

Hafiz Haq

**Modelling a
sustainable
industrial
ecosystem**



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Tiivistelmä <p>Taloudessa tapahtunut muutos kohti resurssitehokkuutta ja kiertotaloutta on ollut avainasemassa pyrittäessä kohti kestävää kehitystä. Suomessa tehdyt hankkeet jätteiden ja hiilijalanjäljen vähentämiseksi ovat olleet merkittäviä. Tässä tutkimuksessa esitetään lähestymistapaa, jossa mallinnetaan kestävää teollista ekosysteemiä perustuen aikaisempaan kirjallisuuteen ja seuraten elinkaariarviointien vakio-ohjeistuksia. Malli koostuu synergisten verkostoyhteyksien tunnistamisesta, jolla helpotetaan materiaalien vaihtoa, kvantifioidaan ympäristövaikutuksia, tuotteiden elinkaarikustannuksia ja jätteenkäsittelyn kustannuksia, materiaalivirtoja verkostossa ja energiankäytön optimointia. Mallia on sovellettu tapaustutkimukseen Sodankylässä, missä viranomaiset suunnittelevat uusien yritysten perustamista vauhdittamaan paikallistaloutta. Lisäksi malli tutkii uusille yrityksille energiaa jakavien sähkön ja lämmön yhteistuotantoon rakennettavien voimalaitosten edullisuutta. Tutkimuksessa myös selvitetään mahdollisuutta voimalaitoksesta vapautuvan ylijäämälämmön varastoimiseksi.</p> <p>Tilastoaineistoa ja muuta informaatiota, joka liittyy teollisen symbioosin verkostoon, on saatu Suomen Luonnonvarakeskuksesta. Aineisto, joka liittyy voimalaitoksen rakentamiseen, hankittiin viranomaisilta Sodankylästä. Työssä käytettiin kahta porakaivoihin perustuvaa kausilämpöenergiajärjestelmää. Molempien toiminta varmennettiin kokeellisilla mittauksilla. Aineisto koskien ensimmäistä järjestelmää kerättiin Kanadan luonnonvaratiedoista ja toista järjestelmää koskien tieto hankittiin Kokkolassa käynnistetystä pilottihankkeesta.</p> <p>Teollisuusosapuolten synergiasuhteet tunnistettiin verkkomatriisilla. Tuotteiden elinkaari- ja jätteenkäsittelykustannuksiksi saatiin 115,2 miljoonaa euroa ja 6,42 miljoonaa euroa. Kustannussäästöt jätteenkäsittelyssä olivat yksi symbioottiseen ympäristöön osallistumisen eduista. Potentiaalisiksi energiankäytön optimoinnin kustannussäästöiksi ennustettiin 0,63 miljoonaa euroa. Tapaustutkimuksessa energian optimointiin sisältyi fossiilisen polttoaineen korvaaminen uusiutuvalla polttoaineella ja lämmön uudelleenkierrätys. Kasvihuonekaasujen päästöjen arvioitiin vähentyneen alueella 53–78 prosenttia. Lisäksi uuden voimalaitoksen laskelmat näyttävät, että tarvitaan 16 prosenttia tukea investoinnille, jotta se olisi kannattavaa. Arvioinnin mukaan ehdotetun ylijäämälämmön lämpövaraston kapasiteetin tulisi olla 280 kW.</p>		
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<p>Abstract</p> <p>Transforming business towards resource efficiency and the circular economy has been the key for sustainable development. The efforts in Finland for reducing waste and the carbon footprint are noteworthy. This research proposed an approach for modelling a sustainable industrial ecosystem, based on previous literature and following standard guidelines of life cycle assessment. The model entails identifying synergetic network connections to facilitate material exchange; quantifying environmental impact; life cycle cost assessment of products and waste management; analysis of material flow in the network; and energy optimisation. The model is implemented on a case study from Sodankylä, Finland where the municipality plans to establish new businesses to boost its local economy. Furthermore, the model investigates profitability of the construction of combined heat and power plants that deliver energy to the new businesses. The study also analyses the possibility of storing excess heat released from the power plants.</p> <p>Data and information relating to an industrial symbiosis network came from the Natural Resources Institute Finland. Data associated with the construction of the power plants were acquired from the municipality of Sodankylä. There is evaluation of two configurations of seasonal borehole thermal energy system. Both were validated with experimental measurements. Data for the first configuration were collected from Natural Resources Canada; data about the second were acquired from a pilot project in Kokkola, Finland.</p> <p>Synergetic relations of industrial participants are identified by a network matrix. The life cycle cost of products and waste management are projected at €115.20 million and €6.42 million respectively. Waste management cost reduction is one of the benefits of participating in a symbiotic environment. The potential cost saving from energy optimisation in the study is forecasted at €0.63 million. This optimisation included heat recovery and replacing fossil fuels with renewable fuel. Reduction in the region's greenhouse gas emission is estimated at 53 % to 78 %. Furthermore, the evaluation of new power plants indicated they need a 16 % subsidy on investment to be profitable and that the proposed heat storage for excess heat should have a capacity of 280 kW.</p>		
<p>Keywords Sustainability, circular economy, industrial symbiosis network, life cycle assessment</p>		

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Abbreviations and symbols

IS	Industrial symbiosis
LCA	Life cycle assessment
CHP	Combined heat and power plant
LCC	Life cycle cost
BTES	Borehole thermal energy system
DHC	District heating and cooling
DLSC	Drake landing solar community
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrous oxide
I_a	Investment cost
M_a	Maintenance cost
O_a	Operational cost
R_a	Revenue
r	Interest rate
TS	Temperature sensor
k_g	Thermal conductivity of the ground
ρ	Density
C_p	Specific heat capacity of the ground
d_i	Inner diameter
d_{io}	Inner diameter of inlet and outlet
d_t	Thickness of pipe
D	Depth of heat exchanger
D_b	Borehole to borehole distance
T_o	Initial temperature
T	Boundary temperature
D_i	Inner diameter of heat exchanger
V	Volumetric flow rate
d	Thickness of pipe
E	Energy consumption
n	Number of industries

t	Time
T	Number of years
W	Water consumption
M	Material consumption
P	Product
SW	Solid waste
WW	Wastewater
C_p	Cost of product
e	Discount rate
W_i	Waste input
UBC_i	Unit budget cost
UT_i	Unit transfer
UAT_i	Unit anticipated transfer
NTF	Net tax factor
UEC_i	Unit externality cost
Z	Cost reduction
C_{waste_heat}	Cost of waste heat
C_{tax}	Cost of carbon tax
$LCOH$	Levelized cost of heat
$LCOE$	Levelized cost of electricity
a	Number of years
Q	Produced power
NPV	Net present value
CF	Cash flow
EF	Emission factor
q	Heat flux
u	Velocity of carrier fluid
A	Area
f_D	Darcy's friction factor
d_h	Hydraulic diameter
Q_{wall}	Wall heat transfer
h	Coefficient of heat transfer
Z	Wetted perimeter

Publications

This thesis consists of five publications, referred in the text as:

1. Haq, M. K. U. Hafiz; Hiltunen, Erkki. (2019). An inquiry of ground heat storage: Analysis of experimental measurements and optimization of system's performance. *Applied thermal engineering*, 148, 10-21.
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3. Haq, Hafiz; Välisuo, Petri; Kumpulainen, Lauri; Tuomi, Ville; Niemi, Seppo. (2020). A preliminary assessment of industrial symbiosis in Sodankylä. *Current research in environmental sustainability*, 2, 100018.
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4. Haq, Hafiz; Välisuo, Petri; Mesquita, Lucio; Kumpulainen, Lauri; Niemi, Seppo. (2021). An application of seasonal borehole thermal energy system in Finland. *Cleaner engineering and technology*, 2, 100048.
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Author's contribution

Paper 1: Haq is the main author. Haq constructed the model and validated it with experimental measurements. Haq wrote and edited the paper. Hiltunen supervised the project, arranged the site visit and helped data collection from the company.

Paper 2: Haq is the main author. Haq and Välisuo conceptualised the model. Haq wrote the paper. Välisuo and Kumpulainen helped edit the paper. Tuomi supervised the project. Haq created the modelling scenarios of the paper.

Paper 3: Haq is the main author. Kumpulainen, Tuomi and Niemi supervised the project study. Haq and Välisuo conducted the investigation and conceptualisation of the study. Välisuo created models and simulation reports for industrial symbiosis. Haq wrote and edited the paper.

Paper 4: Haq is the main author. Kumpulainen and Niemi supervised the project. Mesquita provided the details and data of the DLSC project. Haq constructed the model and validated it with experimental measurements. Välisuo helped conceptualise the case study. Haq wrote and edited the paper.

Paper 5: Haq is the main author. Niemi supervised the study. Haq and Välisuo conceptualised the study, conducted data collection and implementation. Haq conducted modelling and simulation. Haq wrote and edited the paper.

1 INTRODUCTION

The United Nations has drawn up an action plan to rid the world of the tyranny of poverty and to take all the necessary transformative steps to nudge the world onto a sustainable track (United Nations 2020). This journey entails seventeen sustainable development goals to achieve economic, environmental and social sustainability. The world is currently facing an existential threat of climate change which compels the European Union and everyone else to reduce environmental pollution, move towards the circular economy and implement resource-efficient growth strategies. (European Commission 2020a). The European Union's aim to become carbon neutral by 2050 requires extensive transformation in many areas. These include clean and affordable energy; the circular economic model for industries; energy efficiency for residential buildings; smart mobility; sustainable farming; industrial cooperation; zero pollution; knowledge sharing; citizen empowerment; and international cooperation (European Green Deal 2020). Responsible production and consumption are strongly associated with well-being, climate action and international cooperation towards a sustainable development goal (Fonseca et al. 2020). Therefore, synergetic relations and industrial cooperation, together with the appropriate policy making, are vitally important for sustainable initiatives (Zimon et al. 2019).

Industrial symbiosis can be defined as a shared platform to achieve sustainability, whereby industrial collaborators exchange materials to turn waste into raw materials. There has been significant development of industrial symbiosis in Europe as businesses are encouraged to make the transformation towards sustainable and circular practices (Domenech et al. 2019). These practices include enhancement of existing business models by adding environmental and social layers on top of the customary economic layer to illustrate how an organisation generates value (Joyce and Paquin 2016). Businesses are expected to consider the environmental and social impacts of their products as well as the regional and national impact of business activities (Daddi et al. 2015).

There are many methods available in literature to evaluate life cycle assessment, environmental impact and social aspect of industries in a symbiotic environment. However, these studies lack a comprehensive tool that quantifies the major aspects of an industrial symbiosis network. This study addresses that by presenting an approach for modelling sustainable industrial symbiosis. The model is applied to a case study of a symbiotic environment in Sodankylä, Finland, where new business development is under consideration. Furthermore, the study also analyses the profitability of combined heat and power (CHP) plants in Sodankylä by applying a

techno-economic assessment and the creation of a 3D model of a seasonal borehole thermal energy system to store waste heat from the plants.

1.1 Background

Industrial symbiosis (IS) literature has revealed a clear focus on certain parameters that are essential to evaluate the performance of a symbiotic network. These include environmental impact and a life cycle assessment (LCA) that quantifies environmental pollution, consumption and production of energy and material flow in the IS network (Sokka et al. 2010, Mattila et al. 2010). A symbiotic environment also provides a platform where industries collaborate to share resources efficiently and collectively reduce environmental impact and waste (Sokka et al. 2011, Mattila et al. 2012). The concept of an industrial ecosystem must target reducing environmental impact of industries and achieving sustainable development in a region by industrial collaboration focused on reducing waste and recycling (Dong et al. 2016). The architecture of an IS network presents a great challenge, as the location of the industries appears to have a significant impact on the performance (Aissani et al. 2019). Material exchange among industrial participants in an IS network is established by knowledge-sharing, with the objective of reducing raw material intake and waste production (Domenech and Davies 2011). An IS network benefits from a sustainable symbiotic environment by sharing a common platform of life cycle inventory of products (Van Berkel 2010, Suh and Hupes 2005). Martin et al. (2015) presented an approach to estimate the environmental benefits of an IS network, using guidelines from LCA literature. Similarly, Kerdlab et al. (2020) proposed evaluation of environmental performance using multi-level LCA. Both studies failed to consider the methodological aspect of identifying network connections and optimal assessment of energy flow. This thesis presents a comprehensive approach to model industrial symbiosis in accordance with the standard guidelines of life cycle assessment (ISO 2006, ILCD 2010). The model includes identification of IS network connections and the quantification of material flow (LCA), costs of products and waste management (LCC) and environmental impact. Additionally, the model evaluates energy optimisation of the IS network, acquired from another study (Afshari et al. 2020). Furthermore, the model is applied to a case study of business development in Sodankylä, Finland. This municipality plans to establish five new businesses to boost the region's local economy. The five businesses are: six CHP plants, a biogas reactor, greenhouse farm, fish farm and insect farms.

The CHP plants will be one of the most important industries in the region as they will be responsible for delivering energy to all the new business projects. Heat for the region is currently produced by a power plant which uses fossil fuels to produce

energy. The municipality of Sodankylä plans to eliminate the use of fossil fuels from district heat production, in accordance with the energy policy of Finland (Finnish Energy 2019). Therefore, construction of new wood-fuelled CHP plants is under consideration. District heat producers are obliged to take account of the challenges arising from urbanisation and digitalisation (Paiho and Saastamoinen 2018). These challenges include utilisation of efficient renewable fuels and integration of biomass into district heat production (Kurkela et al. 2019). Finland increased the use of forest fuelwood from 18.8% to 21% and also increased its use of industrial wood residue from 10.2% to 12% (Finnish Energy 2020a). European Union encouragement to use bioenergy sources for district heat production has been expedited by means of refining carbon taxes (Finnish Energy 2020b). This thesis analyses the profitability of new wood-fuelled CHP plants in the region by conducting a techno-economic assessment. The plants have capacity to produce 4.3 MW of energy. Heat consumption in the region varies significantly between summer and winter. The low summer requirement means that only two CHP plants will operate and the rest will be shut down for maintenance. This imbalance of energy consumption and production leads to 1.5 MW of excess heat. The excess heat can be recovered by constructing a seasonal borehole thermal energy system (BTES).

An important aspect of constructing a symbiotic environment is that it provides an opportunity to reduce waste and utilise resources efficiently. Waste heat from CHP plants offers scope for business development and renewable energy stored in BTES can be for district heating and cooling (DHC) applications. District heating in Finland supplied by renewable energy sources accounted for 45% in 2012 (European Commission 2020b). Stored heat can be delivered to the distribution network during winter to reduce the power plants' consumption of input fuel. Furthermore, the stored heat is also suitable for distribution to the region's new business or residential developments in a centralised or decentralised low-temperature DHC application (Lund et al. 2014). This thesis constructs a 3D model similar to the configuration of the Drake Landing Solar Community (DLSC) project in Alberta, Canada. The model simulates charging a BTES with excess heat from the CHP plants. An application of low-temperature DHC is presented, showing how the BTES can be used to distribute heat energy in the region.

1.2 Objectives and scope

The objective of this thesis was to create a model of a sustainable industrial ecosystem. The approach was applied to a case study from Sodankylä, Finland where new business development is under consideration. This development includes

businesses in the energy and agriculture sectors. The approach used identified the synergetic relations among all businesses and presented the environmental impact of a symbiotic environment. The thesis also evaluated the profitability of new wood-fuelled CHP plants and showed reduced environmental impact of district heat production. Furthermore, the thesis analyses the charging and operational performance of a BTES. The scope of the thesis included analysis of achievement of sustainability and circular economy in industrial symbiosis, reduction of environmental impact in district heat production and maximising the use of renewable energy from seasonal BTES. To achieve the objectives of this research study, the thesis required 1) Collecting data of five industries from Natural Resources Institute Finland (Luke); 2) Evaluating the profitability of CHP plants and verifying with comparative estimates by Luke; 3) Constructing 3D models of BTES and validating with experimental measurements.

1.3 Research approach

The thesis approach includes both qualitative and quantitative research methods. A novel sustainable model of industrial symbiosis is created, based on previous literature and standard guidelines for life cycle assessment. The study also implemented techno-economic assessment to evaluate profitability of CHP plants with novel estimation of the environmental impact of district heat production with a variety of input fuels. Moreover, the study created 3D models of BTES to analyse the charging and discharging operation of the system. This study used several case studies to evaluate a sustainable industrial ecosystem, which included data collection from five different industries. Results are comparable with any model based on standard guidelines from life cycle assessment literature. The study also validated 3D models of seasonal BTES with experimental measurements collected from the DLSC project from Natural Resources Canada and from a pilot project in Kokkola, Finland.

1.4 Research questions

The thesis aims to answer three research questions:

Q 1. Sustainability of industrial ecosystem

- How is an IS network identified among business participants? What is the quantity and material flow of an IS network? What is the life cycle cost and environmental impact of an IS network? Is it possible to achieve energy optimisation in an IS network? (Papers 3, 5)

Q 2. Profitability of new CHP plants

- Are CHP plants a profitable investment? What is the environmental impact of district heat production after construction of new CHP plants? (Paper 2)

Q 3. Possibility of storing excess heat from CHP plants

- What is the configuration of a BTES model? How many BTES are required to store all the excess heat produced during summer? (Papers 1, 4)

Five research publications are used to answer these research questions. The novelty of the study is to apply modelling to facilitate the construction of a sustainable industrial ecosystem. The modelling combines various methods and compiles a comprehensive platform to identify network connection, to quantify material flow, environmental impact and life cycle costs and also to evaluate energy optimisation. Also included is the design of an approach to evaluate the profitability of CHP plants with respect to government subsidy, payback time and reduction in environmental impact. Finally, there is simulation to evaluate how excess heat from CHP plants can be harnessed in heat storage and then used in a centralised or decentralised energy distribution network.

The objective of Paper 1, titled, “An inquiry of ground heat storage: analysis of experimental measurements and optimisation of system’s performance,” was to construct a 3D model of seasonal heat storage, charged by heat from solar collectors during the summer. The model was validated with experimental measurements from a pilot project in Kokkola, Finland.

The objective of Paper 2, titled, “An economic study of combined heat and power plants in district heat production,” was to analyse the current state of district heat production and the profitability of new wood-fuelled CHP plants. The study also presented the cost of heat production and analysed the reduced environmental impact after the new CHP plants begin to contribute to the district heating network. The data were collected from the municipality of Sodankylä.

The objective of Paper 3, titled, “A preliminary assessment of industrial symbiosis in Sodankylä,” was to propose an architecture of symbiosis and to quantify the monetary value and costs of the symbiotic environment. The study also quantified the costs of waste management and showed the monetary benefits of industrial cooperation. The data were collected from Natural Resources Institute Finland (Luke).

The objective of Paper 4, titled, “An application of seasonal borehole thermal energy system in Finland,” was to construct a 3D model of heat storage similar to the

DLSC project. The model was validated with the experimental measurements collected from Natural Resources Canada. The same model was used to simulate the charging operation of excess heat from the CHP plants.

The objective of Paper 5, titled, “Modelling sustainable industrial symbiosis,” was to design a comprehensive approach to evaluate IS network connections and to quantify material exchange, life cycle costs, environmental impact and energy optimisation. The data were collected from the Natural Resources Institute Finland (Luke).

1.5 Dissertation structure

Chapter 1 introduces the research topic and conducts a literature review to establish the background. The objectives and scope of the thesis are set and research questions are posed.

Chapter 2 presents the case studies used in the thesis to model a sustainable industrial ecosystem, evaluate the profitability of CHP plants and to model seasonal BTES to store excess heat.

Chapter 3 proposes the model to evaluate industrial symbiosis. The model includes data collection from participants to identify the IS network connection, to calculate the amount of material flow, life cycle cost of product and waste management, its environmental impact and optimal assessment. A techno-economic model is introduced to calculate production cost in CHP plants. The model for heat transfer in the ground is presented.

Chapter 4 presents the results that answer the research questions posed in chapter 1. The proposed models are implemented on case studies to evaluate an industrial ecosystem.

Chapter 5 discusses the results drawn from the study and poses future considerations.

Chapter 6 reveals the findings from the study and draws conclusions.

Chapter 7 summarises chapters 1-6.

2 SUSTAINABLE INDUSTRIAL ECOSYSTEM

This chapter introduces the industrial ecosystem under consideration. Three case studies are presented to address the three research questions posed in the previous chapter. A sustainable industrial ecosystem is defined as one where the industries can cooperate by sharing resources, reduce their waste and environmental impact while maximising output in accordance with a circular economy model. This study evaluates the industrial ecosystem of Sodankylä, Finland, where the municipality plans to open new businesses in the region. These businesses include a greenhouse farm, a fish farm, insect farms, a biogas reactor and CHP plants. The region already has a main power plant to supply energy. The industrial ecosystem consists of five new businesses and the main power plant. The first case study briefly introduces all the industries and the data used in the model. The second case study introduces the CHP plants to be constructed in the region. The third case study presents two configurations of seasonal BTES to store excess heat from the CHP plants.

2.1 Case study 1

This case study is the summary from Paper 3 and Paper 5. Sodankylä, which has a population of 8,300, is located in northern Finland and covers an area of 12,000 km². The municipality of Sodankylä has decided to boost the regional economy by establishing new businesses which will contribute to the region's agriculture sector. A state-of-the-art greenhouse farm will grow horticulture products. There will be a fish farm and the region will have its first insect farms to produce feedstock. The municipality also plans to construct a biogas reactor with biogas upgrading to produce biofuel for the region. The reactor will receive biomass from all the new farms. Six CHP plants are required to supply energy to the new businesses and to reduce the use of fossil fuels at the main power plant.

2.1.1 Main power plant

The main power plant is the primary source for energy production in the region. The plant is capable of producing 34 MW of energy at its maximum output and has a distribution network covering an area of over 30 km². The plant consumes 0.21 MW of primary electricity per year, provided by external suppliers. Currently, the plant uses three input fuels: peat, woodchip and heavy oil. The municipality supplies fresh water to the plant and collects solid waste and wastewater from the plant. Due to its use of fossil fuels, the plant releases residue waste (fly ash).

2.1.2 Combined heat and power plants

The municipality proposes to construct six new CHP plants to supply energy to the new businesses in the region. These are wood-fuelled plants, which are capable of producing 4.3 MW of heat to the network. The efficiencies of heat and electricity production of the plants are 55 % and 29 % respectively. The plants also produce biochar at 10% efficiency. Biochar is an important by-product that is used in the region and sold to the market. Biochar can be used in soil improvement and in drinking water purification and filtration systems. The municipal plant will supply fresh water to the plants; the main power plant will supply primary electricity. The plants do not release any solid waste.

2.1.3 Greenhouse farm

The idea of constructing an improved greenhouse farm comes from the integrated rooftop greenhouse proposed in (Manriquez-Altamirano et al. 2020). The preliminary assessment of the farm assumes 70 kg/m² yield of tomato production across an area of 5,000 m². The farm can also consider growing salad leaves and potted plants in the future. The municipal plant will supply fresh water to the farm, while its inorganic solid waste and wastewater release will be collected by the department of waste management and wastewater treatment. The farm will release a significant amount of energy crop to be delivered to the biogas reactor.

2.1.4 Fish farm

The municipality is investigating the possibility of constructing a fish farm with a capacity of 70 tonnes per year. The preliminary assessment considers the production of whitefish, although typical farms in the region produce either rainbow trout or whitefish. The municipal plant will supply fresh water to the farm; the department of wastewater treatment will collect wastewater from the farm. The farm will produce a significant amount of sludge to be delivered to the biogas reactor.

2.1.5 Biogas reactor

The biogas reactor will be an important industry for the region. The reactor will process bio-waste collected from the agriculture sector as well as other industries in the region. The concept of a biogas reactor comes from the model proposed in (Alaraudanjoki 2016). The planned reactor has a volumetric capacity of 500 m³ and a digestate flow of 2,700 tonnes per year. The main power plant and CHP plants do not produce bio-waste but sludge from the fish farm will be delivered to

the reactor, as will the organic waste released from greenhouse farm. Bio-waste from the insect farms will also form another energy crop delivered to the reactor, and so will bio-waste from a cattle farm, a reindeer farm and a slaughterhouse. The reactor is expected to produce 203,250 m³/year of methane, with an estimated density of 0.72 kg/m³.

2.1.6 Insect farms

The municipality plans to establish an innovative insect farm industry in the region. There are six insect farms considered in the preliminary assessment. Each has an area of 50 m². These farms will be capable of supplying 4.2 tonnes of “hermetia illucens”, otherwise known as the black soldier fly. The insects will be processed to produce feedstock for the fish farm.

2.1.7 Collected data and parameters used

The data collected for this study come from various sources. Estimations by the Natural Resources Institute Finland are used in calculations for the main power plant, CHP plants, fish farm and the greenhouse farm. Data used for the biogas reactor and insect farm evaluations were acquired from literature studies. The collected data consist of input, output and waste release from each industry. Table 1 shows the consumption and production for the main power plant and the five new industries. CHP plants do not produce solid waste; the main power plant produces fly ash. The amount of raw material input to the biogas reactor depends on the amount of bio-waste produced by the agriculture sector. Water consumption is significantly higher in the agriculture sector than in the energy sector. The study considers two types of costs. The first is the cost of the product and the second is the cost of waste management. The product cost consists of the costs of water consumption, raw material and energy consumption. Table 2 presents the cost of each input to all industries.

