, Doranova, Asel, Panayotopoulos, Dimitris, Roman, Laura, 2019. Mapping Industrial Symbiosis Development in Europe_ typologies of networks, characteristics, performance and contribution to the Circular Economy. Resour. Conserv. Recycl. 141, 76–98. https://doi.org/10.1016/j.resconrec.2018.09.016.

Entocube, 2020. Leading Cricket Farming Technology From the North. https://entocube.com/en/ (accessed 28 July 2020).

European Commission, 2011. ISIM-TCC-Industrial Symbiosis an Innovative Method in Tackling Climate Change, FINAL Report Covering the Project Activities From 01/01/2010 to 31/12/2012, LIFE08 ENV/H/000291.

European Commission, EU Construction & Demolition Waste Management Protocol, 2016. Directorate-Gen$$eral for Internal Market. Industry, Entrepreneurship and SMEs.

Finland, Statistics, 2020. Fuel Classification. http://tilastokeskus.fi/tup/khkinv/khkaasut_polttoaineluokitus.html (accessed 28 July 2020).

Green Deal, 2020. The European Green Deal Call. https://www.businessfinland.fi/49bdb1/globalassets/finnish-customers/horizon-2020/esitysaineistot/green-deal-webinaari-04062020.pdf (accessed 01 July 2020).

Hirschnitz-Garbers, Martin, Hinzmann, Mandy, Watkins, Emma, ten Brink, Patrick, Milios, Leonidas, Soleille, Sebastien, 2015. Measure synthesis support for industrial symbiosis, a framework for member states to support business in improving its resource efficiency. Project Work on Specific Contract 070201/2014/694448/ETU/ENV.F1.

Jacobsen, Noel Brings, 2006. Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. J. Ind. Ecol. 10, 1–2. http://mitpress.mit.edu/jie.

Jørgensen, Andreas, Le Bocq, Agathe, Nazarkina, Liudmila, Hauschild, Michael, 2008. Methodologies for social life cycle assessment. Int. J. LCA 13 (2), 96–103. https://doi.org/10.1065/lca2007.11.367.

Joyce, Alexandre, Paquin, Raymond L., 2016. The triple-layered business model canvas: a tool to design more sustainable business models. J. Clean. Prod. 135, 1474–1486. https://doi.org/10.1016/j.jclepro.2016.06.067.

Lapeco, 2020. Lapland Consortium of Municipalities. https://lapeco.fi/ (accessed 28 July 2020).

Manríquez-Altamirano, Ana, Sierra-Pérez, Jorge, Muñoz, Pere, Gabarrell, Xavier, 2020. Analysis of urban agriculture solid waste in the frame of circular economy: case study of tomato crop in integrated rooftop greenhouse. Sci. Total Environ. 734, 139375. https://doi.org/10.1016/j.scitotenv.2020.139375.

Martinez-Sanchez, Veronica, Kromann, Mikkel A., Astrup, Thomas Fruergaard, 2015. Life cycle costing of waste management systems: overview, calculation principles and case studies. Waste Manag. 36, 343–355. https://doi.org/10.1016/j.wasman.2014.10.033.

Niemi, Jyrki, Väre, Minna, 2018. Agriculture and Food Sector in Finland 2018, Natural Resources and Bioeconomy Studies 35/2018. Natural Resource Institute Finland (ISBN: 978-952-326-601-8).

OECD, 2012. The Future of Eco-innovation: The Role of Business Models in Green Transformation, OECD/European Commission/Nordic Innovation Joint Workshop, Danish Business Authority, Langelinie Allé 17, Copenhagen, Denmark.

OECD, 2019. Taxing energy use 2019, Using taxes for climate action. http://www.oecd.org/tax/taxing-energy-use-efde7a25-en.htm (accessed 28 July 2020).

Paquin, Raymond L., Busch, Timo, Tilleman, Suzanne G., 2015. Creating economic and environmental value through industrial symbiosis. Long Range Plan. 48, 95–107. https://doi.org/10.1016/j.lrp.2013.11.002.

Posch, Alfred, 2010. Industrial recycling networks as starting points for broader sustainability-oriented cooperation? J. Ind. Ecol. 14 (2). https://doi.org/10.1111/j.1530-9290.2010.00231.x.

Prices and Costs, 2020. Statistics Finland. https://www.stat.fi/tup/suoluk/suoluk_hinnat_en.html (accessed 13 July 2020).

Richardson, James, 2008. The business model: an integrative framework for strategy execution. Strat. Change. 17. John Wiley & Sons, Ltd, pp. 133–144. https://doi.org/10.1002/jsc.821.

Schwarz, Erich J., Steininger, Karl W., 1997. Implementing nature's lesson: the industrial recycling network enhancing regional development. J. Clean. Prod. 5 (1–2), 47–56 (199. SO959-6526(97)00009–7).

Short, Walter, Packey, Daniel J., Holt, Thomas, 1995. A Manual for Economic Evaluation of Energy Efficiency and Renewable Energy Technologies. National Renewable Energy Laboratory, A National Laboratory of the U.S. Department of Energy.

Timonen, Karetta, Harrison, Eric, Katajajuuri, Juha-Matti, Kurppa, Sirpa, 2017. Environmental Cost Accounting Methodologies, Natural Resources and Bioeconomy Studies. Natural Resource Institute Finland (ISBN: 978-952-326-520-2).