Table 1. Yearly production and consumption

Parameter	Main power plant	CHP plants	Greenhouse farm	Fish farm	Insect farms	Biogas reactor
Functional unit	Heat, electricity	Heat	Tomatoes	White fish	Feed stock	Biogas
Energy (MWh)	1840 ¹	3372 ¹	4380 ³	501 ¹	17 ²	2216.28 ⁴
Water (m ³)	-	-	6132 ³	35040 ¹	218.57 ²	-
Material (tonne)	54686.60 ¹	8574 ¹	560 ³	82.43 ¹	40 ²	2742.5 ⁴
Product	86899 ¹ (MWh)	27900 ¹ (MWh)	350 ³ (tonne)	70 ¹ (tonne)	1.43 ² (tonne)	2505.22 ⁴ (tonne)
Waste water (m ³)	-	-	-	31010.40 ¹	216.30 ²	-
Solid waste (tonne)	8230.70 ¹	-	213.50 ³	437.12 ¹	25.26 ²	-

1- Estimation of Natural Resources Institute Finland (Luke).

2- Based on (Smetana et al. 2019).

3- Based on (Manríquez-Altamirano et al. 2020).

4- Based on (Alaraudanjoki 2016).

Table 2. Cost of raw material, energy, and water consumption

Industry	Cost of material (€/year)	Cost of water consumption (€/year)	Cost of energy consumption (€/year)
Main power plant	1.80 ¹ million	-	73,600 ¹
CHP plants	0.78 ¹ million	-	0.13 ¹ million
Greenhouse farm	0.40 ³ million	6,990 ³	0.20 ³ million
Fish farm	0.78 ¹ million	40,000 ¹	16.67 ¹ million
Insect farms	12,000 ¹	250 ¹	680 ¹
Biogas reactor	2,400 ²	-	88,000 ²

1- Estimation of Natural Resources Institute Finland (Luke).

2- Based on (Smetana et al. 2019).

3- Based on (Manríquez-Altamirano et al. 2020).

The cost of waste management consists of the solid waste collection and transport costs. Table 3 shows this for all the industries. Industrial waste is categorised into three types: economic waste; environmental waste; and societal waste. Economic waste handling refers to transport and collection cost. Environmental waste handling refers to the environmental cost for wastewater and carbon tax. Societal waste cost refers to the shadow cost and unintended cost of the industry. Table 4 presents the industries' environmental impact, consisting of their carbon footprint and greenhouse gas emissions. Emission factors of the energy sector are from the database of the Intergovernmental Panel on Climate Change (IPCC). Data relating to emissions from fish farm come from the Natural Resources Institute Finland (Luke). Greenhouse farm and insect farm emission data are collected from literature studies.

Table 3. Economic, environmental and social costs of waste product/ by-product

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	-	1000 ² (€)
	Societal	154.35 ³	2 ³ (€/tonne)
Main power plant	Economic	8230.69 ¹	1.50 ³ (€/tonne)
	Environmental	24682.11 ⁵	35 ⁷ (€/tonne)
	Societal	8230.69 ¹	6 ³ (€/tonne)
CHP plant	Economic	-	-
	Environmental	1019 ⁵	5 ³ (€/tonne)
	Societal	-	-
Biogas reactor	Economic	2500 ⁶	1.50 ³ (€/tonne)
	Environmental	402.50 ^{5 & 6}	5 ⁵ (€/tonne)
	Societal	2500 ⁶	5 ³ (€/tonne)
Insect farms	Economic	20.95 ⁸	2 ¹ (€/tonne)
	Environmental	216.30 ⁸	1.82 ¹ (€/tonne)
	Societal	20.95 ⁸	5 ³ (€/tonne)

1- Estimation of the Natural Resources Institute Finland (Luke).

2- Based on municipal price (Lapeco 2020).

3- Based on (Martinez-Sanchez et al. 2015).

4- Based on (Manriquez-Altamirano et al. 2020).

5- Based on (Finland statistics 2020).

6- Based on (Alaraudanjoki 2016).

7- Based on (Taxing energy use 2019).

8- Based on (Smetana et al., 2019).

Table 4. Yearly environmental impact

Parameter	Main power plant	CHP plants	Greenhouse farm	Fish farm	Insect farms	Biogas reactor
CO ₂ (tonne)	30880.94 ¹	14861.76 ¹	595 ⁴	1309 ²	0.21 ³	-
CH ₄ (tonne)	15.64 ¹	1.35 ¹	-	-	216.30 ³	-
N ₂ O (tonne)	0.62 ¹	0.27 ¹	-	-	25.26 ³	0.014 ¹

1- Based on (IPCC 2006).

2- Estimate of the Natural Resources Institute Finland (Luke).

3- Based on (Parodi et al. 2020).

4- Based on (Manríquez-Altamirano et al., 2020).

2.2 Case study 2

This section summarises the system description from Paper 2, relating to So-dankylä's proposed construction of Syncraft's wood-fuelled CHP plants. Each plant has an adjustable capacity of producing 700 kW heat and 200 kW electricity known as CW700-200 (Syncraft 2020). This technology consists of three main processes. The first is drying the woodchip. This is followed by pyrolysis and then gasification. Figure 1 shows the process flow through the plant. Drying takes place at 200 °C, reducing the woodchip fuel's moisture content from 30 %-60 % down to 15 % before gasification (Sansaniwal et al. 2017). Pyrolysis takes place at 500 °C, which oxidises the chamber to burn the dried fuel (Guan et al. 2016). The input fuel decomposes during this process, forming a volatile compound and solid residue (Dhyani and Bhaskar 2018). The volatile compound is burned further by oxidising the chamber at 850 °C in a floating-bed reactor. The compound consists of liquid tar and gases, resulting in impurities after oxidation. These impurities can be collected at the bottom of the reactor (Kumar et al. 2009): adding water to them produces biochar. The steam is cooled at the top of the reactor before scrubbing at 100 °C (Kirubakaran et al. 2009). The final gas produced is injected into the gas engine at 25 °C at the end of the plant. The engine produces heat energy and electricity for distribution to the network. Table 5 presents the cost parameters used in the calculation. The cost of six CHP plants is estimated at €16.5 million. The minimum income from selling biochar is assumed at €1.1 million per year.

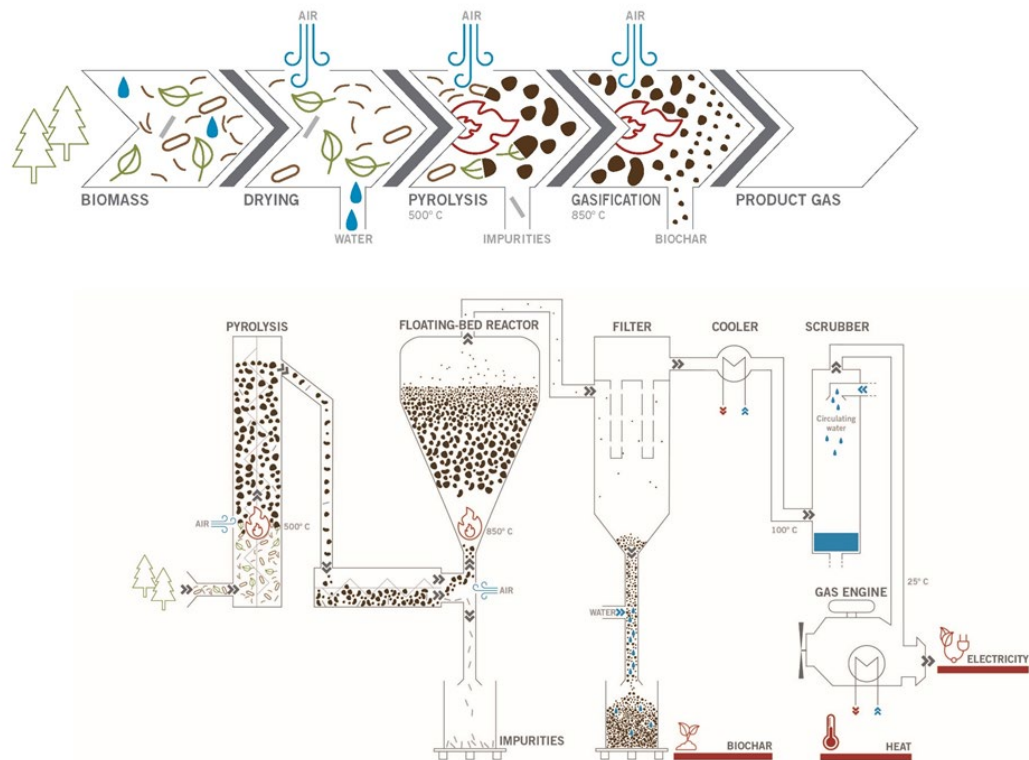


Figure 1. Process flow diagram of combined heat and power plant.

Table 5. Cost parameters for six units of plants

Items	Symbol	Value
Investment cost	I_a	€16.5 (million)
Maintenance cost	M_a	€0.2 (million/year)
Operational cost	O_a	€0.1 (million/year)
Revenue	R_a	€1.58 (million/year)
Interest rate	r	4%
Fuel cost	-	€1.7 (million/year)
Biochar selling price	-	€1.1 (million/year)

2.3 Case study 3

This section presents two configurations of seasonal BTES from Paper 4 and Paper 1. The configuration from Paper 4 represents a centralised low-temperature, small district network for storing and distributing excess heat from CHP plants. The configuration from Paper 1 shows an example of a decentralised heat distribution application.

2.3.1 Configuration 1

This section summarises Paper 4. The focus of the study is to construct a 3D model of a BTES similar to the DLSC project in Okotoks, Alberta, Canada. Comsol Multiphysics software was used to create the model. The configuration consists of 144 boreholes with heat exchanger pipes in a hexagonal shape, shown in Figure 2. There are 24 strings of heat exchanger pipes in parallel, each with six pipes connected in series between the inlet in the centre and the outlet at the outermost edge. The depth of each pipe is 35 m and there is 2.25 m between any two adjacent pipes. The ground has a dimension of 36x34x52 m. Table 6 presents the material properties of the heat exchanger. The positions of all the temperature sensors (TS) are shown as red dots. Temperature sensors from the centre to the left are indicated as TS24.1 to TS24.7; sensors from the centre to the right are shown as TS23.1 to TS23.7. Sensors for the core temperature of the ground are represented as TS22.1 to TS22.7. The inlet temperature sensor is shown as TS13.

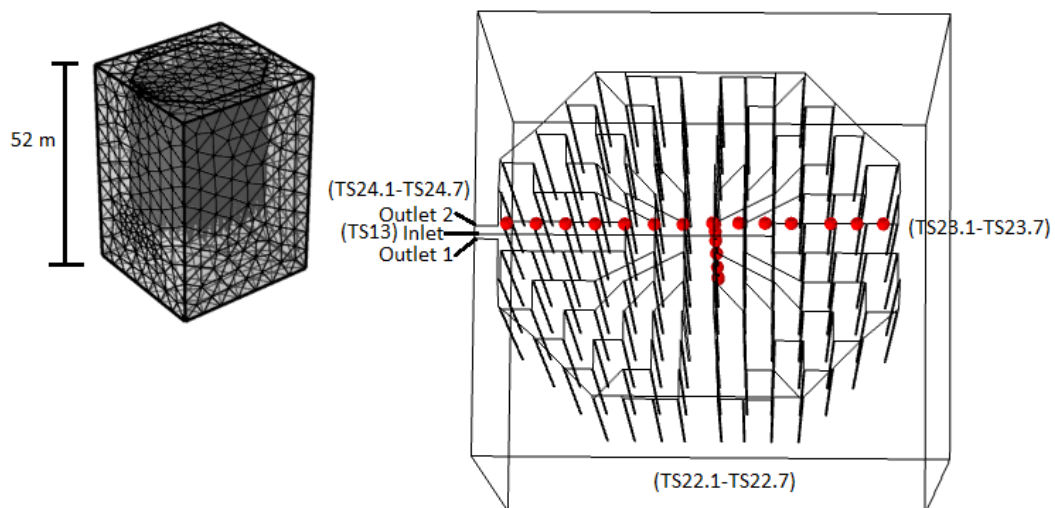


Figure 2. Borehole thermal energy system. Red dots represent the temperature measurement locations. Sensors TS23.1-TS23.7 and TS24.1-

TS24.7 measure the temperature across the ground: sensors TS22.1-
TS22.7 measure the core temperature of the ground.

Table 6. Material properties of the ground and heat exchanger

Name	Symbol	Value
Thermal conductivity of the ground	k_g	1.07 (W/m·K)
Density of the ground	ρ	1520 (kg/m ³)
Specific heat capacity of the ground	C_p	1014 (J/kg·K)
Inner diameter of heat exchanger	d_i	25 (mm)
Inner diameter of inlet and outlet	d_{io}	65 (mm)
Thickness of pipes	d_t	1.5 (mm)
Depth of heat exchanger	D	35 (m)
Borehole-to-borehole distance	D_b	2.25 (m)

2.3.2 Configuration 2

This section summarises Paper 1. Comsol Multiphysics software was used to create a 3D model of a BTES, based on a pilot project in Kokkola, Finland. The model consists of 13 borehole heat exchangers configured in two concentric rings, shown in Figure 3. The depth of the heat exchangers is 40 m, except one in the centre, which is 50 m deep. The distance between any two adjacent heat exchangers is 2.5 m. The distance between the heat exchanger in the centre and the outermost ring is 5 m. The ground radius is assumed at 15 m and the depth estimated at 51 m. Table 7 presents the material properties of the model.

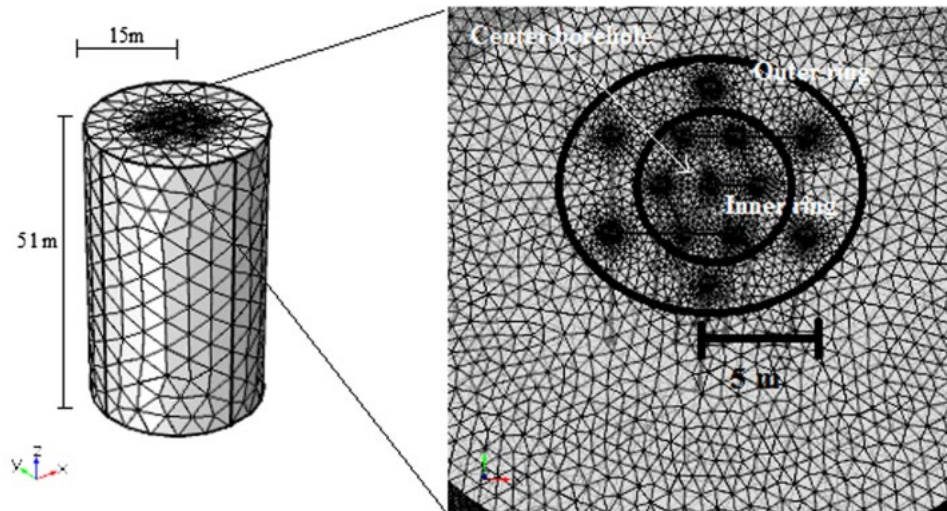


Figure 3. Borehole thermal energy system. The configuration is suitable for decentralised applications.

Table 7. Material properties of the ground and heat exchanger

Name	Symbol	Value
Thermal conductivity of the ground	k_g	3.4 (W/m·K)
Initial ground temperature	T_o	8 (°C)
Boundary temperature of ground	T	8 (°C)
Inner diameter of heat exchanger	D_i	35.2 (mm)
Volumetric flow rate	V	1 (l/s)
Thickness of pipe	d	2.4 (mm)

3 METHOD

This chapter consists of three sections to address the research questions posed in chapter 1. The first section deals with method development for sustainable industrial symbiosis. The second addresses the profitability of CHP plants. The third section proposes a seasonal BTES to store excess heat from CHP plants.

3.1 Model of sustainable industrial symbiosis

This section proposes a model for a sustainable IS network. The model, shown in Figure 4, is applicable to a synergetic environment where resources are shared among industrial participants. The model is divided into three sections: input data; model construction; and result. Input data refers to the data collection from industries. The data help evaluate the business sector, the system's boundaries and functional units. The central model for the IS network is further divided into three sub-sections: identification of material exchange in IS network; quantification of materials, costs and environmental impact; and energy optimisation.

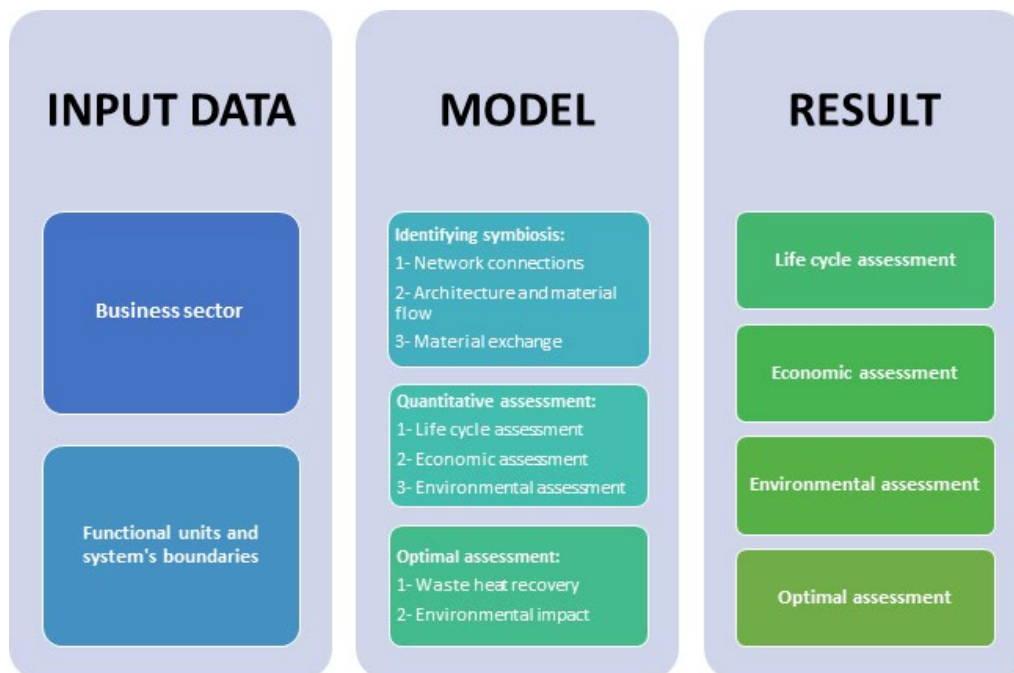


Figure 4. A model of sustainable industrial symbiosis.

This section summarises Paper 5. The model applies cradle-to-gate boundaries assessment. This means the data collected from industries represent input consumption (including raw material, energy, and water) and output production (including product, solid waste, wastewater and environmental impact). The data are used to identify the business sector and form synergetic relations among industries. Domenech and Davies (2011) showed the construction of an IS network matrix, which is used in the model. The network matrix helps create the architecture of material flow and identify material exchange among industries. After identification of an IS network, quantitative assessment is conducted. This subsection quantifies life cycle assessment (LCA), life cycle cost of product and waste management (LCC) and an environmental assessment. LCA estimates the amount of consumption and production in the IS network. The parameters are expressed in Equations (1) to (6):

$$E_{IS} = \sum_{t=1}^T \sum_{i=1}^n E_n \quad (1)$$

$$W_{IS} = \sum_{t=1}^T \sum_{i=1}^n W_n \quad (2)$$

$$M_{IS} = \sum_{t=1}^T \sum_{i=1}^n M_n \quad (3)$$

$$P_{IS} = \sum_{t=1}^T \sum_{i=1}^n P_n \quad (4)$$

$$SW_{IS} = \sum_{t=1}^T \sum_{i=1}^n SW_n \quad (5)$$

$$WW_{IS} = \sum_{t=1}^T \sum_{i=1}^n WW_n \quad (6)$$

where E represents energy consumption; W represents water consumption; M represents raw material consumption; P represents produced product; SW represents solid waste release; and WW represents wastewater release. T represents the number of years ($T=20$) and n represents the number of industrial participants.

The model conducts an economic assessment, which includes LCC of products and waste management. Martinez-Sanchez (2015) suggested further division of the life cycle cost of waste management into: economic cost (LCC_{eco}), environmental cost (LCC_{env}) and societal cost (LCC_{soc}). LCC parameters are illustrated in Equations (7) to (10):

$$LCC_{IS} = \sum_{t=1}^T \sum_{a=1}^n (C_p(1+e)^{-1}) \quad (7)$$

$$LCC_{eco} = \sum_{t=1}^T \sum_{i=1}^n [W_i(UBC_i + UT_i)] \quad (8)$$

$$LCC_{env} = \sum_{t=1}^T \sum_{i=1}^n [W_i(UBC_i + UT_i + UAT_i)] \quad (9)$$

$$LCC_{soc} = \sum_{t=1}^T \sum_{i=1}^n [W_i(UBC_i * NTF + UEC_i)] \quad (10)$$

where C_p represents the production cost; e represents the discount rate ($e=1.5\%$); W_i represents the amount of input waste (waste release from each industry); UBC_i represents the unit budget cost; UT_i represents the unit transfer cost (cost related to collection and transport of waste); UAT_i represents the unit anticipated transfer cost (anticipated increase or decrease in cost); NTF represents the net tax factor (shadow price); and UEC_i represents the unit externality cost (unintended cost). i and n represent unit cost activity and number of industries respectively. The production cost (C_p) consists of the price of raw material, energy and water consumption, feedstock, input fuel and labour. The environmental assessment of an IS network represented in Equations (11) to (13):

$$CO_{2IS} = \sum_{t=1}^T \sum_{i=1}^n CO_{2n} \quad (11)$$

$$CH_{4IS} = \sum_{t=1}^T \sum_{i=1}^n CH_{4n} \quad (12)$$

$$N_2O_{IS} = \sum_{t=1}^T \sum_{i=1}^n N_2O_n \quad (13)$$

where CO_2 , CH_4 and N_2O represent emissions of carbon dioxide, methane and nitrous oxide respectively. The standard carbon footprint is taken into account for agriculture industries. Methane and nitrous oxide emissions from the agriculture sector are negligible due to waste collection by the department of waste management and wastewater treatment. The energy sector is the major source of emissions in the IS network. The environmental assessment includes only the standard parameters provided either in the previous literature or according to the IPCC guidelines. Afshari et al. (2020) showed energy optimisation in an IS network. Energy optimisation is characterised by design assessment and variation of energy supply and demand (seasonal variation). The optimal assessment is illustrated in Equation (14):

$$Z = \sum_{i=1}^n (C_{waste\ heat} + C_{tax}) \quad (14)$$

where Z , $C_{waste\ heat}$ and C_{tax} represent optimal assessment of cost reduction, cost of waste heat and cost of carbon tax due to the use of fossil fuels respectively. The optimal assessment shows the possible cost reduction in an IS network by heat

recovery and replacing fossil fuel with renewable fuel. A significant amount of cost could be reduced by storing waste heat from power plants. The waste heat can be retained in a heat storage system when energy supply exceeds demand and can be sold when demand is high. The optimal assessment is not applicable when fossil fuels are not used in the energy industry and heat recovery is not possible.

3.2 Techno-economic assessment of combined heat and power plants

This section summarises Paper 2. The profitability of CHP plants is evaluated by balancing three parameters: government subsidy on investment, net present value and payback time. The cost of energy production (*LCOH/LCOE*), net present value (*NPV*) and emissions in CHP plants are illustrated in Equations (15) to (17) (Welsch et al. 2018):

$$LCOH/LCOE = \frac{\sum_{a=0}^{a_{end}} (I_a + M_a + O_a - R_a)(1+r)^{-a}}{\sum_a^{a_{end}} Q_a(1+r)^{-a}} \quad (15)$$

$$NPV = \sum_a^{a_{end}} CF_a(1+r)^{-a} \quad (16)$$

$$Emissions = Fuel * EF \quad (17)$$

where a represent number of years; I_a is investment cost; M_a is yearly maintenance cost; O_a is yearly operational cost; R_a is yearly revenue; r is discount rate; and Q_a is produced power. The life cycle of the CHP plants is assumed to be 20 years. Levelized cost of heat and electricity determines the cost per MWh. CF_a represents the cash flow. Depreciation cost is not included in the calculation. Net present value shows the monetary value of CHP plants. EF represents the emission factor of the energy sector (IPCC 2006). Emissions from the CHP plants consist of carbon emissions and other greenhouse gas emissions.

3.3 Modelling a borehole thermal energy system

This section summarises Paper 4 and Paper 1. Comsol Multiphysics was used to create 3D models of two BTES. A heat transfer in solids interface module and a non-isothermal pipe flow interface module were used to conduct the simulation study. A non-isothermal module estimates heat transfer to a heat exchanger and the surrounding ground due to carrier fluid flow. A heat transfer module calculates

heat transfer in the immediate ground geometry. Heat transfer in solids and non-isothermal pipe flow are illustrated in Equations (18) to (21):

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot q = Q \quad (18)$$

$$q = -k \nabla T \quad (19)$$

$$\rho A C_p u \cdot \nabla T = \nabla \cdot A k \nabla T + f_D \frac{\rho A}{2 d_h} |u|^3 + Q_{wall} \quad (20)$$

$$Q_{wall} = hZ(T_{ext} - T) \quad (21)$$

where ρ represents density; C_p is specific heat capacity; T is temperature; t is time duration; q is heat flux; k is thermal conductivity; and Q is volumetric heat source. u represents velocity; d_h is hydraulic diameter; f_D is dimensionless Darcy's friction factor; A is cross sectional area of the pipe; Q_{wall} is external heat transfer; and Z is wetted perimeter. An automatic tetrahedral mesh created the nodes and the edge elements. The simulation allows the heat transfer interface and the non-isothermal flow interface to work simultaneously, resulting in an evaluation similar to conjugate heat transfer, not to be confused with computational fluid dynamics (CFD).

4 RESULTS

4.1 Implementing case study 1

This section summarises Paper 5 and Paper 3. Implementation of a sustainable model includes identification of an IS network connection, quantitative assessment and optimal assessment.

4.1.1 Identifying symbiosis

The synergetic connections of the IS network are presented in Table 8. Possible network connections (material exchange) are indicated by “1” and no material exchange is indicated by “0”. Table 8 does not recognise the department of waste management and wastewater treatment.

Table 8. Synergetic connections of the IS network

Industry	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

There are three types of material exchange possible among the industries: energy, bio-waste and recyclable waste. In the given case study, bio-waste consists of sludge and energy crops. Fertilisers and biochar are considered as recyclable waste. Solid waste or non-recyclable waste consists of residual waste, inorganic waste and fly ash. Figure 5 shows material exchange among industrial participants, with arrows indicating the various inputs and outputs.

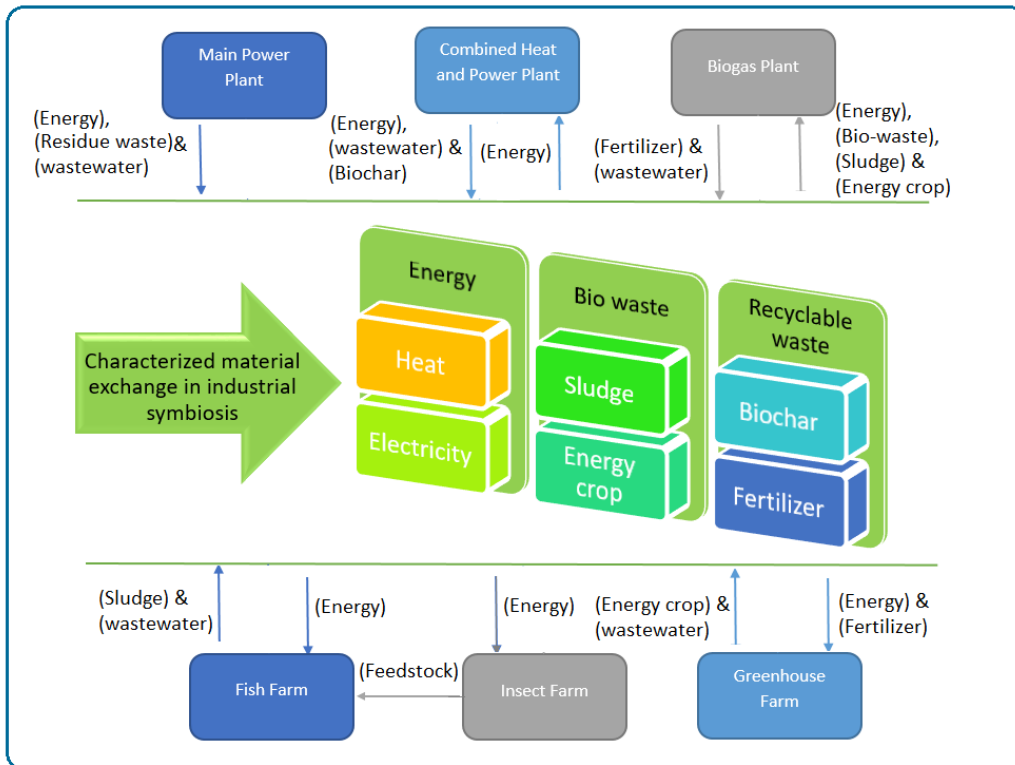


Figure 5. Identified material exchange among industries.

Figure 6 depicts the envisaged architecture of material flow in Sodankylä, Finland. The municipal authority maintains the synergetic relations among industries. The department of waste management and the department of wastewater treatment are essential components of the municipality. External suppliers provide primary energy for the main power plant as well as the input fuels and raw materials. The main power plant supplies primary energy to CHP plants. The CHP plants are responsible for supplying energy to all new businesses in the region. The municipal water plant supplies water to all the businesses in the area. The architecture represents a circular economy scenario, where waste from one industry is raw material for another, resulting in waste reduction.

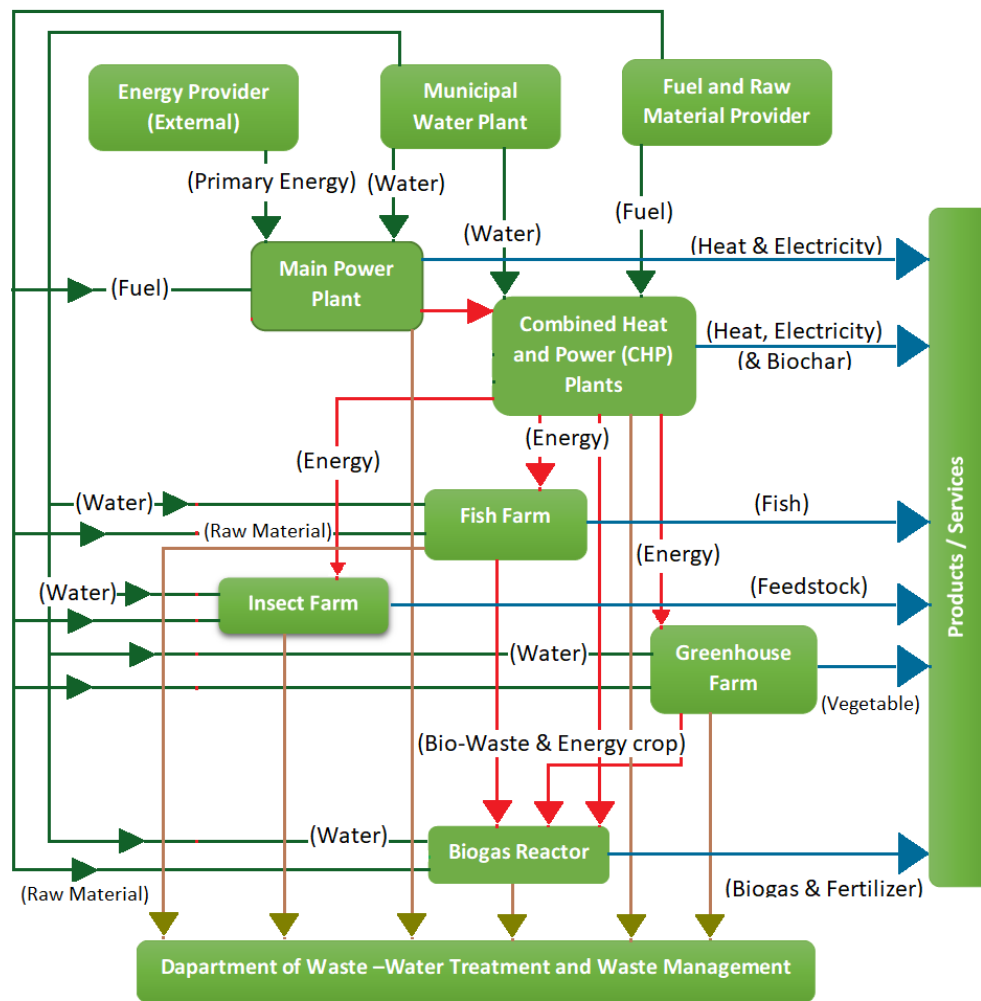


Figure 6. Architecture of the IS network. Blue nodes represent output; green nodes represent input; and red nodes represent material exchange.

4.1.2 Quantitative assessment

Figure 7 presents the calculated material flow in the IS network. Material flow of the industries includes consumption and production. Raw materials consist of eggs for the insect farms, fish for the fish farm, tomato plants for the greenhouse farm and input fuels for the power plants. Raw material for the biogas reactor comes from regional businesses. However, external suppliers also may provide bio-waste to the reactor. The product of the IS network includes the by-product of all the industries. Water consumption in the agriculture sector is significantly higher than

in the energy sector. The fish farm is the biggest water consumer in the IS network. Similarly, there is significant wastewater from the agricultural sector.

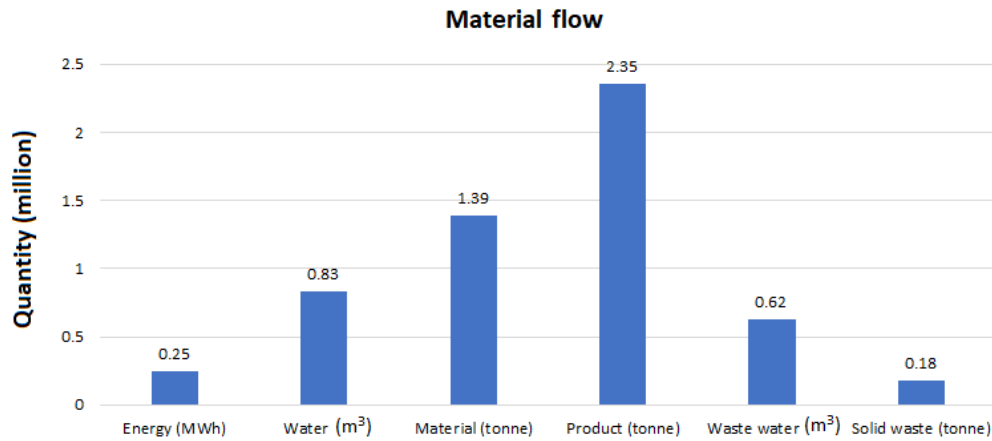


Figure 7. Life cycle assessment of the IS network.

The life cycle cost of products in the IS network is illustrated in Figure 8. The total cost is projected at €115.20 million. The product from the main power plant has the highest production cost, closely followed by that from the CHP plants. The insect farms' production costs would vary, depending on the amount feedstock needed in the region. The cost of product and waste management are separated so that the municipality can incentivise the business participants to save cost on waste management and material exchange. The life cycle cost of waste management is depicted in Figure 9. The total waste management cost is projected at €6.42 million. Environmental cost is the highest of all the categories, forecasted at €4.82 million. Environmental and societal costs can be reduced by replacing fossil fuel with renewable fuel. Economic life cycle cost is marginal, considering twenty years of transport and waste collection.

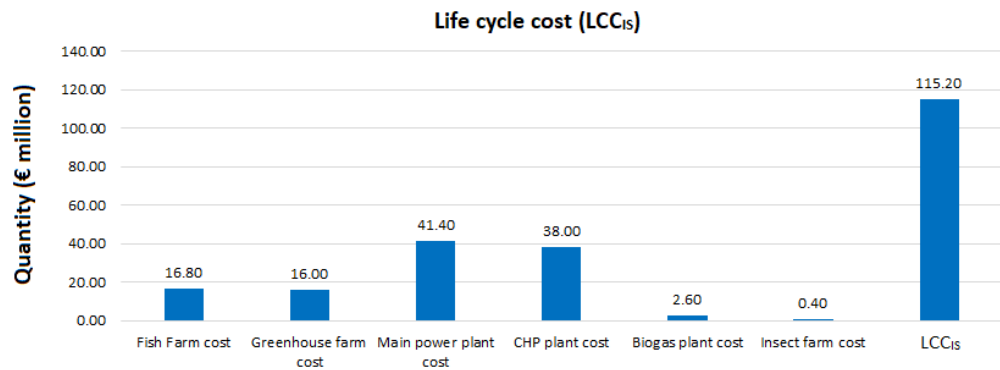


Figure 8. Life cycle cost of products in the IS network.

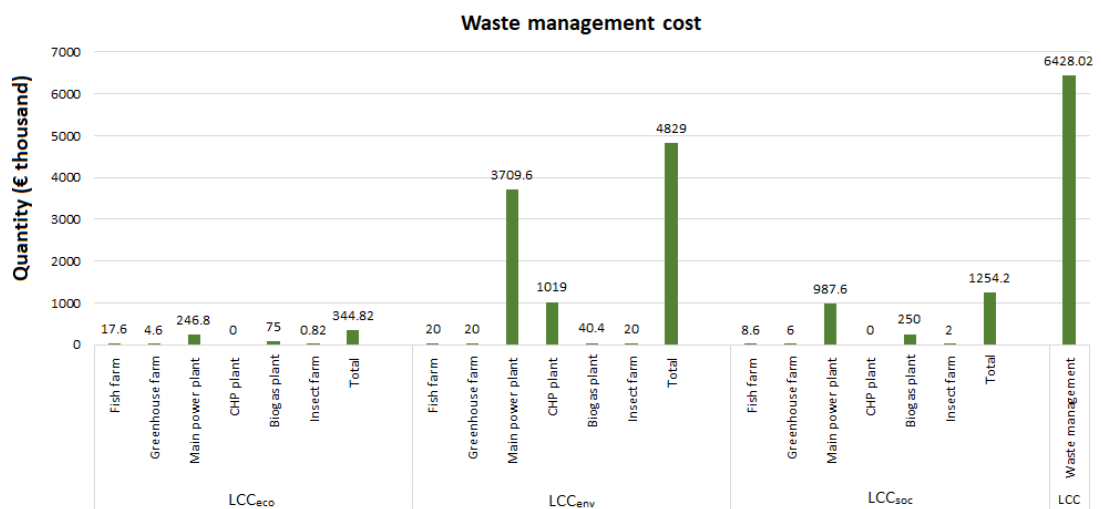


Figure 9. Life cycle cost of waste management in the IS network.

The environmental assessment of the IS network is illustrated in Figure 10. The total carbon dioxide emission is calculated at 0.95 million tonnes. The highest carbon dioxide release comes from the main power plant, estimated at 30,000 tonnes each year. The second highest carbon dioxide release comes from the CHP plants, calculated at 14,000 tonnes each year. Carbon emissions from the agriculture sector are the standard product carbon footprints. Carbon emission from the biogas reactor is marginal, due to biogas upgrading. Greenhouse gas emissions from both the agriculture sector and the biogas reactor are negligible. The total methane

emissions are estimated at 339.8 tonnes, which includes emissions from the CHP plants and the main power plant around 1.35 and 15.64 tonnes respectively each year. The total nitrous oxide emissions are calculated to be 18.2 tonnes, which includes emissions from the CHP plants and the main power plant at 0.27 and 0.62 tonnes respectively each year.

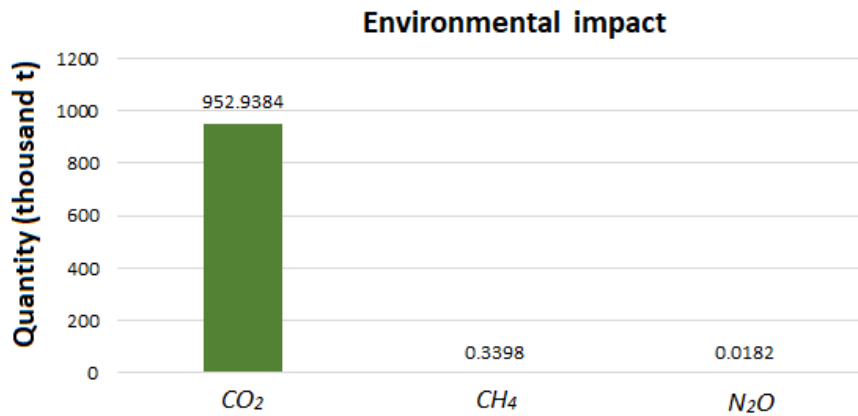


Figure 10. Environmental assessment of the IS network.

4.1.3 Optimal assessment

An energy optimisation study is conducted in order to reduce the environmental impact and cost of products. The cost saving potential is analysed by considering the imbalance between energy supply and demand during the summer. Due to the low energy demand in summer, only two CHP plants will run at full load and the rest can be shut down for maintenance. A preliminary assessment indicated 1.53 MW of excess heat between June and August. This excess heat can be recovered by storing it in a seasonal heat store. The stored heat can be used in winter when the demand is significantly higher. Another opportunity for cost reduction is eliminating the use of fossil fuels from the main power plant. Figure 11 presents the potential cost reduction in the IS network. The savings value of the excess heat recovery project is €0.18 million per year and the fossil fuels' carbon tax cost that can be avoided is estimated at €0.45 million per year. Thus, a total of €0.63 million per year can be saved by implementing heat recovery and replacing fossil fuel in the IS network.

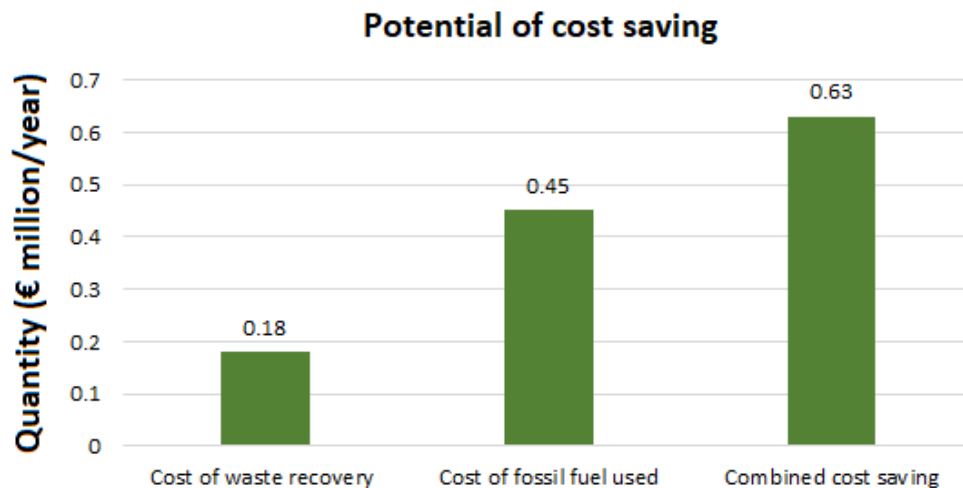


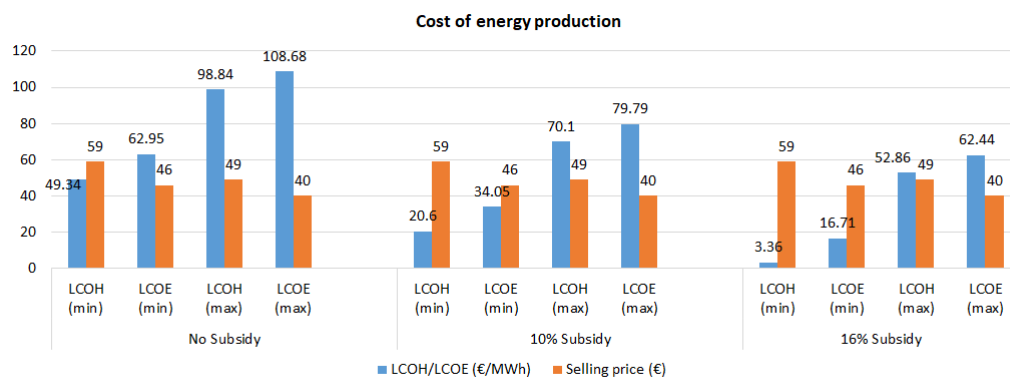
Figure 11. Optimal assessment of the IS network.

4.2 Implementing case study 2

This section summarises Paper 2. Table 9 presents three profitable scenarios for the CHP plants, each based on a different level of government subsidy for the investment cost. The first scenario uses no subsidy on the investment cost and results in a net present valuation of €5 million, with a very long payback time. The second scenario assumes 10% subsidy on investment cost and provides a value of €6.6 million with an improved payback time. The third scenario considers a 16% subsidy on investment, giving an NPV of €7.6 million with a 10-year payback period. Scenario 3 is relatively better than the other two scenarios, with a reasonable payback time and percentage subsidy. Figure 12 depicts the cost of energy production at the CHP plants, assuming the same three scenarios. The production costs are significantly higher in the first scenario. The cost of production is marginal in the second scenario with 10 % subsidy on investment cost. However, the production cost is optimal in the third scenario with 16% subsidy on investment cost. The optimal minimum costs of heat and electricity production are estimated at €3.36 per MWh and €16.71 per MWh respectively.

Table 9. Profitable scenarios for combined heat and power plants

Parameter	Investment option	NPV (million €)	Payback time (years)
Scenario 1	No subsidy	5	15
Scenario 2	10% subsidy	6.6	12
Scenario 3	16% subsidy	7.6	10

**Figure 12.** Production cost of combined heat and power plants.

The main power plant can use input fuel in three ways in the current situation. First, peat can be used as the sole input fuel. This is an economical option because peat is cheaper than woodchip. The second option is to use all the current fuels (woodchip, peat and heavy oil). The third option is to replace the fossil fuels with woodchip fuel. Figure 13 shows that environmental emissions from district heat production are significantly high when either solely peat or the combination of all three input fuels is used in the main power plant. Consequently, the recommended option is to use only woodchip input fuel in the CHP plants and also in the main power plant. With renewable fuel in the region, this strategy can reduce greenhouse gas emissions by between 53 % and 78 %. The economical option is to use peat input fuel for heat production. However, this would elevate carbon emissions by 37 % compared to the renewable fuel option, resulting in additional carbon tax. Due to the high production imbalance between summer and winter, the fossil fuel option may seem viable in order to fulfill the district's peak consumption demand.

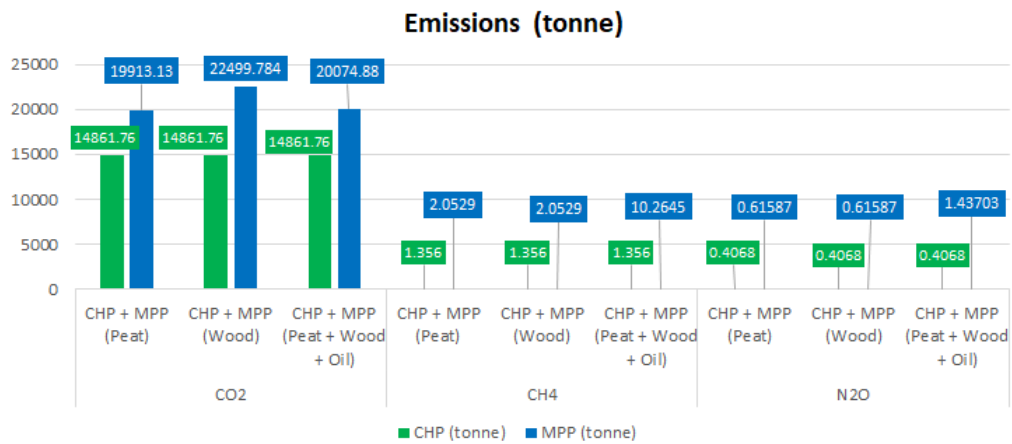


Figure 13. Emissions from district heat production.

4.3 Implementing case study 3

This section presents two configurations. Configuration 1 (for a centralised BTES) includes the simulation of storing excess heat from the CHP plants. Configuration 2 (for decentralised BTES) does not simulate storing the excess heat. However, the application of seasonal BTES is similar for a decentralised heating network.

4.3.1 Configuration 1

This section summarises Paper 4. The preliminary analysis projects a heat surplus of 1.53 MW every year. Figure 14 shows surplus heat being stored in a BTES during the summer. The stored heat can be delivered via the same network during the winter. The simulation results reveal that 0.28 MW of heat energy is stored in the BTES at the end of the charging operation. This means five BTES could be constructed to harness all the excess heat from the CHP plants. Figure 15 illustrates five years of the charging and discharging cycle in a BTES. The discharging heat rate is a constant 120 kW. The heat extraction could be increased, if needed, but this would affect the injection operation and vice versa.

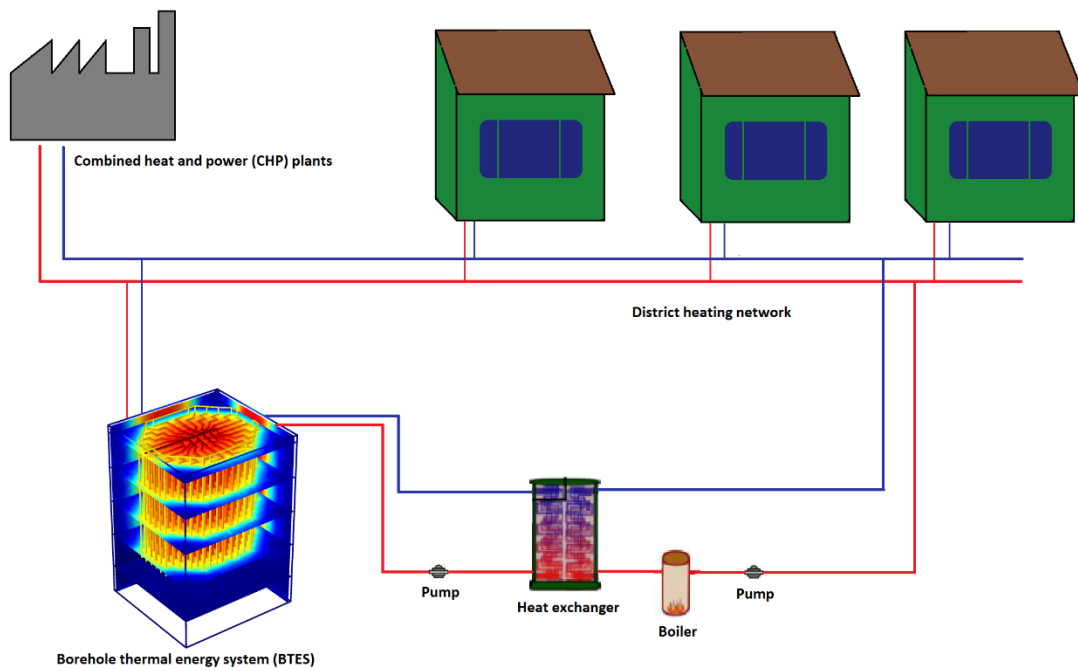


Figure 14. Application of a borehole thermal energy system. Combined heat and power plants deliver excess heat to the heat storage during summer. The stored heat is distributed to the network during winter.

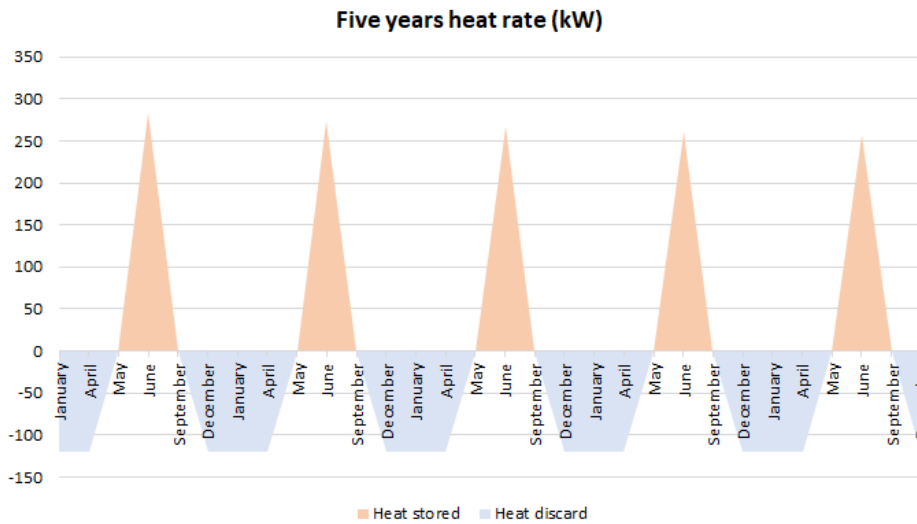


Figure 15. Five years' operation. Excess heat charges storage during June – August; stored heat can be extracted from the storage during September – May.

4.3.2 Configuration 2

This section summarises Paper 1. Configuration 2 represents a decentralised application of a BTES. This configuration is capable of storing a maximum of 50 kW of excess heat. The simulation conducted tested the capacity of the BTES with an injection rate from 30 to 60 kW, depicted in Figure 16. Thermal distribution of the BTES revealed that the temperature rose to 26 °C when injecting with 40 kW power; to 32 °C with an injection rate of 50 kW; and to 34 °C with 60 kW. The temperature rise indicates that a 50 kW injection rate is optimal for the given configuration because little significant temperature rise is seen at a higher injection power. This configuration can be used for a small building in a remote location.

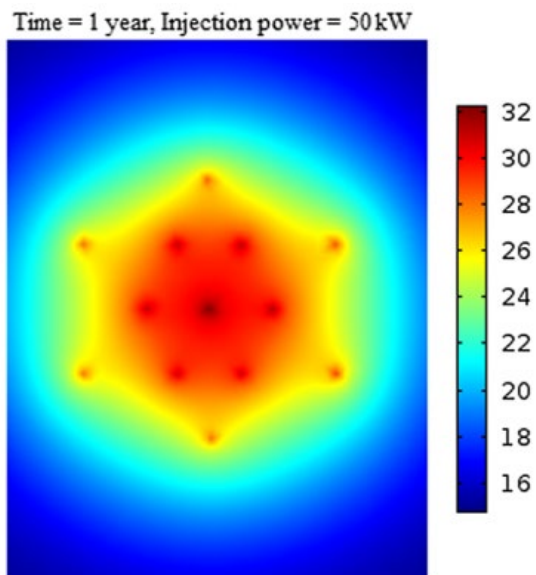


Figure 16. Heat rate of injection. The temperature distribution produced with respect to the injection power in the given configuration.

5 DISCUSSION

A typical life cycle assessment study focuses on maximising the production capacity of an industry and on reducing waste and environmental impact. Aissani et al. (2019) and Martin et al. (2015) argued the development of various reference scenarios to compare with the existing and hypothetical scenarios in an IS network. However, their comparative analysis of existing case study with various hypothetical scenarios expands the computation and reduces the comprehensibility of the model. The approach presented in this thesis eliminates the necessity of reference scenarios, building a comprehensible model by means of material exchanges and avoiding unusable data assessment. Furthermore, Suh and Huppes (2005) proposed life cycle inventory methodology to evaluate an IS network. This thesis implemented an input data section that keeps a quantified inventory of all industries, while adding estimates of wastewater and solid waste releases, which are an essential feature of a sustainable IS network. Sokka et al. (2010) and Mattila et al. (2010) argued for the importance of reducing the environmental impact of an IS network. Waste management solutions play an important part in reducing the environmental impact, so this thesis evaluated life cycle cost of a waste management solution, showing business participants in the IS network would have a similar waste reduction strategy acquired from (Van Berkel 2010).

The research methods from management and technical studies reviewed for this research lack a comprehensive platform and business sector identification to evaluate an IS network. This thesis provides an approach that combines methods from both management and technical disciplines. It addresses most areas of IS network evaluation, affirming the standard guidelines of life cycle assessment. However, the presented model has limitations, depending on the type of industries and data associated with the IS network assessment.

Paper 5 proposed an approach to model a sustainable IS network. The model identified material exchange among industries and estimated environmental, economic and life cycle assessment. It also evaluated energy optimisation in the network. It is recommended that average or maximum data values should be used to avoid sensitivity analysis. The construction of reference scenarios should also be avoided. The implemented approach had a limited number of products and few exchanges, simplifying the evaluation of network connection. However, the complexity of the system may increase with multiple products and exchanges when estimating the transport and collection of waste and the environmental assessment. It is recommended to limit the environmental and economic constraints of the system by carefully planning the waste management transport and location of the industries for new development in an IS network. Energy optimisation in an IS

network is achieved by assessing the location of the industries (Afshari et al. 2020). The implemented energy optimisation affects fossil fuel use in district heat production. Replacing fossil fuels with renewable fuel would generate a significant cost reduction. In addition, heat recovery is proven to be an important aspect when reducing the cost of heat production.

Paper 3 also focused on identifying material exchange among similar case studies, and on quantifying the cost of products and waste management in an IS network. The study further conducted a valuation of the IS network, forecasted at €43.69 million. The life cycle cost of product and waste management are projected at €93.04 million and €6.41 million respectively. The purpose of the study was to evaluate the monetary gain of industrial cooperation. The combined valuation of industries increased by 14.65 % under a symbiotic environment, with cost reduction of 6.8 % compared to a non-symbiotic environment.

The profitability of CHP plants depends on the government subsidy and payback time on the investment cost. The cost of heat production was found to be optimal with a 16% subsidy on investment, with a reasonable payback time of 10 years. However, additional subsidy could significantly reduce the payback time on investment and the cost of heat production would also fall. The environmental impact of district heat production would reduce significantly after the construction of the CHP plants and the region will be able to produce clean energy. The case study presented three different scenarios for selection of input fuel. The CHP plants and the main power plant used renewable fuel in the first scenario, resulting in the best environmental outcome for the region. The second scenario proposed using peat and woodchip fuels. This is the most economical option for the region, but at the expense of a slight compromise on the environmental aspect. The third scenario suggested no change to the existing input fuels (peat, woodchip and heavy oil) for the main power plant. Peak energy demand in winter could be significantly above the expected average, so heavy oil would be able to compensate for this fluctuation.

Paper 2 also highlighted the current state of district heat production in Sodankylä, presenting the energy demand of the region as well as its environmental impact. The study also introduced the technology of the proposed CHP plants. Furthermore, an alternative approach was presented, analysing the option of installing an industrial heat pump. The analysis showed that such a heat pump was economically viable in some regards but drawbacks in terms of finding a heat source for the pump due to Sodankylä's geographical location makes it an even more expensive option for the region.

Application of seasonal BTES provides business development opportunity in Sodankylä. Two configurations were analysed to store excess heat from CHP plants.

Configuration 1 proposed a centralised low-temperature distribution network, whereas configuration 2 presented a decentralised application. The proposed configurations can be considered either independently or simultaneously for storing excess heat. The capacities of configurations 1 and 2 were estimated at 0.28 MW and 50 kW respectively. Configuration 2 is suitable for remote buildings. On the other hand, configuration 1 is suitable for a low- temperature heating network.

Paper 4 also validated the constructed model with the experimental measurements of the DLSC project. The accuracy was estimated at 95 %. The data were collected from Natural Resources Canada. The study analysed data of eleven years' operation and created an artificial neural network model for heat charging and discharging. The accuracy of the model was calculated at 97 %. Independent simulations were made for both charging and discharging operations.

Paper 1 also validated the model with experimental measurements of a pilot project in Kokkola, Finland. The accuracy of the model was estimated at 96.6 %. The study introduced the pilot project, with schematic diagrams of solar collectors and ground heat storage. Temperature profiles of solar collectors were projected and the model's simulated average borehole temperature was compared with experimental measurements.

6 CONCLUSION

This thesis proposed a model of an industrial ecosystem in Sodankylä, Finland. The system consisted of six industries from the energy and agriculture sectors. The region has an existing power plant for distribution of energy to the network. The municipality has planned to develop five new industries in the area: six CHP plants, a greenhouse farm, insect farms, fish farm and a biogas reactor. Furthermore, these industries are expected to participate in an IS network. The network provides a platform for industries to share resources and also to reduce waste and environmental impact in the region. Papers 1-5 were used to model the industrial ecosystem. The study's proposed approach shows the construction of an IS network where material exchange is facilitated, where raw materials, costs, and environmental impact are quantified and where energy optimisation is implemented. The approach showed the estimation of cost savings, waste reduction and environmental impact. The study also highlighted the importance of CHP plants as the clean energy supplier to all local industries in the area. The construction of CHP plants encourages the use of renewable fuel in district heat production and makes the region carbon neutral. The study further emphasised the cost savings achievable by recovery of the excess heat from the CHP plants. Heat recovery provides a business opportunity to construct heat storage. It stores excess heat during summer when heat demand is low and distributes heat to the network during winter when demand is high. The study presented two configurations of BTES for storage of the excess heat. Configuration 1 described a centralised, low-temperature, small district heat network similar to the DLSC project solution. Configuration 2 illustrated a decentralised application of heat storage, referring to a pilot project in Finland. The following conclusions are drawn from this research study in attempting to answer the three research questions posed (see 1.4):

1. The material exchange among industries could be identified by constructing an IS network matrix. The matrix showed which industries exchange materials.
2. Evaluating the quantity of material flow in the IS network highlighted the consumption and production of industries. The projections showed that the agriculture sector consumes a significant amount of water as well as releasing substantial wastewater in the network.
3. Life cycle cost of products was projected at €115.20 million. Currently, the production cost of the main power plant is significantly higher than that of the other industries. This cost will be reduced once the CHP plants start distributing energy to the network. Similarly, the life cycle cost of waste

management was estimated at €6.42 million. The waste management cost in the main power plant is higher than in other industries because of its fly ash release and carbon tax. These costs will be reduced once the plant replaces fossil fuels with renewable fuel.

4. Carbon dioxide release from the area was estimated at 0.95 million tonnes. Carbon dioxide release is not taxed when renewable fuels are used to produce energy. Similarly, methane and nitrous oxide releases were projected at 340 tonnes and 18 tonnes respectively.
5. Cost reduction from energy optimisation was estimated at €0.63 million per year. These savings are derived from heat recovery and reduction of carbon tax. They become costs when excess heat is not stored in heat storage and the main power plant uses fossil fuels.
6. The study confirmed that the construction of CHP plants is profitable investment for the region. The costs of heat and electricity production with a 16 % subsidy were projected at €3.36 per MWh and €16.71 per MWh respectively. The plants are valued at €7.6 million with a payback time of 10 years.
7. Three scenarios were proposed to produce district heat. The first scenario suggested that both CHP plants and main power plant use woodchip fuel to produce energy, reducing greenhouse gas emission by between 53 % and 78 %. However, the cost of renewable fuel is higher than if using peat. The second scenario is to use both woodchip and peat fuels. Peat is cheaper than woodchip but would incur additional carbon taxes because of its emissions. The third scenario is to use a combination of woodchip, peat and heavy oil. This option may help handle the rapid fluctuation of energy demand in the region.
8. Two BTES configurations were presented in the study. The first configuration proposed a centralised low-temperature, small district network with BTES capacity of 280 kW. The second configuration showed decentralised heat storage with a capacity of 50 kW. Five BTES installations similar to configuration 1 were recommended to store all the excess heat released from the CHP plants.

Future research into modelling industrial ecosystems will include intensive digitalisation of consumption and production in an IS network. The digitalised platform will allow companies to make matches automatically and develop the best ways to exchange materials and reduce waste and environmental impact.

7 SUMMARY

The main goal of this thesis was to model a sustainable industrial ecosystem. The model included data collection; identifying business sector and network connections to facilitate material exchange; and estimation of environmental impact, life cycle costs, material flow and energy optimisation in an IS network, according to the standard guidelines of life cycle assessment literature. The approach implemented a case study of industrial symbiosis from Sodankylä, Finland. The municipality planned to establish new businesses in the region to boost local economy. These businesses were expected to adopt the circular economy model and transform the region to carbon neutrality. The proposed symbiotic environment facilitates material exchange among industries, synchronises their waste management strategy and reduces their waste and carbon footprints. The study further investigated the profitability of new power plants and estimated the cost of energy production, based on various levels of investment subsidy. The reduction of the environmental impact of district heat production was evaluated, based on three different input fuel scenarios. The thesis also analysed the possibility of storing excess heat from the new plants.

The life cycle cost of product and waste management in the IS network is projected at €115.20 million and €6.42 million respectively. The combined cost of waste management is construed as cost saving due to participation in the symbiotic environment. The estimated savings in greenhouse gas emissions due to operation of the industrial ecosystem are projected at 53 % to 78 %. The potential for further cost reduction by energy optimisation is forecasted at €0.63 million every year.

Three case studies (Papers 1-5) were presented in the study to answer the posed research questions. The model construction from Paper 5 was implemented on the case study described in Paper 3. The model was based on the previous research studies and standard guidelines of life cycle assessment literature. Data on industrial symbiosis were collected from the Natural Resources Institute Finland (Luke). The second case study, from Paper 2, applied techno-economic modelling. The model was implemented to estimate the cost of heat and electricity production. Power plants data were collected from the municipality of Sodankylä. The third case study presented different configurations of heat storage. Configuration 1, from Paper 4, implemented a model of BTES similar to the Canadian DLSC project. The model was validated with experimental measurements. Data were collected from Natural Resources Canada. Configuration 2, from Paper 1, constructed a heat storage model similar to a pilot project in Kokkola, Finland. This model was also validated with experimental measurements using data collected from HUR, the host company of the pilot project in Kokkola.

This research presents an improved model of a sustainable industrial ecosystem. The study, which is based on standard guidelines of life cycle assessment, facilitates industrial cooperation and helps reduce waste, life cycle cost and carbon footprint.

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An inquiry of ground heat storage: Analysis of experimental measurements and optimization of system's performance

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HIGHLIGHTS

- Thermal response analysis of ground heat storage pilot project over one-year period.
- A unique perspective of ground heat storage with the help of schematic diagrams.
- Modelling ground heat storage pilot in COMSOL after validation with line source model.
- Implementation of optimal mode of operation.
- Thermal response of the system over five years with input power variation.

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ABSTRACT

One of the imminent challenges in Europe is to increase the use of decentralized energy production with or without backup from the main grid. Heat demand in Europe during winter is evidently higher than the rest of the year. With the development in the fields of solar thermal collectors and ground heat storage system, decentralized energy production enables net zero building implementation. This study investigates thermal response of a ground heat storage system over two consecutive charging period from June 2016 till August 2017. Heat energy (collected from solar collectors) is injected in the ground heat storage during summer season. Experimental measurements are presented in the study. Strategy of charging heat storage is proposed in order to conduct an optimal operation. The collected charging temperature (input signal) and initial conditions are applied in the model and results indicate that temperature of the ground rose from 8 °C to 18 °C within a period of one year. Temperature distribution of ground heat storage is predicted to be 24 °C over five-year period of operation. Thermal response of the ground heat storage is predicted between 18 °C and 34 °C over one-year period with variations in the injection power from 30 kW to 60 kW. Multi-year heat transfer in a standard Finnish soil is estimated to an average of 1.2 GJ.

1. Introduction

Development of decentralized ground heat storage has increased in the past few years followed by the concern of energy conservation and reducing greenhouse gas emission. Ground heat storage has the potential to significantly decrease the amount of electricity consumption on space heating and domestic hot water production. In order to achieve this goal, a proper assessment of ground heat storage is required. Ground heat storage is sometimes referred to as seasonal heat storage when utilized with systematic seasonal charging. It requires a heat source, usually solar thermal collectors in non-industrial applications. Performance of solar collectors quantify the amount of energy charged in the heat storage [1,9]. Heat exchange from solar collectors

to ground heat storage demands high efficiency of solar collectors [25,20]. Location of heat storage is also an important constraint which influence the efficiency of the heat storage system [5]. Thermal properties of soil vary with geography in the same way as solar radiation [3]. The use of ground heat storage is redundant in some hot climate where solar energy is readily available at all time and solar collectors can be used directly with a ground source heat pump for space heating and hot water production [16].

Ground heat storage consists of heat exchanger pipes buried in the ground and heat storage materials (which in most cases a combination of soil, rocks and insulation). Heat exchanger pipes are either U-tube (single/double) or coaxial tube configuration in most applications. Spiral coils may also be utilized depending on the application [2,11].

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Modeling of heat extraction from boreholes are discussed in details in [4]. Heat transfer in a single borehole is analyzed based on thermal characteristics of heat exchanger pipe [6]. Experimental study shows that storage tank is a necessary component along with solar collectors in some applications to achieve 90% efficiency [15]. Multiple modes of operations are implemented with respect to the climate and energy demand of the consumer [28]. Heat pump performance significantly improves by altering the mode of operation in different seasons. For example, utilizing solar collectors directly for space heating rather than charging boreholes during autumn. In some cold climate, direct use of solar energy is prioritized for space heating in combination with a suitable heat pump [27].

Configuration of ground heat storage depends on the energy consumption. Higher energy consumption requires additional boreholes or deeper boreholes. Ground heat storage is often characterized by size which is either used for district heating applications or decentralized energy storage. An example of district heating application is prominent in recent years where 97% solar fraction has been achieved after five years of operation [18,19]. Cost of seasonal heat storage remains a debate when implementing in a decentralized energy storage [24]. One of the challenges of implementing ground heat storage on a decentralized scale is groundwater movement. Literature reveals that there is little heat loss in the ground heat storage (grouted) with normal groundwater movement but heat loss is catalyzed by an unusual groundwater movement [14]. Another challenge is to estimate thermal resistance of the borehole which may vary with respect to the depth of the ground and high temperature fluctuations [12]. Economic feasibility with respect to the performance of seasonal heat storage remains questionable in both large and small scale applications [13]. Literature concerning ground heat storage have evolved with an emphasis on utilizing heat storage with a heat pump, solar collectors and a storage tank. In cold climate, off-grid houses where domestic hot water production is just as important as space heating with the same heating appliance, a combination of heat pump, solar collectors and a tank is used with controlled operation [10,23]. In other residential buildings, a combination of solar collectors, ground and heat pump system is more appealing with an efficient solar collector [26,29]. Ground heat storage applications are getting cheaper by developing accurate system configuration in shallow ground [7] which is an important factor in reducing the cost of drilling.

Reducing cost in ground heat storage remains an important constraint in developing more applications of decentralized energy storage. Perhaps, optimal configuration and improved performance of heating systems are key to advance the use of ground heat storage. Operation and design of thermal energy storage are essential components to obtain a desired performance of the system [17]. Environmental criteria is another important constraint which may increase the cost of system operation. Life cycle of the system may be assessed based on the economical and operational measures. Optimal design is achieved on the distribution side by balancing the energy supply to the population based algorithm or price-based demand response [22,8]. System may also be improved by considering the fluctuations in thermal properties of ground heat storage materials [21]. In the next section, given system is elaborated in details along with the measurements and operations. Numerical model is implemented in the following section to optimize the performance with controlled mode of operation. The constructed model is then validated with an analytical method. Results are discussed in the second last section. At last, conclusions are drawn.

2. Description of pilot project

The Pilot project is constructed at a warehouse in Kokkola (Finland) where solar collectors are placed at roof of a building covered with plastic, where parallel combination of pipes are made from inlet to outlet of solar collectors. Temperature of the fluid is recorded into a database. Boreholes and neighboring ground are insulated to minimize

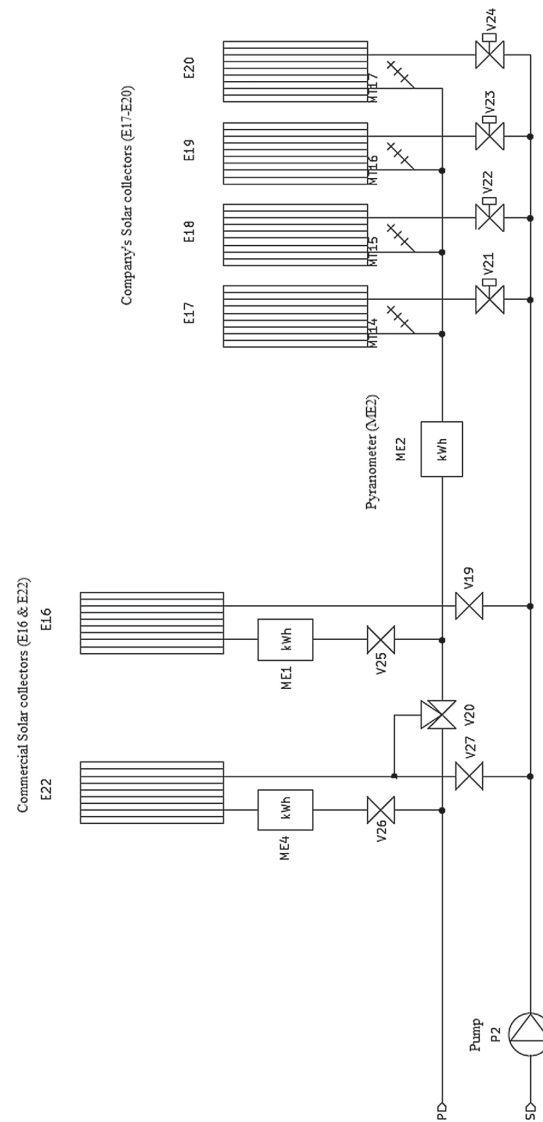


Fig. 1. Schematic diagram of the solar collector circuit in combination with pump circulating carrier fluid, temperature sensors and valves are drawn. (Courtesy of Edward Stenman).

heat losses from the surface of the heat storage. There are two types of solar collectors used at the pilot. (E17-E20) are company made, (E22 & E16) are commercial product depicted in (Fig. 1). Solar collector constructed with aluminum based substrate with dark insulated coating on top. The collectors were divided into four profiles initially. One profile was uncovered, two of them had double plastic covers and the last one had single plastic. After one month of observation, it was concluded that profile with single plastic had the highest performance compared to others, since double plastic reflect most of the light and the collectors did not get enough time to absorb heat, while wind blew heat away. In schematic, pump (P2) circulates cold fluid into common entrance channel and warm fluid leaves the collectors from common exit channel. Extra valves (V27 & V19) are placed serially to install more solar collectors, if required. Total area of solar collector is about 97

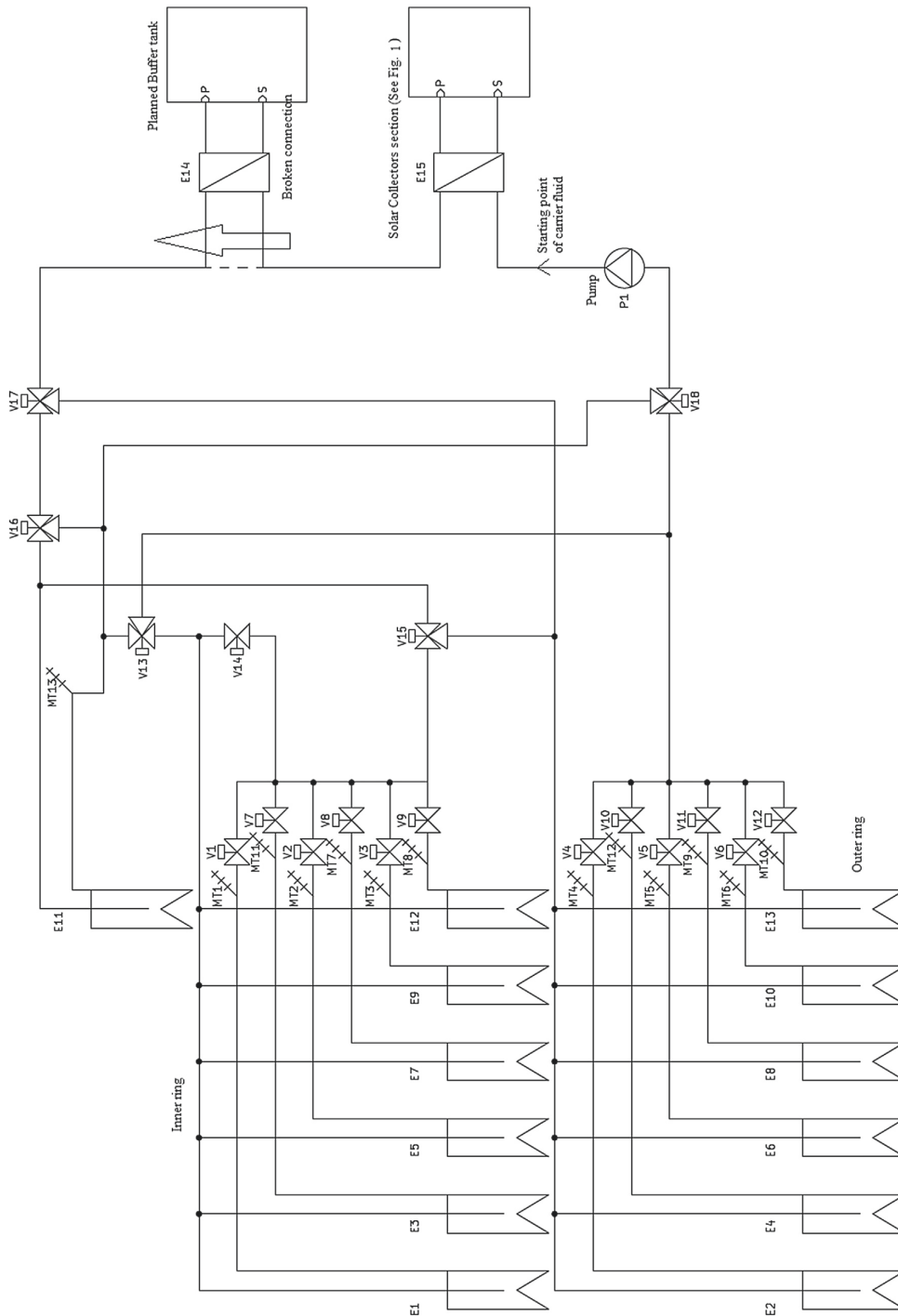


Fig. 2. Schematic diagram of the ground heat storage circuit, consists of thirteen boreholes, temperature sensors and valves placements are drawn. (Courtesy of Edward Stenman).

square meters. Volumetric flow rate varies from 0.5 to 1 (l/s). V21-V24 and M14-M17 represent valves and temperature sensors respectively. 30% of ethylene glycol solution is used as carrier fluid. System operates with a logic design circuit in which pump starts automatically if the air temperature rises higher than the ground temperature during summer time while neglecting the temperature below 0 °C.

E14 is the water storage tank depicted in (Fig. 2). Heat energy injected in the ground heat storage to induce temperature rise, as temperature rises high enough, the excessive heat is transferred to the tank. Dimensions of the tank are not mentioned in the text since tank's volume depend on the consumer's demand and the pilot is focused on storing heat energy in the ground heat storage. Complete circuit design resembles Drake landing project. Heat storage contains thirteen boreholes (E1-E13) in a circular configuration where six boreholes are installed at the outer ring, other six are placed at the inner ring and the last one in the center, system is portrayed in (Fig. 4). All boreholes are 40 m deep except one in the center (E11), which is 50 m deep. There are eight sensors (MT) installed in each borehole, starting from 5 m in the ground at every 5 m distance. These sensors are connected serially, starting from heat exchanger, carrier fluid circulates through the heat storage which is connected to the solar collectors and feed directly into the center borehole. Center borehole then becomes distributor to the inner ring, outlets of the inner ring are connected with the inlets of the outer ring for charging. All the outlets are controlled with valves (V1-V18) by turning on or off. Independent control of the valves is possible in the system. All outlets are equipped with temperature sensors (MT1-MT6). In the first few weeks of operation, the sensors at the center borehole broke down which were later replaced. At the pilot, charging operation was random due to on-going construction work in the beginning. The center borehole was charged for a considerable amount of time during summer season.

Thermal response of solar collectors are presented in four profiles. Efficiency of the collector profiles were calculated with Eq. (2). Temperature measurement data was put in Eq. (1) to calculate the power of solar collectors illustrated in (Fig. 3). The differences among these profiles are small. Profile 2 shows a maximum power of 25 kW which is the least capable solar collector in terms of performance. The efficiency plot suggests that profile 4 has the highest performance among the four profile.

$$Q_c = mC_p(T_{out} - T_{in}) \quad (1)$$

$$\eta_{collectors} = \frac{Q_c}{GA} \quad (2)$$

where Q_c (W) is solar collector's power, m (kg/s) is mass flowrate, C_p (J/kg·K) is specific heat capacity, T (°C) is temperature either at inlet or outlet of the collectors, η is efficiency, G (W/m²) is solar irradiation (measured from a Pyranometer installed at the project site) at collector's profile and A (m²) is area of solar collectors.

3. Modeling ground heat storage

A model of ground heat storage is implemented in Comsol (Fig. 4) based on the information given about the pilot project. This model contains 13 boreholes which are arranged in a circular configuration. All boreholes are 40 m deep except one in the center, which is 50 m deep. Borehole to borehole distance is assumed to be two and a half meters. U-tube heat exchanger configuration is modeled in the simulation as contrary to the pilot's coaxial tubes due to modeling restrictions (Comsol allows pipe flow interface to calculate heat transfer in and around pipes using Multiphysics, coaxial heat exchanger does not allow to compute pipe flow on the geometry). Total radius of ground heat storage is about 5 m and surrounding ground is assumed to be 15 m in radius to visualize the thermodynamics of the ground. Simulation is arranged over a period of one year (06.2016–08.2017). The model is simulated with collected input data and initial conditions of

the pilot site. Heat transfer in the ground is defined as:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot q = Q \quad (3)$$

$$q = -k \nabla T \quad (4)$$

where ρ (kg/m³) is density, C_p (J/kg·K) is specific heat capacity, T (°C) is temperature, t (s) is time duration, q (W/m²) is heat flux, k (W/m·K) is thermal conductivity of the ground and Q (W/m³) is volumetric heat source in the region. Boundary conditions describe as follows (Dirichlet and Neumann):

$$T = T_0 \quad (5)$$

For a complex model such as this, both Dirichlet and Neumann boundary conditions are identified. The initial condition of the ground heat storage is measured from the pilot site at the beginning of the construction and input in the simulation. Convective heat transfer occur at the boundary with a heat transfer coefficient (h) described as:

$$q = h(T_{ext} - T) \quad (6)$$

Heat transfer in pipe reacting by the pipe flow is described as:

$$\rho A C_p u \cdot \nabla T = \nabla \cdot A k \nabla T + f_D \frac{\rho A}{2d_h} |u|^3 + Q_{wall} \quad (7)$$

where u (m/s) is velocity, d_h (m) is hydraulic diameter, f_D is dimensionless Darcy friction factor, and A (m²) is cross sectional area of the pipe.

$$Q_{wall} = hZ(T_{ext} - T) \quad (8)$$

$$d_h = \frac{4A}{Z} \quad (9)$$

$$h = Nu \frac{k}{d_h} \quad (10)$$

$$Nu_{turbulent} = \frac{\left(\frac{f_D}{8}\right)(R_e - 1000)P_r}{1 + 12.7\left(\frac{f_D}{8}\right)^{\frac{1}{4}}(P_r^{\frac{2}{3}} - 1)} \quad (11)$$

$$R_e = \frac{\rho u d_h}{\mu} \quad (12)$$

$$P_r = \frac{C_p \mu}{k} \quad (13)$$

where Q_{wall} (W/m) is external heat transfer, Z (m) is wetted parameter, and Nu is Nusselt number. Coefficient of heat transfer is an effective component for heat exchange between pipes with its surrounding. Nusselt number for internal laminar flow in a circular pipe is 3.66 constant value. μ (Pa·s) is dynamic viscosity of fluid, R_e is non-dimensional Reynold's number, P_r is non-dimensional Prandtl number. Element size in the mesh settings selected to be normal which produced 56,751 domain elements, 1082 boundary elements, and 1270 edge elements. Thermal properties and variables are presented in Table 1. Material of the ground is assumed to be metamorphic rock which is common in Finland. Surface and bottom temperature of the heat storage is assumed to be same as initial ground temperature (T_0) in the simulation hence neglecting the air temperature.

The proposed control mode of this system is based on the measurements of the ground and the air temperature. Operation starts with a watchdog timer (a separate application to prevent crash in the main application). It assures that all the sensors in the system are attached to the circuit, if any sensor does not respond or produce error, system will automatically restart and send notification. Time duration of the day is taken into account. Flow chart of the system is illustrated in (Fig. 5). Borehole in the center of heat storage is continuously charging as soon as the temperature of solar collector rises greater than the temperature of the ground heat storage. Charging boreholes at the inner or outer

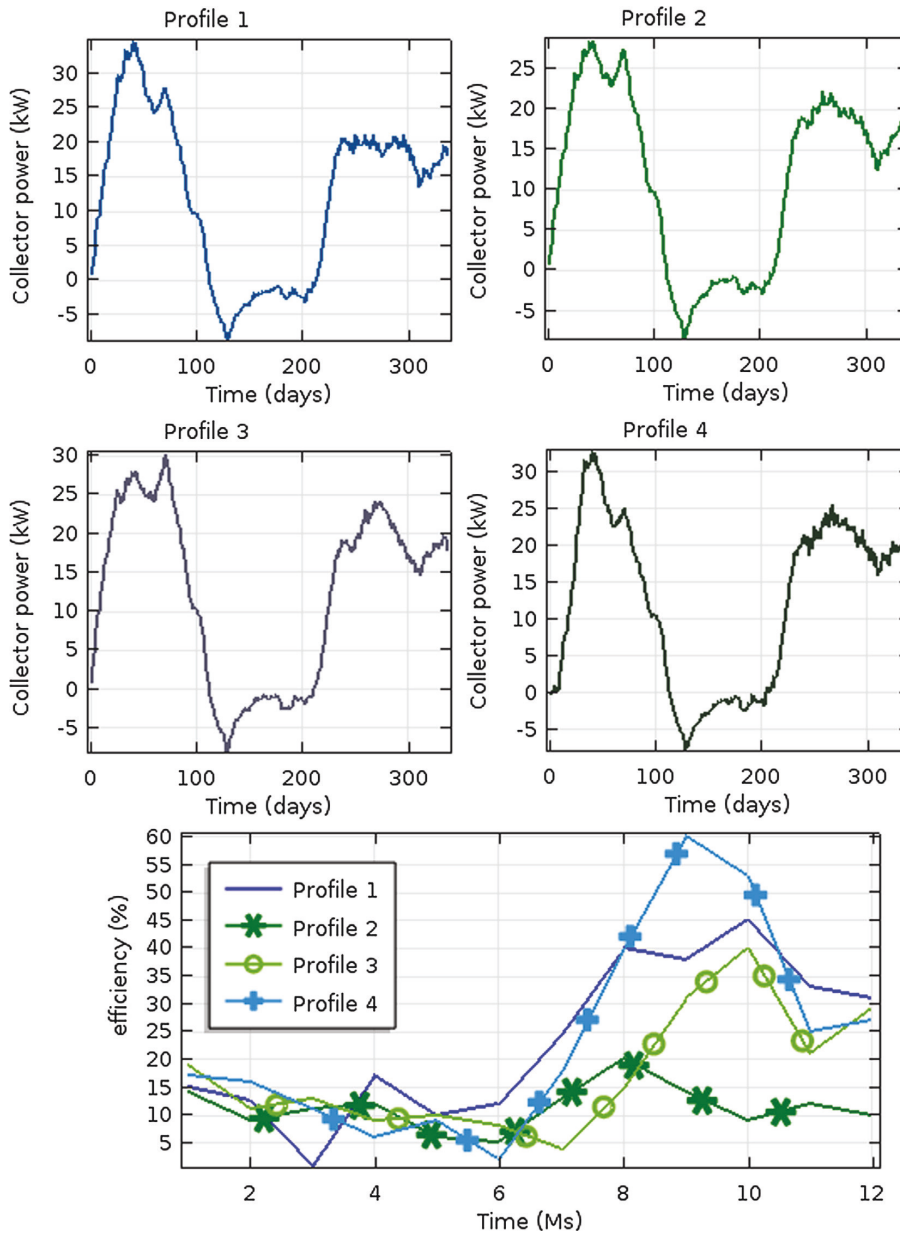


Fig. 3. Average daily solar collector power of four profiles are presented and efficiency of the profiles are illustrated between the periods of 06.2016–06.2017 (0–12 months).

rings also depends on the temperature difference. If the temperature of inner ring is lower than the borehole in the center than inner ring starts charging. If the temperature of outer ring is lower than the borehole in the center and the inner ring than outer ring starts charging.

4. Validation of the Comsol model

In order to validate the constructed model, a simulation is made to compare a single borehole wall temperature. Line source model is widely used to estimate the temperature rise in a borehole. For a

comparative study, a model is presented in (Fig. 6) where a U-tube heat exchanger pipe is buried in the ground with an identified point to calculate temperature rise in the borehole. To compare it with line source, a constant heat source is applied along with an initial condition. The temperature change in the borehole is expressed as [30]:

$$\Delta T(r, t) = \frac{Q}{4\pi k} \int_u^\infty \frac{e^{-u}}{u} du \tag{14}$$

$$u = \frac{r^2}{4\alpha t} \tag{15}$$

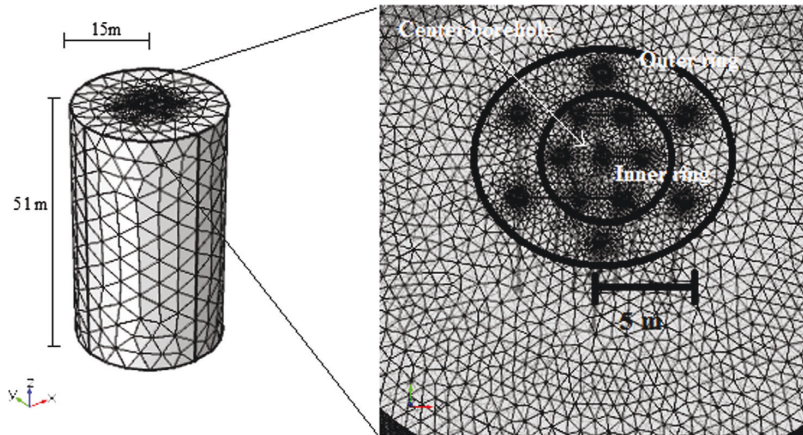


Fig. 4. Model of the ground heat storage, thirteen U-tube heat exchanger pipes buried in the ground heat storage connected in series manner forming two rings or circular configuration.

Table 1
Parameters used in the simulation.

Name	Symbol	Value
Thermal conductivity of ground	k_g	3.4 (W/mK)
Initial ground temperature	T_0	8 (°C)
Boundary temperature of storage	T	8 (°C)
Inner diameter of pipe	D_i	35.2 (mm)
Volumetric flow rate	V	1 (l/s)
Thickness of pipe	d	2.4 (mm)

where ΔT (°C) is the temperature gradient, Q (W/m) is the heat rate of the heat source, k (W/m·K) is the thermal conductivity of the ground, r_b (m) is the radius of the borehole, α (m²/s) is thermal diffusivity, and t (h) is time duration. Temperature change influences the borehole initial temperature, which can be stated as:

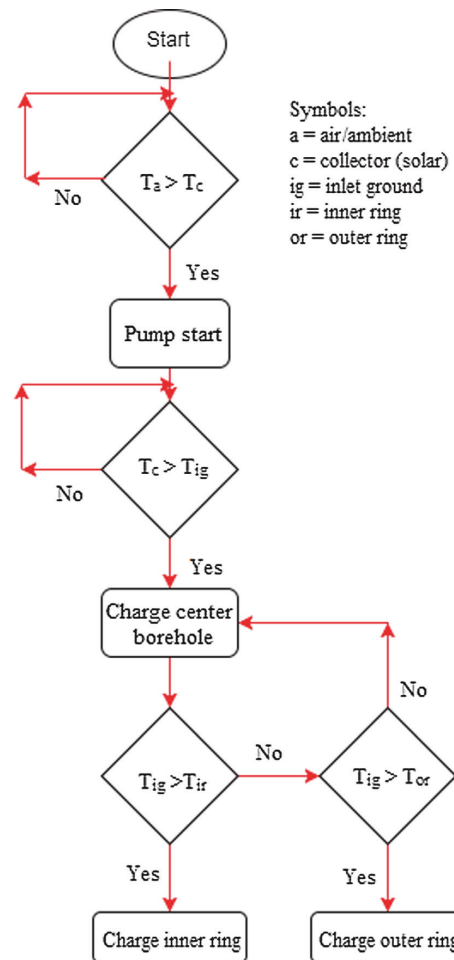
$$T_w(t) = T_0 + \Delta T(r, t) \tag{16}$$

where T_w (°C) is the borehole wall temperature, and T_0 (°C) is the initial temperature of borehole. Initial conditions of the borehole along with the heat source is given in Table 2.

Both models are implemented for a duration of 96 h. Results are compared in (Fig. 7). The initial borehole temperature exponentially increases up to 24 °C. Most of the exponential rise in the plot is recorded in the first half of the operation. Only a 2 °C rise is witnessed in the second half. The percentage of error is estimated at maximum 7% in (Fig. 8). An average error is predicted at 3.4% for the constructed model. Fluctuations of temperature rise between line source and Comsol models are due to fundamental differences in parameter consideration. Comsol uses both heat transfer as well as pipe flow interfaces. Pipe flow considers the geometry of the heat exchanger pipe along with the flow rate of the carrier fluid. While line source uses exponential function to interpret the temperature rise with a constant heat source. The model depicted in (Fig. 4) is constructed to study the pilot project which is an extension of single borehole system.

5. Results and discussion

Experimental measurements and simulated calculations are presented in this section. The input signal is demonstrated in (Fig. 9) which shows the average temperature of the carrier fluid circulating through heat exchanger pipes in the heat storage. The duration of collected data is about fifteen months which includes summer of 2016 and 2017. This data collection reveals the temperature rise during two consecutive



Symbols:
a = air/ambient
c = collector (solar)
ig = inlet ground
ir = inner ring
or = outer ring

Fig. 5. Proposed charging mode of operation. Flow chart depicting the system from control side perspective.

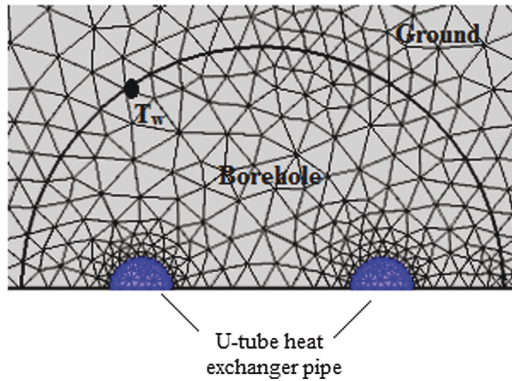


Fig. 6. Model of a single borehole heat exchanger.

Table 2
Parameters used in the simulation.

Parameter	Symbol	Value
Radius of borehole	r_b	150 (mm)
Heat source power	Q	8400 (W)
Initial ground temperature	T_0	6 (°C)
Thermal conductivity of the ground	k	3.4 (W/m·K)

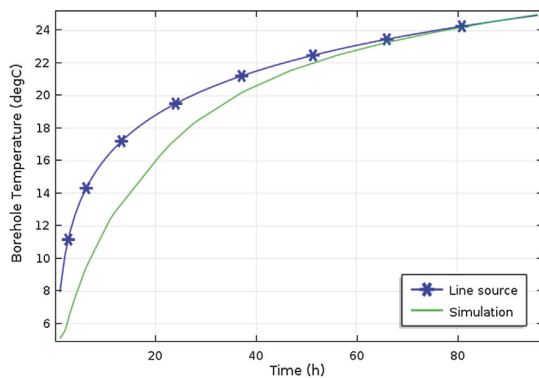


Fig. 7. Comparing Line source and Comsol models for temperature rise in a borehole.

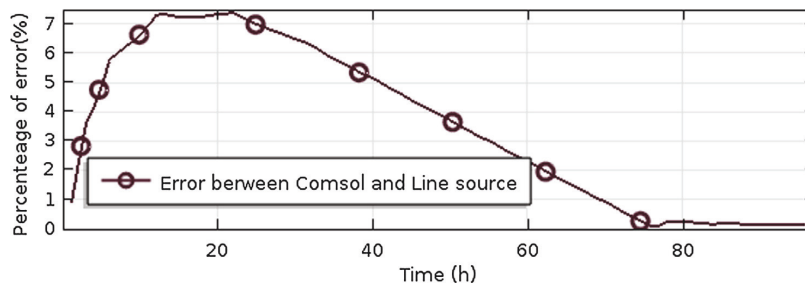


Fig. 8. Percentage of possible error between Line source and Comsol models.

seasonal charging of the heat storage.

5.1. Measurements of ground heat storage at pilot project

The average borehole temperature is presented in (Fig. 10) which contains three sections. First section reflects the temperature plot of borehole in the center (E11 see Fig. 2). Second section illustrates temperature of boreholes at the inner ring (E1, E3, E5, E7, E9 and E12 see Fig. 2). Third section shows temperature response of boreholes at the outer ring of heat storage (E2, E4, E6, E8, E10 and E13 see Fig. 2). The valve system is introduced in this study to control all the boreholes independently. Two pumps were used in the circuit. P1 (displayed in Fig. 2) circulates carrier fluid through the heat exchanger (E15). Temperature of the carrier fluid is influenced by the solar collector circuit (shown in Fig. 1). Fig. 10 shows temperature at borehole in the center remained less than 10 °C during the first summer charging due to broken temperature sensor. Second period of charging in summer 2017 shows rise in temperature with an average of 20 °C. Two boreholes out of six at the inner ring shows maximum of 15 °C during summer 2016 charging period while a slight increase during 2017 charging period. The rest of the boreholes at the inner ring remained at 10 °C during summer 2016 while temperature increment of 5 °C was measured during summer 2017. The difference of borehole temperature at the inner ring represents lack of clarity in the charging strategy. It means that two boreholes were charged most of the time compare to the rest of the boreholes. At the outer ring, temperature plot shows a consistent response among the six boreholes where temperature rose from 8 °C during the summer 2016 to 14 °C during summer 2017.

5.2. Simulated calculations

The model depicted in (Fig. 4) is strictly developed with the information of heat storage from the pilot project. Simulations are made by applying the collected input (charging) signal from the pilot to the model. Simulated thermal response of the ground is presented in (Fig. 11) divided into three sections. First section shows the temperature of borehole at the center, second section displays borehole temperature at the inner ring and third section exhibits thermal response of the outer ring. Systematic charging of boreholes reveals small temperature differences in charging period. Boreholes in the center and at the inner ring shows a difference of 2 °C at the peak charging season. The maximum temperature of borehole in the center estimated to be 22 °C while boreholes at the inner ring show a maximum temperature of 20 °C. Temperature difference among the boreholes at the inner ring reflects the serial connection. At the outer ring, borehole temperature peaked at 16 °C during both of the charging season. Temperature of the heat storage is raised from 8 °C to an average of 16 °C during the charging season and an average of 12 °C during the recovery season. Heat transfer is estimated in (Fig. 12) showing a maximum of 2.5 GJ gain during first charging season and a loss of 0.5 GJ during the first recovery season. The average heat transfer in the heat storage is

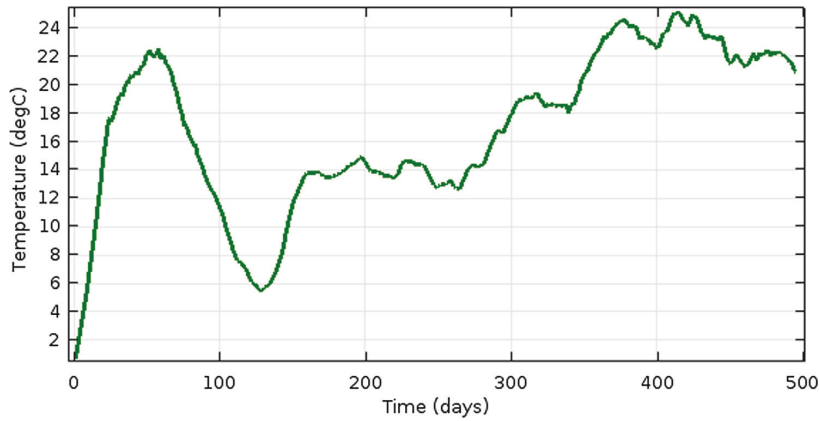


Fig. 9. Input signal collected from the pilot, which is also the inlet temperature of the borehole in the center (see Fig. 4).

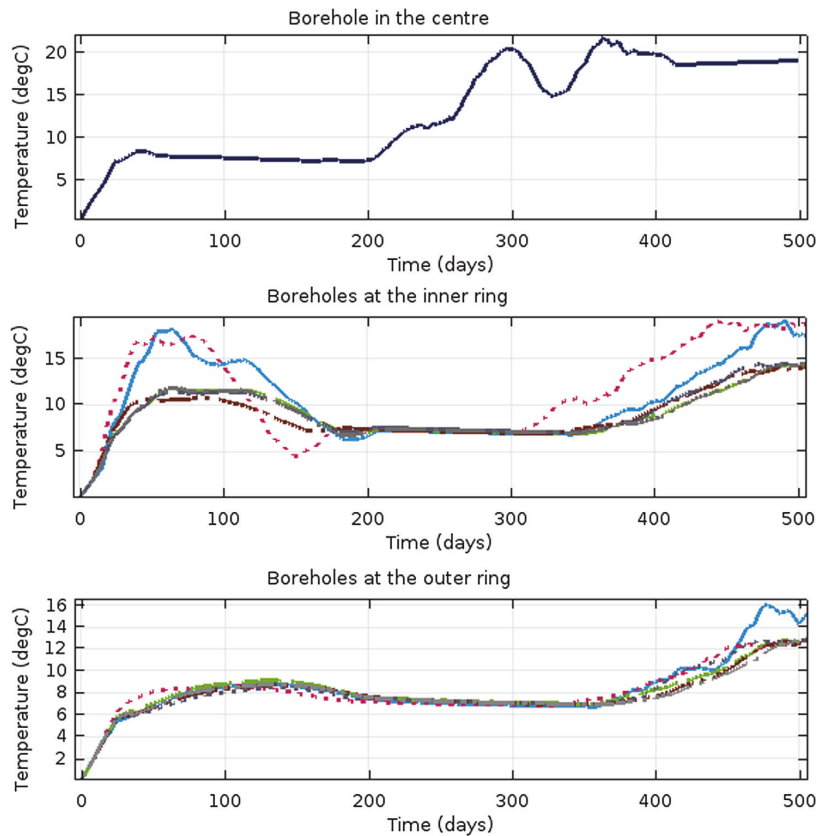


Fig. 10. Average daily borehole temperature collected from the pilot project during of 06.2016–09.2017.

estimated over 2 GJ.

The benefit of developing the system's model is to predict thermal response with a variety of input. An optimizing scenario is projected by varying the input signal of the ground heat storage. Injection power is being raised gradually from 30 to 60 kW in four simulation models with the similar strategy. Thermal response of the ground heat storage is illustrated in Fig. 13 where current injection power induced temperature increase to 18 °C. The stored energy of heat storage is significantly

increased by amplifying the injection power which enhances the temperature to 26 °C with 40 kW, 32 °C with 50 kW and 34 °C with 60 kW. Temperature rise is meaningful between 30–40 kW and 40–50 kW injection power while 50–60 kW does not produce a significant increase in temperature due to the geometrical restrictions.

Another simulation is made using the same input signal collected from the pilot project (see Fig. 9) periodically arranged for five years. Thermal response of the ground is depicted in (Fig. 14) reflecting on the

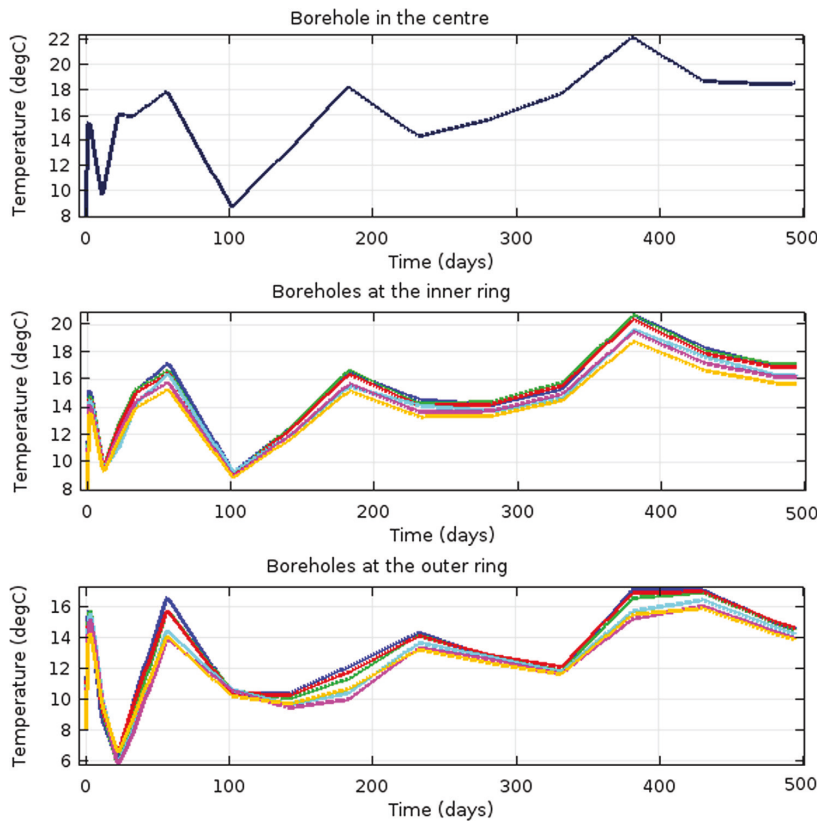


Fig. 11. Simulated thermal response of the ground heat storage.

temperature rise from the day 1 to 5 years. Temperature distribution of ground heat storage is illustrated rather than an average temperature of boreholes. After five consecutive period of charging and recovery periods, the temperature of the ground heat storage rose between 18 °C and 20 °C with the current injection power (30 kW). The charging period remains only three months of summer and the rest of the time is recovery period where little to no energy is injected in the heat storage.

Heat transfer is depicted in (Fig. 15) for five year period. The heat transfer peaks at 1.4 GJ during the fourth charging period. The average heat transfer power remains at 1.2 GJ during the five years simulation period.

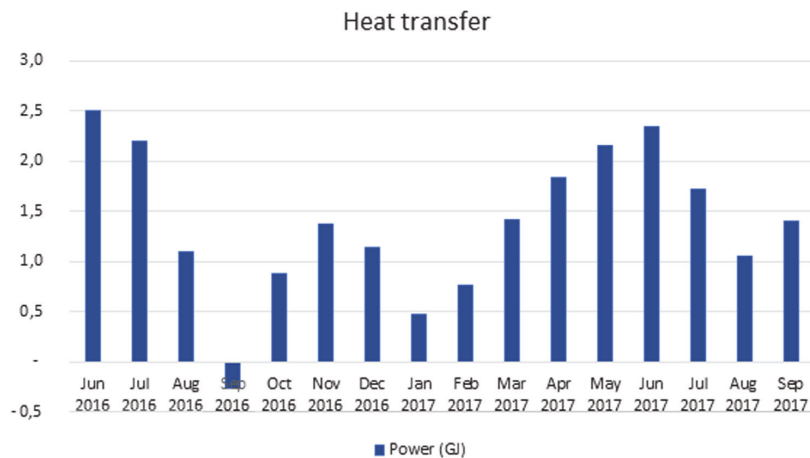


Fig. 12. Average energy transferred to the ground heat storage over one year period.

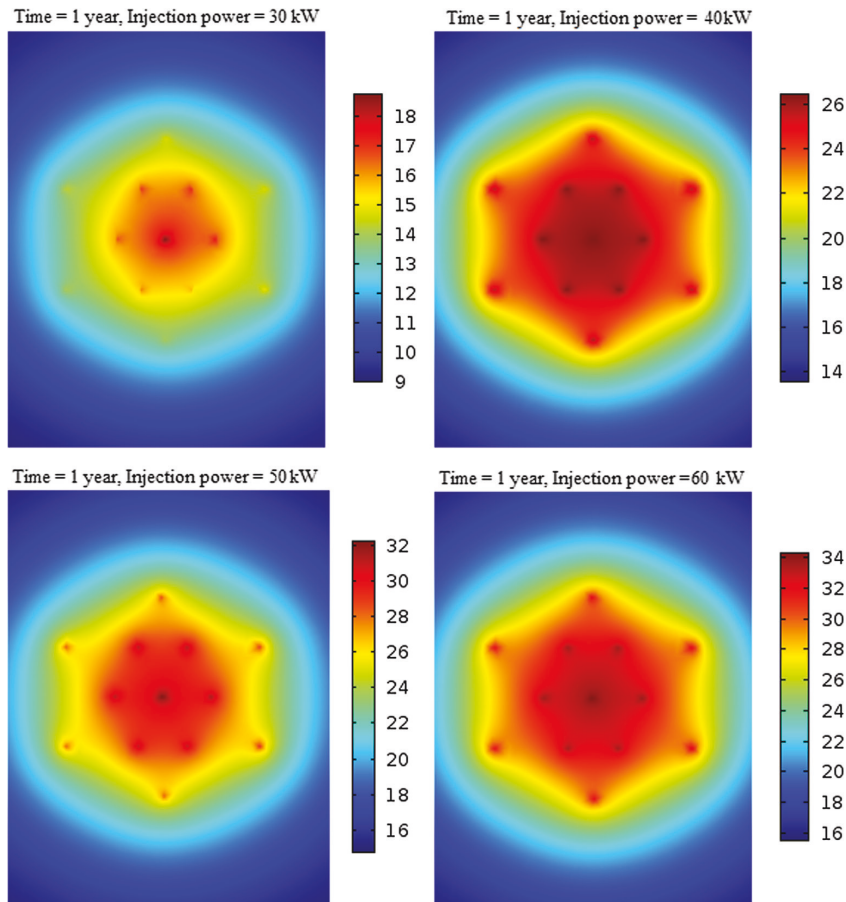


Fig. 13. Temperature distribution of the ground heat storage with a variety of injection power to optimize the thermal response of the ground.

6. Conclusion

This study presents a comprehensive analysis of ground heat storage for two consecutive charging periods of summer 2016 and 2017. The purpose of the study was to create a numerical model based on the experimental design of the heat storage with the best strategy of charging operation. A unique perspective is presented in this study by addressing the schematic diagrams of the given system which fill the gaps from the current literature. Control side of the project is also highlighted with a proposed mode of operation. Heat transfer power of solar collector is presented from experimental site. The given system is simulated with the collected input signal to estimate the thermal response of the ground heat storage. Experimental measurements and simulated calculations are presented. The simulation shows a slight difference in the thermal response of the boreholes. The reason for this is the uncontrollable change of air temperature which has not been taken into account in the simulation, for calculation restrictions. The constructed model is validated with line source method with an average of 3.5% error. The design restriction of the ground heat storage is apparent when injection heat power is increased gradually. Injection power rise from 50 kW to 60 kW is found redundant, since temperature rise of only 2 °C is detected. In order to increase the temperature of the ground heat storage with respect to the injection power, volume of the ground heat storage needs to be increased. The current injection power seems sufficient for the ground heat storage constructed. It is estimated

that, three months of heat injection with the current mode of operation raise the temperature of the ground from 8 °C to 20 °C within five consecutive charging periods. Heat transfer in the ground is calculated at an average of 1.2 GJ for five seasons.

Declarations

Ethics approval and consent to participate.

Not applicable.

Availability of data and materials

Data that is relevant to the manuscript is presented in the text and figures.

Competing interests

The authors do not intend to compete and declare no competing interests.

Consent for publication

The authors declare equal contribution towards the manuscript. The authors edited the manuscript and approved of the final manuscript.

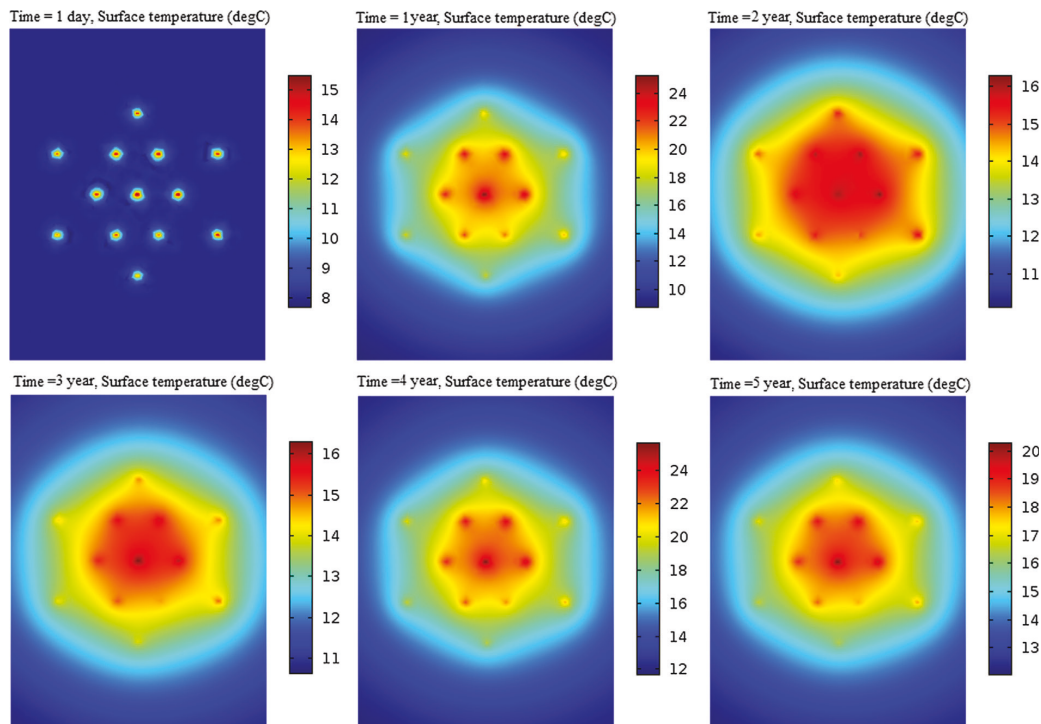


Fig. 14. Temperature distribution of the ground heat storage estimated over five years period with the current injection power (30 kW).

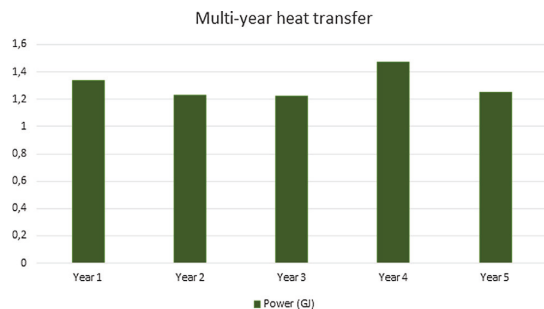


Fig. 15. Average energy transferred to the ground heat storage over five years period.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.applthermaleng.2018.11.029>.

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An economic study of combined heat and power plants in district heat production

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ABSTRACT

Combined heat and power plants are playing an essential role in Finland to reduce carbon dioxide emissions in district heat production. Some of the existing district heat producers need to adopt renewable energy sources to eliminate the use of fossil fuels. The northern countries face a challenge to tackle significant fluctuations of district heat consumption between summer and winter seasons concerning the production cost and the environmental impact of heat production. The municipality of Sodankylä is reorganising the district heat production to reduce emissions by constructing new wood-fuelled CHP plants. These plants will contribute to the existing district heating network. The profitability of CHP plants and the environmental impact in the region need evaluation. Results reveal that the profitable investment for the construction of CHP plants requires 16% subsidy with the predicted cost of heat production at 3.36 €/MWh. CO₂ emissions from fossil fuels can potentially be eliminated by adapting renewable fuel in the existing plant. CH₄ and N₂O emissions from district heat production reduced by 78% and 53%.

1. Introduction

Energy policy in Finland dictates a clear objective for 2050, net-zero greenhouse gas (GHG) emission (Finnish Energy, 2019). Implementing net-zero goal requires setting interim objectives for 2030 and 2040, such as establishing a roadmap for carbon neutrality in the heating systems, targets for renewable energy production, energy management and energy storage. Building a cleaner future will need higher investments in renewable projects alongside nuclear and combined heat and power (CHP) solutions. These incentives will help Finland to achieve its pledge of carbon neutrality by 2035. Energy efficiency enhances by optimising the current state of the power plants by increasing more renewable energy sources and cutting down fossil fuel usage. These measures are incentivised by the government of Finland with massive subsidies either to balance the more expensive renewable technology integration to the current energy producers or to maximise the rate of investments on reducing carbon dioxide emission. Recent literature reveals how CHP plants in Finland can reduce carbon dioxide significantly by adding heat pumps (Clean district heating, 2018).

Sipila et al. (2005) studied three CHP plants elaborating the behaviour of 1–14 MW CHP plant. Simulations showed that biomass is more profitable than a gas power plant. Industrial-scale heat pumps also

provide promising results with reasonable investment and high returns. A notable example of industrial-scale heat pumps in Finland is Esplanade heating and cooling plant (Helen Oy, 2018). Two heat pumps make up for 22 MW heat to the district heating system. The plant inaugurated in 2018 where heat pump used seawater as a heat source. Katri Vala heating and cooling plant said to be the most significant heat pump in the world (Friothers AG, 2017 Oy, 2020). The plant combines five heat pumps with a capacity of 105 MW heating and 70 MW cooling.

The city of Helsinki is investigating the possibilities of using renewable energy from bedrock and caves in Esplanade and Pasila areas. Turku installed heat pump where wastewater used from Naantali power via a 14.5 km long tunnel (Friothers AG, 2017). Several case studies of large-scale heat pumps are available from Sweden and Norway (Friothers AG, 2020). European heat pump association produced a comprehensive report of a large-scale heat pump plant (European heat pump association, 2020). The report consisted of examples from German district heating system, Norway and Finland. When the heat source is readily available for a heat pump, it could be the most economically beneficial application for district heat production. Arpagaus et al. (2018) reviewed the availability of high-temperature heat pumps in the European market with a variety of potential ranging from 90 °C to 160 °C supply temperature. The study revealed that heat source temperature

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between 40 and 60 °C required to produce 80–100 °C of supply temperature. The deep borehole heat exploration proved expensive in the northern areas. Given the constraints on heat pump applications, CHP plants are promising for the district heat production in Finland. CHP plants produce the majority of the heat in Finland's district heating system where wood residue, forest chip, Coal, natural gas and Peat are the most prominent sources (Paiho and Reda, 2016). The next generation of district heating system will be able to supply 60–70 °C temperature to small districts with the majority of heat production from the renewable sources (von Rheina et al., 2019). These renewable sources include small-scale solar heating plant or seasonal heat storage (Bauer et al., 2010).

The investors should consider renewable energy to optimise the existing power plants. Huang et al. (2017) showed a performance analysis of a small-scale CHP energy production for a remote household where renewable heat incentive significantly improved the economic viability of such a plant. Modelling the dynamics of such complex systems performed with Modelica, IDA-ICE and Apros to study the distribution network for such power plants (Arce et al., 2018). Guelpa et al. (2018) presented an optimal approach to address the peak load of the individual users in a district heating network. Korpela et al. (2017) presented the flexibility of energy production capacity concerning the frequency reserve restoration (FRR) requirements. Dvorak and Havel (2012) proposed an optimisation strategy for CHP plant to maximise the profit and simultaneous planning for electricity trading. Introducing thermal energy storage is a popular choice for designing a district heating network. The weakness of current heat storage systems is the low efficiency of 40% at maximum. Thermal energy storage increases the cost of energy production and requires feasibility analysis (Nuytten et al., 2013). The ground source heat pump is an increasingly popular choice in Finland (Häkämies et al., 2015). Installations of heat pumps have rapidly increased in recent years, which helps reduce greenhouse gas emissions (Laitinen et al., 2014).

Finland reduced emissions by 12% from district heat production (Finnish energy, 2019). The use of Peat and coal reduced from 15.4% to 14% and 19.3%–18% during 2018. The forest fuelwood and the industrial wood residue increased from 18.8% to 10.2%–21% and 12% in the same year (Finnish energy, 2020). There has been incredible encouragement from the EU to use bioenergy sources in district heat production by refining carbon taxes (Finnish energy, 2020). The transition of energy sources has brought some criticism of energy prices fluctuations (Natural resource institute Finland, 2020).

Nonetheless, the government has provided instructions on how to approach this transition in existing CHP plant (Kurkela et al., 2019), and how to use the local biomass efficiently for district heat production (Paiho and Saastamoinen, 2018). The processes of biomass in CHP are fuel procurement, combustion and gasification (Alakangas and Flyktman, 2001). Different CHP plants have fuel-specific procurement processes. There are two types of combustion process: Grate combustion (fixed bed) and Fluidised combustion (fluidised bed) (Jarvinen and Alakangas, 2001).

Gasification allows the fuel to decompose into useable gas and carbon dioxide after filtration. Syngas burned directly to produce steam in case the plant has a steam turbine otherwise directly used in gas turbine (Situmorang et al., 2020). In a combined cycle power plant, the gas turbine combined with a steam turbine to produce electricity (Al Saedi et al., 2000). The produced steam fed into a steam turbine to produce more electricity (Kontor, 2013). Further details of CHP processes elaborated in (Madadian et al., 2014).

There is a clear gap in the literature to present profitability assessment of the construction of CHP plants in Finland. A significant reduction in the use of fossil fuels from district heat production requires highlighting the economic and environmental benefits of using renewable energy sources in CHP plants. The investments in utilizing renewable energy sources in CHP plants encouraged by presenting economic. The study projects emissions reduced from heat production in Sodankylä. The

distribution network combines heat production from both existing and new CHP plants. The novelty of the study is to project emissions from district heat production for variety of input fuels option for existing plant. The next section elaborates the current state of the plant, highlighting input fuels and proposes a model for new CHP plants. The following section presents methodology of the study, section 4 reveals the results, and the study concludes in section 5.

2. System description

This section describes the current state of the system and restructuring plans—a conventional biomass CHP plant presented in (Fig. 1). There are three essential processes. 1- Fuel procurement, 2- Combustion and 3- Gasification.

2.1. Current system

Figure (2) shows a street view of the existing plant in Sodankylä, where stocks of Woodchip, Peat and boiler depicted. The peak demand for heating varies with the quality of input fuels. Fluidised bed combustion provides a nominal efficiency of 90%. The boiler maintains stable combustion with the help of extensive capacity inert bed material, low levels of NOx achieved with a low operating temperature. NOx level reduced by injecting ammonia or urea at the exhaust. Sulphur emissions controlled by injecting alkali sorbent compounds such as lime and variants. The fluidised bed operates between 800 and 950 °C.

Power consumption of the region projected in (Fig. 3). The plant shows woodchip stock on the left corner along with the processing chambers for Peat and Woodchip. Conveyer belt conjoins the fuels to the burning chamber and rest of the processes. In winter, air temperature in the region can be as low as −34 °C. Peak power consumption during the winter season estimated over 21 MW. The annual average production calculated at 9.92 MW, shown in (Fig. 4). The plant produces heat in the region with input fuels Peat, Woodchip and heavy oil calculated at 5.73 MW, 3.55 MW and 0.43 MW respectively. Most of the electricity supply in the region bought from external suppliers. The maximum capacity of the plant is 34 MW with network distributed over 30 km² in length.

The average carbon dioxide emissions from the plant plotted in (Fig. 5). The Finnish statistics database estimated the emission factors on fossil fuels (Statistics Finland, 2018). Peat contributes the majority of the carbon dioxide emissions. By replacing Peat with a renewable energy source, the region can reduce a significant amount of carbon dioxide emission. According to OECD (2019), the carbon tax of using fossil fuel can be as high as 25 €/tCO₂. The emission factors of methane and nitrous oxide took from IPCC emission factor database (Intergovernmental panel on climate change, 2006).

2.2. Proposed system

The proposed Syncraft wood-gas plants will use the available energy resources in the region. The proposed size of the power plant known as CW700-200 (Syncraft, 2020). This plant is capable of producing 700 kW of high-temperature heat with 200 kW of electricity. The plant consists of three major processes, including drying of biomass followed with Pyrolysis and gasification depicted in (Fig. 6). The drying process

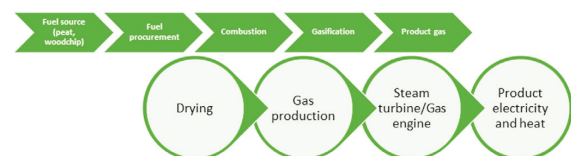


Fig. 1. Conceptual process representation of combined heat and power (CHP) plant.



Fig. 2. Current Combined Heat and Power (CHP) plant in Sodankylä, Finland (maps.google.com).

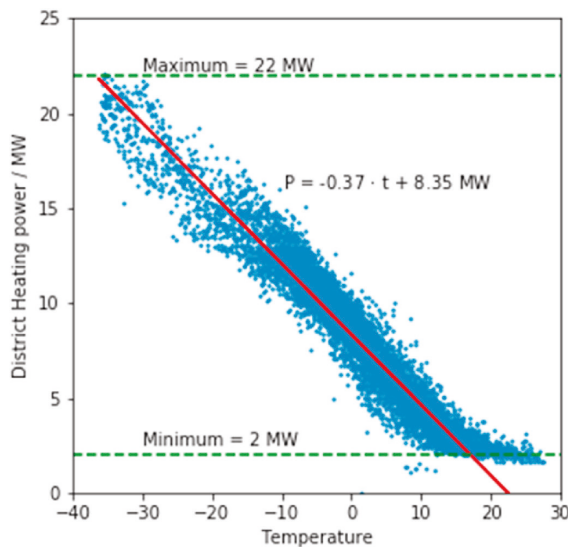


Fig. 3. District heat consumption for the year 2016.

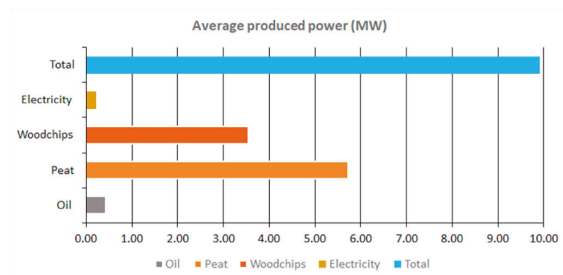


Fig. 4. Average power production of the current state of CHP.

implemented to reduce the moisture content from the biomass varies between 30 and 60%. This process takes place at 200 °C, after which the moisture content in biomass reduces to 15% optimal for gasification (Sansaniwal et al., 2017). The second process is Pyrolysis, where the air added to burn the dried fuel at a temperature of 500 °C (Guan et al., 2016). During this process, hemicellulose, cellulose and lignin in the biomass decomposed to form volatile compound and solid residue (Dhyani and Bhaskar, 2018). The volatile compound consists of gases and liquid tar. This compound further burned by adding more air at a

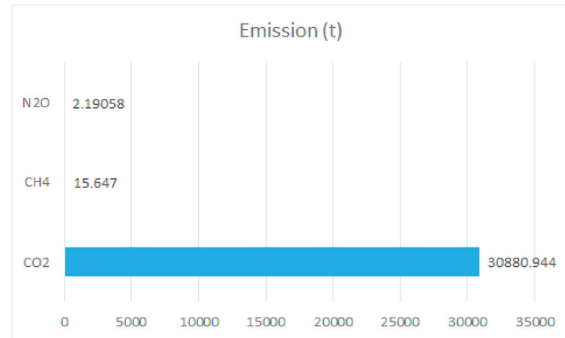


Fig. 5. Carbon dioxide and greenhouse gases emissions from the plant.

temperature of 850 °C in the floating bed reactor resulting in impurities collected at the bottom of the reactor (Kumar et al., 2009). Steam took out from the top of the reactor for filtration—added water to the compound left at the bottom producing Biochar. The gas then cooled at a temperature of 100 °C before entering the scrubber to remove pollutants (Kirubakaran et al., 2009). The gas injected into the gas engine at a temperature of 25 °C. The electrical efficiency of the engine estimated between 29 and 31% (Ruiz et al., 2013). The exhaust temperature from the engine used to provide heat for the district heating network. Biomass gasification further elaborated in (Ramos et al., 2018).

2.2.1. Technical assessment of the proposed system

The yearly average heat consumption of the region predicted over 8 MW. Six CHP plants proposed to meet the requirement of the region. The energy distribution of the plant illustrated in (Fig. 7). The plant consumes 4.838 MWh of energy including 5.171 MWh of electricity to operate. The quality of the fuel determines the amount of heat production. High-temperature heat makes up 55% of the energy production along with 29% of electricity production—the amount of electricity production directly related to the efficiency of the gas engine. Distributed high-temperature heat makes up 90% of the produced heat, 10% of the produced heat use for drying process in the plant, and 10% of the produced electricity contributes to plant power consumption. Biochar is a by-product of the plant. The production of Biochar estimated at 10% of the total production. The plant has minimal losses of 6%.

2.2.2. Economic assessment of the proposed system

An economic assessment of the proposed system conducted to facilitate the decision making of the project. A life cycle assessment of the project reveals the profitability of the project (Gaine and Duffy, 2010). Hennessy et al. (2018) concluded that the ORC is not feasible in the Nordic market conditions, but it can be feasible under different market conditions with low installation costs. System components such as heat pumps and thermal energy storage are only feasible if the investment costs are reasonable and operational costs are low (Dominkovic et al., 2015). Other economic parameters include depreciation cost, unaccounted in the current state of the study. More information on economic modelling detailed in (Short et al., 1995). A significant amount of costs reduced by predicting the best time to shut down some plants during summertime when heat demand is relatively lower than the wintertime (Dahl et al., 2017). Schweiger et al. (2017) showed the economic benefit of the utilizing the power to heat ratio in a district heating system where the negative residual load converted to the district heat load. The investment cost evaluated based on provided prices by Syncraft. The Natural Resource Institute Finland provided an initial estimate for operation and maintenance cost presented in Table 1. The cost of maintenance and operation of six CHP units is €0.2 million/year. The revenue estimated by adding the income from Biochar product, electricity, and heat (Table 2).

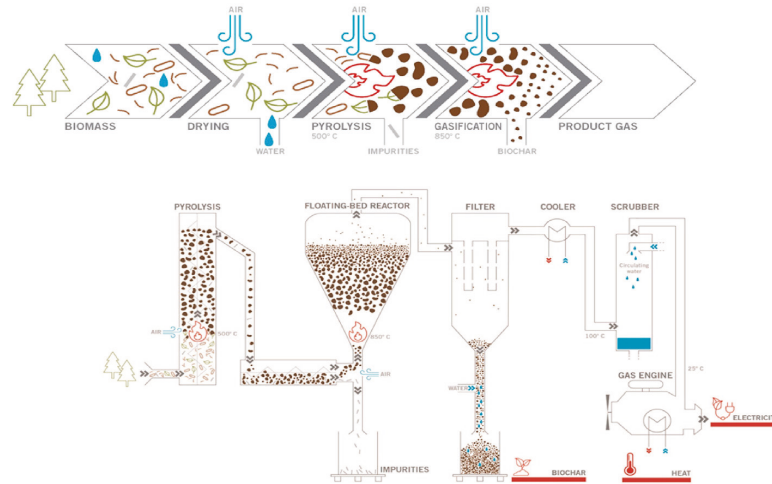


Fig. 6. Process flow representation of the proposed combined heat and power (CHP) plant.

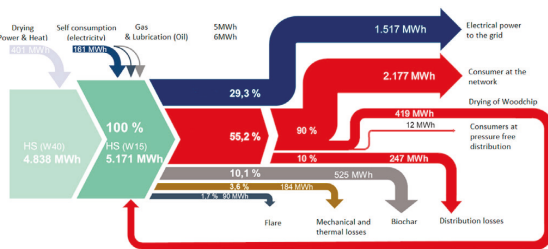


Fig. 7. Proposed model of the combined heat and power (CHP) plant (Synkraft CW700-200).

Table 1
Parameters used in the calculation.

Items	Symbol	Value
Investment cost	I_a	€16.5 (million)
Maintenance cost	M_a	€0.2 (million/year)
Operational cost	O_a	€0.1 (million/year)
Revenue	R_a	€1.58 (million/year)
Interest rate	r	4%
Investment cost of Heat pump	I_a	€7.6 (million)
Interest rate for Heat pump	r	6%
Revenue from the Heat pump	R_a	€5.16 (million/year)

2.3. An alternate option to the proposed system

A viable option compared to the proposed system is to install an industrial heat pump. The industrial heat pump has a relatively low investment cost and high efficiency of heat production and reduces the investment cost by more than half of the cost of the proposed plants. An industrial heat pump covers the heating requirements as well as the cooling requirements of the region and capable of providing 10 MW of heat to the district heating system with around €7 million of investment cost according to the research data collected by the contractors. The installation of heat pump rejected due to unavailable heat source required. The unavailability of heat sources such as seawater or deep borehole makes the consideration of heat pump impossible in this study

because of the geographical location of the region. The seawater heat source is unavailable in Sodankylä and drilling deep boreholes in northern Finland is expensive. Therefore, an industrial heat pump altogether excluded from the proposed system. Nonetheless, the economic assessment of the alternate option conducted. The Levelized cost of heat production from heat pump estimated at 3.77 €/MWh. The interest rate for installing the heat pump assumed at 6%. The revenues collected from the heat production from an industrial heat pump are three times higher than the revenues collected from the proposed CHP plants. The industrial heat pumps are a very interesting area to replace conventional fossil fuel energy sources. If the energy source for the heat pump were readily available, the installation would provide a very feasible investment opportunity to maximise the revenues.

2.4. Analysis of the restructuring

The heat production in Sodankylä prone to enormous carbon dioxide emission, which results in a high tax rate on the product. The amount could very well exceed over a hundred thousand euros in carbon taxes with the use of Peat and heavy oil. According to the OECD (2018), emission from woodchip burning considered carbon-free. A significant reduction in carbon dioxide emission achieved by constructing the new plants. The proposed system will use the local Woodchip helping the regional economy and reduce significant taxes from heat production—Biochar sold to the local farms in the region.

During November and March, the heat capacity of the region rapidly increased. The maximum and minimum capacity during the winter season estimated at 14.72 MW and 10.45 MW with an average 12 MW. Under these circumstances, the proposed Synkraft plants expected to operate at full capacity of 4.6 MW. The energy deficit recovered from the

Table 2
Preliminary costs of proposed plants.

	Energy	Price	Total price
Number of stations	6		€16.5 (million)
Number of yearly hours/station	6000		
Consumed fuel cost			€1.7 (million)
High temp heat produced (Mwh)	24,120	€49-59	
Electricity produced (Mwh)	16,560	€40-46	
Biochar (ton)		€225	€1.1 (million)

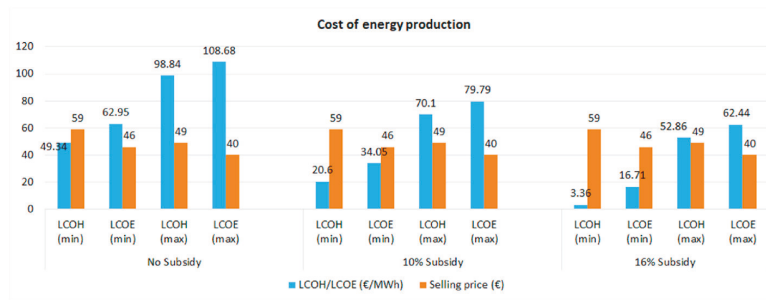


Fig. 8. The cost of energy production in combined heat and power (CHP) plants.

existing plant where wood pellets co-fired with the Woodchip. The wood pellets will contribute 50% of the solid input fuel in the existing plant. During the winter season, the energy production from the existing plant recommended at 7 MW with an average of 5 MW. The heat capacity of the region systematically reduced during April and May at 7.87 MW and 6.12 MW with a proportional increase during September and October at 5.71 MW and 7.92 MW.

3. Methodology

The district heat production consists of the existing plant and the proposed CHP plants. Levelized cost of energy production includes all the costs parameters to provide the production cost over a life cycle of power plants. It formulated as (Welsch et al., 2018):

$$LCOH / LCOE = \frac{\sum_{a=0}^{a_{end}} (I_a + M_a + O_a - R_a)(1+r)^{-a}}{\sum_{a=0}^{a_{end}} Q_a(1+r)^{-a}} \quad (1)$$

where, a is the number of years, I_a is the investment cost, M_a is the yearly maintenance cost, O_a is the yearly operational cost, R_a is the yearly revenue, r is the discount rate, and Q_a is the produced power. These costs summed up for the entire life of the power plant. Parameters used to calculate the cost of production presented in Table 1. Levelized cost of heat and electricity is an estimate of the cost per unit power concerning the total investments in a lifetime of the plant. It highlights the difference between the cost of production and selling price of the energy. The net present value formulated as:

$$NPV = \sum_a CF_a(1+r)^{-a} \quad (2)$$

where NPV is the net present value, CF_a is the cash flow and r is the discount rate. A depreciation cost avoided in this study, which may result in underestimation of the net present value of the project. Net present value illustrates the profitability of the investment in CHP plants. The NPV facilitates the decision-making on the construction of CHP plants. The study also uses the illustrated economic model to present an optimal investment scenario for the construction of CHP plants. The environmental impact of the district heat production calculated by standard IPCC guidelines. Emissions from energy production formulated as (Intergovernmental panel on climate change, 2006):

$$Emissions = Fuel * EF \quad (3)$$

The environmental impact includes carbon dioxide and greenhouse gas emissions. $Emissions$ calculated in ton of carbon dioxide, methane and nitrous oxide. $Fuel$ is the amount of fuel consumed in (TJ) for both CHP and main power plant. EF is the emission factor (t/TJ) for fuels used in

Table 3

The profitability of the possible scenarios.

	Investment option	NPV (million €)	Payback time (years)
Scenario 1	No subsidy	5	15
Scenario 2	10% subsidy	6.6	12
Scenario 3	16% subsidy	7.6	10

plants.

4. Results and discussion

This section presents economic assessment and profitability of the proposed CHP plants. The emissions generate from the combined district heat production estimated. The projected emissions illustrate three options of input fuel for existing CHP plant.

4.1. Profitability of the proposed CHP plants

The costs of the proposed model of power plants presented in Table (2)—maximum capacity of given power stations delivered with 6000 h in a year—the Levelized cost of energy production presented in (Fig. 8). There are three scenarios depicted with subsidy investigation. The first scenario does not assume any subsidy in the calculation. The maximum cost of heat production estimated at 98 €/MWh with a selling price of 49 €/MWh, while the maximum cost of electricity calculated at 108 €/MWh when the selling price is 40 €/MWh.

Similarly, the minimum cost of heat and electricity production presented. LCOH calculated at 49 €/MWh with a selling price of 59 €/MWh while LCOE estimated at 62 €/MWh with a selling price of 46 €/MWh. The second scenario considered a subsidy of 10% on investment cost. The minimum cost of heat production predicted at 20 €/MWh with a selling price of 59 €/MWh while the maximum cost predicted at 70 €/MWh with a selling price of 49 €/MWh. Besides, the minimum cost of electricity production predicted at 34 €/MWh with a selling price of 46 €/MWh while the maximum cost predicted at 79 €/MWh with a selling price of 40 €/MWh. The third scenario assumed a 16% subsidy on investment cost. The minimum and maximum cost of heat production projected at 3.36 and 52.86 €/MWh while the minimum and the maximum cost of electricity production projected at 16.71 and 62.44 €/MWh.

The profitability of CHP plants showed in Table 3. Scenario 1 revealed a valuation of €5 million with a payback time of 15 years, making it an unattractive project for the investors. The payback time is too long, and the profitability is minimal. Scenario 2 estimated value of €6.6 million with a payback time of 12 years, an improvement from the previous

scenario but still unappealing to the investors. The payback time, preferably under 10 years, considered a reasonable investment opportunity. Therefore, Scenario 3 resulted in an optimal valuation of €7.6 million with a payback time of 10 years. Scenario 3 provides an optimal payback time under 10 years. The profitability of scenario 3 is relatively better than the rest of the scenarios with a 16% subsidy.

4.2. District heat production in sodankylä

District heat production combines energy production from both new and existing CHP plants. The proposed CHP will contribute to the existing district heat network. The average contribution from both plants in district heat production illustrated in (Fig. 9). The CHP plants run at full load during the entire year except for summer season (June–August). Two of the six CHP plants close during summer for service and maintenance. The average production from the existing plant fluctuates significantly during the year. The plant shuts down in July. The average required heat production from existing plant estimated at 6.5 MW.

District heat in Sodankylä can produce with three input fuel options. The existing CHP plant can adopt renewable fuel (Woodchip), eliminating the fossil fuel emissions. The CH₄ and N₂O emissions reduce by 78% and 53% using renewable fuel. Peat is also a viable option to use in the existing plant. Peat is cheaper than Woodchip with higher energy coefficient. The amount of carbon dioxide reduced to 37% compared to the current production. The CH₄ and N₂O emissions reduce by 78% and 53% using Peat. The plant can also keep the current combination of input fuels (Peat + Woodchip + Heavy oil) for district heat production. The carbon dioxide emissions reduced by 34% compared to the current model of district heat production. The CH₄ and N₂O emissions reduce by 25% and 16% using input fuels (Peat + Woodchip + Heavy oil). One reason to prefer this system is to fulfil the peak consumption during January, November and December. The peak consumption during winter season exceeds 22 MW that requires the use of heavy oil fuel in district heat production. The district emissions illustrated in (Fig. 10). CHP referred to the proposed CHP plant. MPP is the existing power plant.

4.3. Discussion and future consideration

The study conducts economic assessment of the proposed CHP plants in Sodankylä. The cost of production from new plants determined and the profitability calculated. The distribution of heat in the region combines the production from both new and existing CHP plants to the network. Three input fuel options (fossil fuel and renewable fuel) presented for the existing plant. The plant can adapt renewable fuel for entire year, eliminating the use of fossil fuels. Current production from renewable fuel generates 3.55 MW of heat. The average monthly consumption of the district heating network between April–October met with renewable fuels without adding additional fuel to the plant.

On the other hand, heat consumption rose significantly between January–March and November–December, which will require the main power plant to produce 10.91 MW of heat energy. During the winter season, the main power plant can either maximise renewable input fuel or combine fossil fuel. The decision solely depend on compromising either economical or environmental aspect. The combined input fuel increase the emissions significantly in the region. The plant may avoid heavy oil fuel and use combined Woodchip and Peat. An economic point of consideration is the standard IPCC emission factors on the capacity of heat production. The emission factor of 5 MW plant is significantly higher than 50 MW plant. An economical way of district heat production is to use peat fuel when the demand is higher than 5 MW reducing significant amount of taxes.

5. Conclusion

The study evaluates the possibility of constructing a new combined heat and power plant with a renewable energy source. The existing

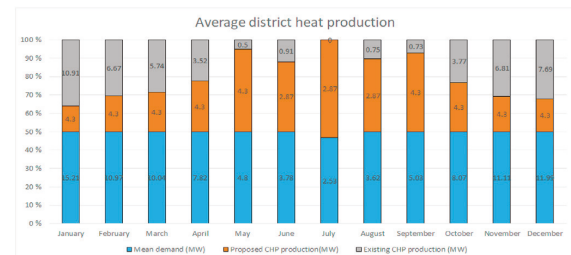


Fig. 9. Average heat production and consumption in Sodankylä.

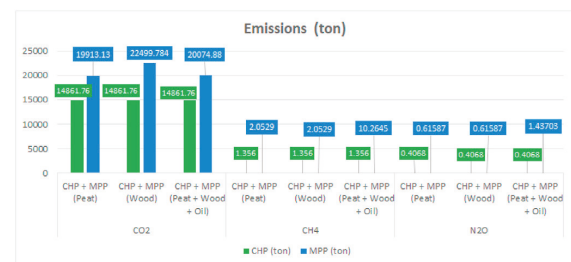


Fig. 10. Emissions from district heat production in Sodankylä.

structure of the heat production discussed in detail, the demand for new plants highlighted, and the construction of new plants illustrated with technical information and economic assessment. The plants expected to deliver 4.3 MW of heat to the district heating network with only 6% losses. Biochar estimated 10% of the total production from the plant sold to the local and external markets. There are three economic scenarios drawn presented in the study and an optimal economic scenario reported with a reasonable payback time. The optimal energy production of the plant estimated with 16% subsidy. The cost of heat and electricity production resulted at 3.36 and 16.71 euros per MWh.

The goal of the municipality is to reduce the overall emissions from the region. The emissions from district heat production significantly reduced with the construction of CHP plants. The study also articulates three possible scenarios to operate the existing plant. The plant can entirely run with available fuel, either Woodchip (renewable fuel) or Peat (fossil fuel). Although Woodchip fuel costs slightly higher than Peat, district heat production from renewable fuel is highly recommended considering the amount of greenhouse gas reduction and carbon tax savings. Peat input fuel is economically attractive, but there is an uncertainty of Peat tax rate in Finland. Increase in Peat tax is under the government's consideration. The cost of production from Peat fuel may become more expensive after a few years. The district heat consumption during winter is significantly higher in Sodankylä compared to the rest of the year. During the peak season, the main power plant uses heavy oil fuel to meet the demand. In the future, the municipality should consider peak shaving for the environmental impact of district heat production.

Declarations

Ethics approval and consent to participate.
Not applicable.

Availability of data and materials

All relevant data presented in the manuscript.

Conflicts of interest

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

Consent for publication

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

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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 km² 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 km². 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>).

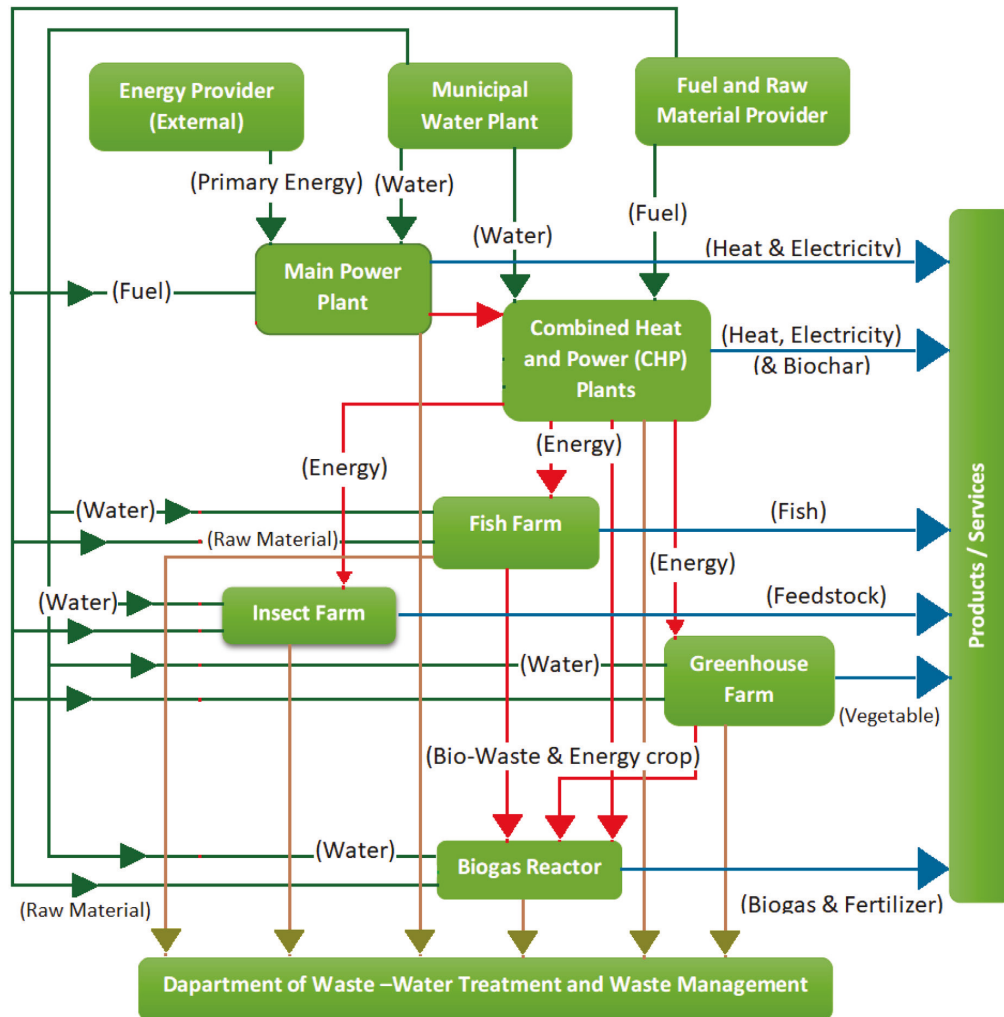


Fig. 2. The architecture of industrial symbiosis in Sodankylä, Finland. Material flow shows inputs and outputs of the nodes, identified with various colours. Green represents the input; blue depicts the output and red reflects the material exchange. (For interpretation of the references to colour in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

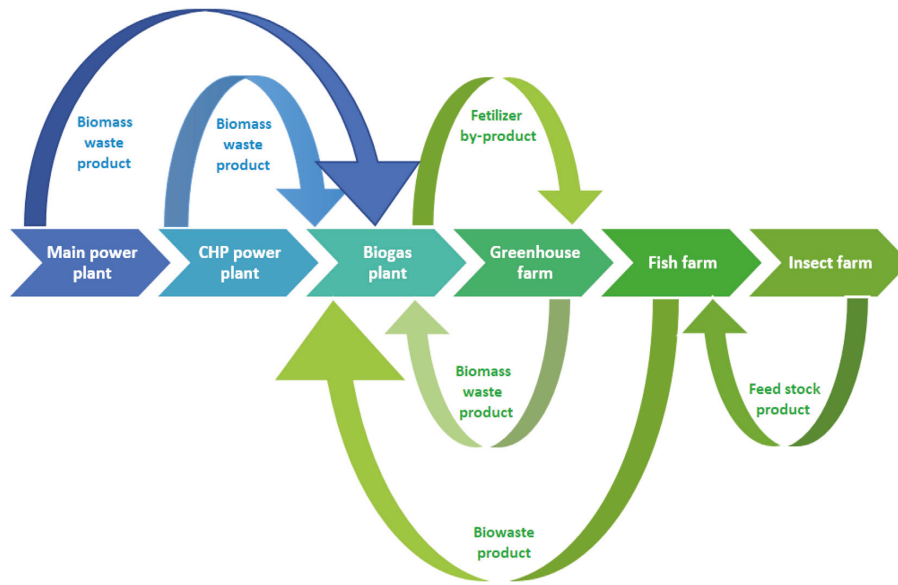


Fig. 3. Representation of circular economy in industrial symbiosis.

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.

Sodankylä's case, the preliminary assessment is based on a greenhouse farm with an area of 5000 m², producing a yield of 70 kg/m². 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

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.

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.

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.

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 m³, 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 m³/year, with an estimated density of 0.72 kg/m³. 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

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	¹ 135000 (€/year)
Revenue from the product	¹ 168291 (€/year)
Interest rate	¹ 3%
Investment cost	² 0.40 (€ million)

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

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 m². 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.

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):

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

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

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).

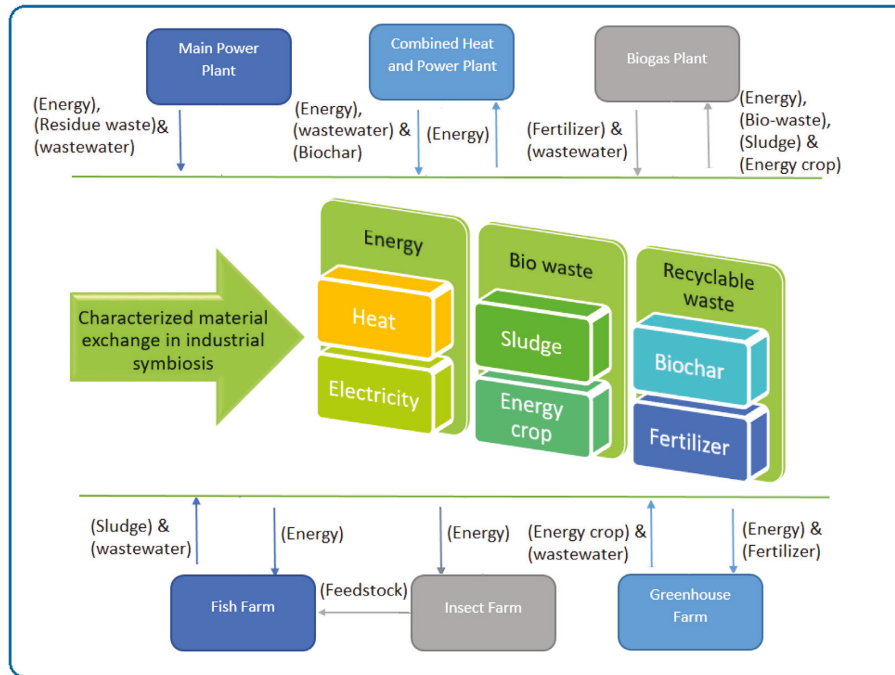


Fig. 4. Material (by-product) characterization in industrial symbiosis. The energy produced in the material exchange is surplus energy, which would otherwise go to waste if not utilised in industrial symbiosis.

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):

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

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

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

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).

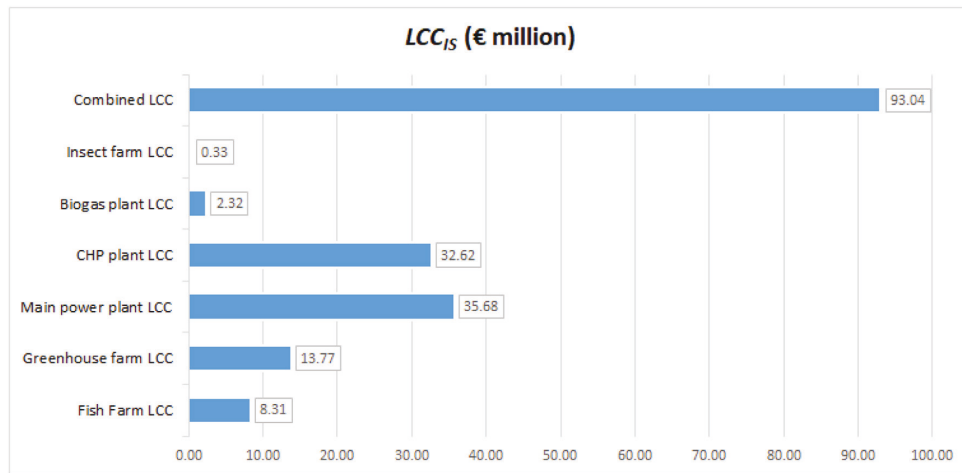


Fig. 5. Life cycle cost (LCC_{IS}) of industries participating in industrial symbiosis.

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

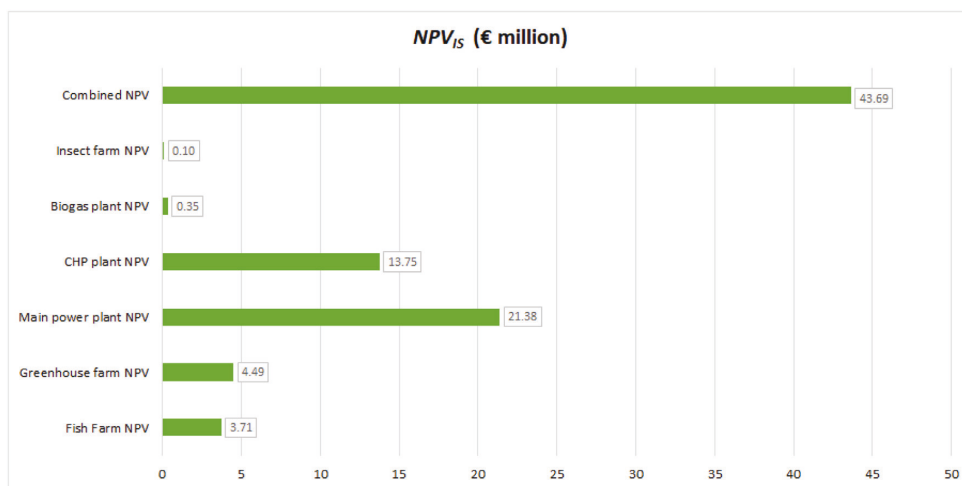


Fig. 6. Net present value (NPV_{IS}) of industries participating in industrial symbiosis.

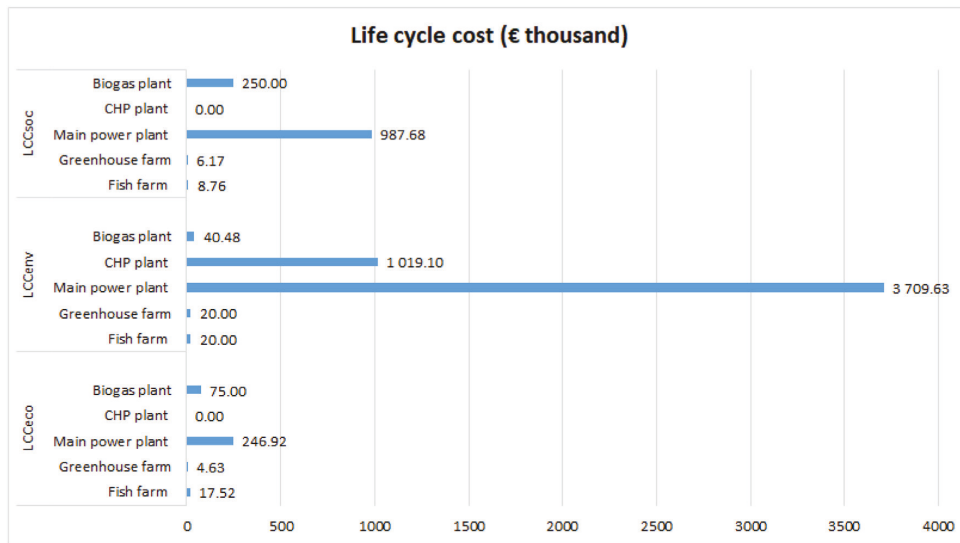


Fig. 7. Life cycle costs of waste products of companies.

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

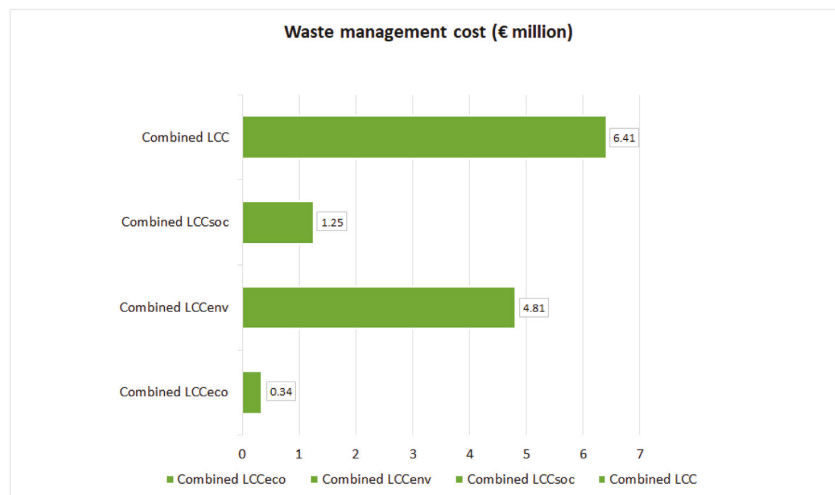


Fig. 8. Combined waste management cost.

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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An application of seasonal borehole thermal energy system in Finland

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ABSTRACT

Borehole thermal energy system is an important component of the future low temperature heating networks. Applications of such systems are available around the world presenting various configurations. However, the mobility of the system from solar assisted to industrial heat has not yet evaluated. A 3D model of borehole thermal energy system created similar to Drake landing solar community project configuration. This model is validated with experimental measurements. The accuracy of the model estimated at 95%. Experimental measurements further utilized to create an artificial neural network model to predict modes of operation (charging/discharging). The accuracy of the model calculated at 97%. This study presents a possible application of storing excess heat from combined heat and power plants in Sodankylä, Finland. The municipality of Sodankylä is planning construction of new combined heat and power plants. These plants systematically shutdown during summer season leaving 1.53 MW of excess heat. The heat surplus can be stored in a heat storage. Simulations reveal that the model has storage capacity between 250 kW and 285 kW. In addition, there is a potential of five borehole thermal energy storage to store the entire excess heat. The novelty of the study is to test the mobility of borehole thermal energy system from solar assisted storage to industrial excess heat storage. The model used in a standardized manner considering the conventional combined heat and power plants supply temperature for working configuration of heat storage.

1. Introduction

Europe's strategy on district heating and cooling (DHC) encourages to decarbonisation of buildings, energy efficiency management, automation and control, and reuse industrial waste heat (EU strategy, 2016). In 2012, DHC supplied by renewable energy sources amounts to 14% in Europe and 45% in Finland (EU analysis, 2020). The use of fossil fuels in DHC expected to replace by wind power, heat pump and heat storage (Smart energy transition, 2018). Adaptation of renewable energy sources increased recently with industrial heat pumps and deep borehole heat in Finland. This transformation towards the future of district heat production brings challenges in energy efficiency of buildings, integration of solar assisted heat production, and energy production in cold climate (Paiho and Reda, 2016). Integrating heat pumps in decentralized heat production widely accepted in Finnish climate (Laitinen et al., 2014). The recent global commitment to DHC and recognition of carbon dioxide emission reduction identified as moderate (Werner, 2017). However, Europe is eager to increase energy production with DHC with a clear emphasis on utilising renewable sources and reducing carbon dioxide emissions.

The next conceptual phase of heat production appears to be 4-generation district heating and cooling system (4GDHC) (Lund et al., 2014). This allows the implementation of low temperature thermal grid, integration of smart energy systems, waste heat recycling, and low energy space heating. Low energy DHC is comparatively expensive than the conventional heat production (Kofinger et al., 2016). However, the expectations are positive for low energy DHC network implementation. This requires demand-side management and renovation of pipes in the network (Energistyrelsen, 2011). Refurbishment of buildings and installation of substations recommended in some cases (Brand and Svendsen, 2013). Potential to reduce supply temperature in DHC systems is sufficient. Ostergaard and Svendsen (2017) reported the benefits of reducing the supply temperature to 45 °C on several Danish single-family houses. Supply temperature of DHC system as low as 35 °C in a high heat density region investigated by carefully assessing the return temperature (Yang and Svendsen, 2017). The implementation of ultra-low supply temperature could significantly improve the performance fifth generation DHC systems. This allows heat producers to reduce heat losses and take the opportunity to integrate variety of low-temperature waste heat sources (Rhein et al., 2019). In addition, models of building and DHC,

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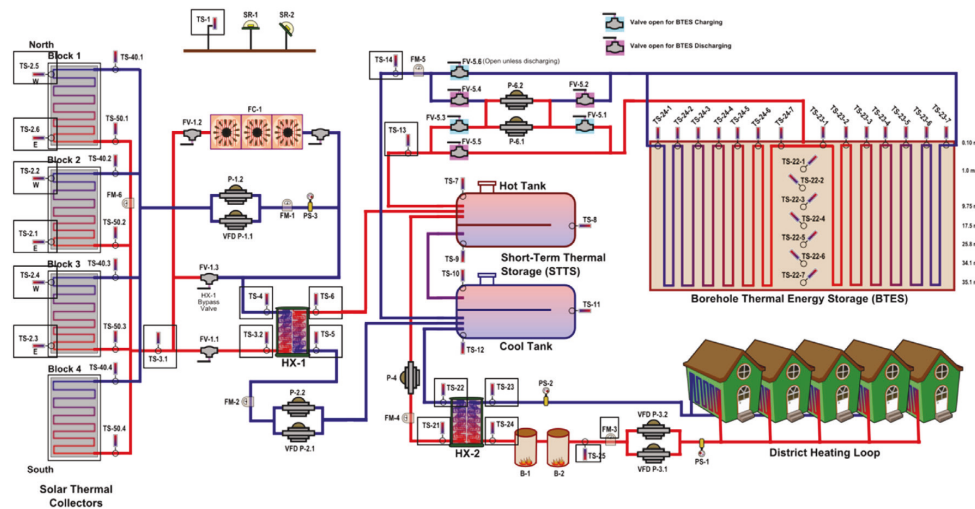


Fig. 1. Schematic diagram of the system. The schematic shows the positions of all the temperature sensors, flow meters, pump and valves. The collected dataset used in the study is marked with green box.

energy transport losses, and indoor climate should be analysed for maximising efficiency (Risberg et al., 2015). An important component of implementing future DHC is Borehole thermal energy system (BTES). A BTES implements either in centralized or decentralized heat production. Installation of BTES also presents challenges such as design of the system, energy management between injection and extraction, and heat losses (Li and Wang, 2014). Design parameters of BTES has significant effect on the performance of heating system along with the temperature of the storage. High storage temperature required for heat distribution in big districts (Nordell, 1994). Location of the BTES needs consideration before installation of the system. Heat losses from BTES vary in different climate. Flynn and Siren (2015) investigated the performance of seasonal BTES in five different locations. Results indicated that insulation and low temperature heating system influence the performance of the storage. The northern countries specially requires optimal design to keep stable performance. A BTES requires heat source to store heat energy, which can either decentralized or centralized application (Nussbicker-Lux et al., 2009). In Europe, heat storage extensively used with biomass boilers and combined heat and power plants (Fisch et al., 1998). The capacity of a BTES design depends on either medium borehole or shallow borehole system. Nilsson and Rohdin (2019) evaluated the performance of large-scale BTES in Emmaboda, Sweden. Results indicated that the quantity of heat source influenced the heat extraction from BTES. Application of medium-scale BTES appears more suitable for DHC system application (Rad et al., 2017). However, performance of a BTES determines by optimal design models. Kandiah and Lightstone (2016) investigated an optimized BTES with a buried tank to save ground space. Results revealed that the presence of a tank did not significantly reduce the performance of BTES. Furthermore, comparative performance between a centralized and decentralized district heating system is of importance. Losses in a decentralized DHC found to be less than the centralized system (Rehman et al., 2018).

There is clear gap in the previous research to propose a standard BTES model that can be used in multiple applications such as solar assisted and waste heat. This study proposes a 3D model of BTES and validates with experimental measurements collected from drake landing solar community (DLSC) project organizer. Eleven years of experimental measurements analysed and key information presented. This data also used to create an artificial neural network model for identifying modes of operation (charging or discharging). The model of BTES employed to store

excess heat from combined heat and power (CHP) plants. Charging operations simulated for summer season storing excess heat and discharging operation simulated for rest of the year. Next section presents analysis of DLSC system and artificial neural network model. The following section propose the model of BTES. Results projected in section four. Section five shows applications of BTES and the study concludes in section six.

2. System description

Drake Landing Solar Community (DLSC) project analysed in this study to model BTES and store excess heat from CHP plants. The schematic diagram of the project presented in Fig. 1. Main components of the system consists of solar thermal collectors (Sibbit et al., 2012), short term thermal storage (STTS), borehole thermal energy system (BTES) (Sibbit et al., 2007), heat exchangers (HX), boilers (B), cooling fans (FC), and district heating loop (Renaldi and Friedrich, 2019). There are several temperature sensors (TS), flow meters (FM), pumps (P), and flow valves (FV) to control the mode of operation. The system supplies heat to the district as well as stores heat in BTES depending on heat demand (Sibbit et al., 2015). The cooling fans installed to mitigate the excess heat from solar thermal collectors. Hot and cold tanks connected to the supply and return distribution lines (Sibbit et al., 2011). Boilers function as compensation if supply temperature is lower than the demand of the loop. The system further elaborated in (Mesquita et al., 2017).

2.1. Borehole thermal energy system

The focus of the study is to construct a 3D model of the BTES similar to DLSC project. Therefore, information related to the BTES extracted from the schematic shown in Fig. 1. Sensor measurements recorded every 10 min. Flow valve (FV) controls the movement of carrier fluid in and out of the BTES. Flow meter (FM) recorded volumetric flow rate of the carrier fluid. Inlet (TS-13) and outlet (TS-14) temperature sensors recorded the temperatures to and from the BTES. The data consists of eleven years of sensor measurements. Dataset consists over half a million samples recorded over eleven years of operation every 10 min. This information helps evaluating the optimal design constraints of a centralized or decentralized heat production system. The annual mean air temperature of the region measured at 5 °C with a standard deviation of 11.6 °C. The coldest annual air temperature recorded at -34 °C. The average BTES

Table 1
Parameters used in the artificial neural network model.

Parameter	Value
Model type	Classification-learning method
Number of hidden layer	1
Number of nodes	18
Activation function of hidden layer	Relu
Number of output layer	2
Activation function of output layer	Softmax
Optimizer for compilation	Adam
Loss function	Categorical-crossentropy
Validation split	20%
Number of epochs	10
Input	(TS-7-TS-14), (TS-22-1-TS-22-7), (TS-23-1-TS-23-7), (TS-24-1-TS-24-7), (FM-4-FM-5), (FV-5.1-FV-5.6)
Output	BTES_CHARGING, BTES_DISCHARGING

temperature measured at 38 °C. The average temperature of the hot (TS-8) and cold (TS-11) tank recorded at 55 °C and 47 °C. The minimum, mean and maximum temperature of inlet carrier fluid (TS-13) measured at 0 °C, 55 °C and 89 °C. The mean and maximum volumetric flow rate (FM-5) of the carrier fluid recorded at 1.6 l/s and 4.5 l/s. The percentage of charging and discharging operation of BTES during eleven years estimated at 43% and 20% of the time. The boiler 1 (B-1) and boiler 2 (B-2) used around 1.13% and 5.61% of the time.

2.2. Mode of operation

The dataset contains information on mode of operation (charging/discharging). The mode of operation represents status signal recorded with “BTESCHARGING” and “BTESDISCHARGING”. During charging mode, valves FV-5.1, FV-5.3, and FV-5.6 switched on. Discharging mode, however, switched on valves FV-5.2, FV-5.4, and FV-5.5. The collected dataset indicates five months (May–October) of charging operation performed every year. This means when temperature of STTS (TS-8) is greater than twice the required temperature of the consumer, the charging switches on. Charging operation discontinues if the difference between inlet (TS-13) and outlet (TS-14) temperature is less than 5 °C. However, there are fluctuations in the charging operation. Discharging switches on when temperature of STTS (TS-8) is smaller than inlet (TS-13) temperature.

Table 2
Parameters used in Sodankylä model.

Name	Symbol	Value
Thermal conductivity of the ground	k_g	1.07 (W/m K)
Density of the ground	ρ	1520 (kg/m ³)
Specific heat capacity of the ground	C_p	1014 (J/kg K)
Inner diameter of heat exchanger	d_i	25 (mm)
Inner diameter of inlet and outlet	d_{io}	65 (mm)
Thickness of pipes	d_t	1.5 (mm)
Depth of heat exchanger	D	35 (m)
borehole to borehole distance	D_b	2.25 (m)

3. Methodology

This section presents models of artificial neural network and BTES. Machine learning implemented to Train artificial neural network models (DataCamp, 2020). Artificial neural network model represents the mode of operation (charging/discharging). Mathematical modelling of BTES reveals numerous characteristics and applicability (Hellstrom, 1991; Eskilson, 1987). These models improved to understand the thermal properties of BTES applications (Al-Khoury et al., 2005; Al-Khoury and Bonnier, 2006). FEFLOW is one example used to model and simulate the performance (Diersch et al., 2011). Recent study reveal the influence of groundwater and air temperature (Nguyen et al., 2017). Uncertainty in the ground modelled using the experimental data to create multilayers of the ground, studying the thermal properties and the possibilities to expand the existing project (Tordrup et al., 2017). 3D model of BTES created to study the performance in short-term (Haq and Hiltunen, 2019).

3.1. Artificial neural network

The mode of operation (charging/discharging) of BTES modelled with artificial neural network. This model uses input and output information from the dataset to mimic charging and discharging modes of BTES. Input data consists of temperature, volumetric flow rate, and flow valve measurements. Output data includes status signals for charging and discharging modes. During the charging operation, the dataset indicates “BTESCHARGING = 1” and “BTESDISCHARGING = 0”. The discharging operation indicates “BTESCHARGING = 0” and “BTESDISCHARGING = 1”. Classification-learning method used to train the output variables. Parameters of the model shown in Table 1.

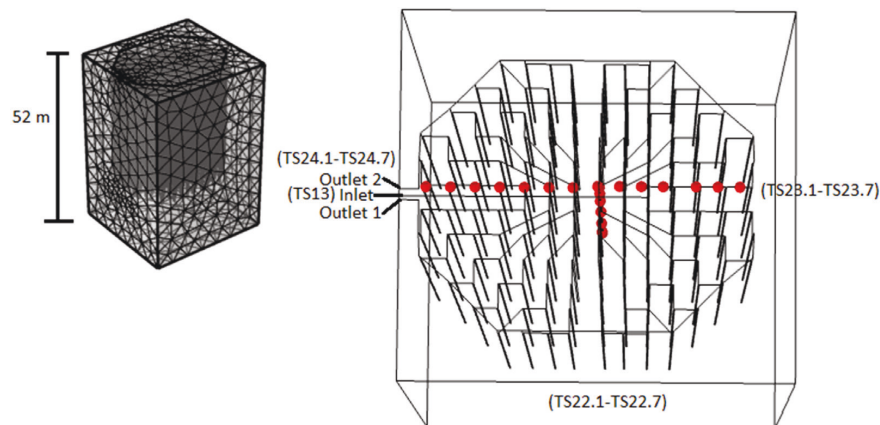


Fig. 2. 3D model of the Borehole Thermal Energy Storage (BTES). Red-dots show the position of the sensors in the system. TS22.1-TS22.7 are the core temperature measurements. TS23.1-TS23.7 and TS24.1-TS24.7 are the ground temperature measurements.

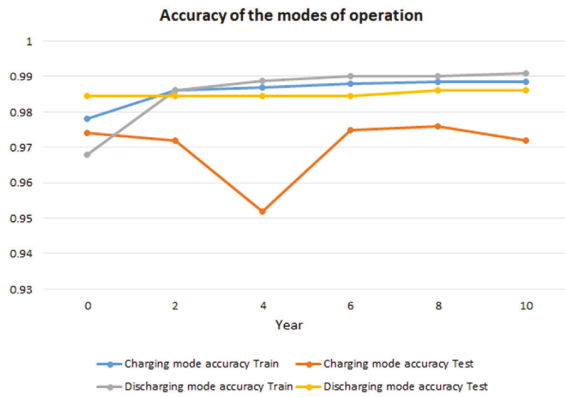


Fig. 3. Accuracy of artificial neural network model for modes of operation.

3.2. Borehole thermal energy system

BTES model implemented in Comsol multiphysics. The hexagonal shaped BTES consists of 144 boreholes heat exchanger pipes shown in Fig. 2. There are six heat exchanger pipes connected in series between inlet and outlet making up 24 strings in total. Each heat exchanger pipe has a depth of 35 m and 2.25 m distance between them. The dimensions of the ground are $36 \times 34 \times 52$ m. The material properties presented in Table 2. The temperature sensors represented as (TS). The position of these sensors depicted with red dots. The core temperatures illustrated as (TS22.1 to TS22.7), ground temperature from centre to right, shown as (TS23.1 to TS23.7), ground temperature from centre to left, presented as (TS24.1 to TS24.7) and inlet temperature represented as (TS13). The boundary conditions consist of inlet temperature (TS13), volumetric flow rate and the initial temperature of the ground.

There are two modules used to simulate the model namely, Heat transfer in Solids and Non-isothermal pipe flow. Heat transfer module is required to compute heat transfer in the ground caused by the heat exchanger pipes. Non-isothermal pipe flow module computes heat transfer caused by the fluid flow in the heat exchanger pipes. Heat transfer in the ground expressed as:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot q = Q \quad (1)$$

$$q = -k \nabla T \quad (2)$$

Where, ρ (kg/m^3) is density, C_p ($\text{J/kg}\cdot\text{K}$) is specific heat capacity, T ($^{\circ}\text{C}$) is temperature, t (s) is time duration, q (W/m^2) is heat flux, k ($\text{W/m}\cdot\text{K}$) is thermal conductivity of the ground and Q (W/m^3) is volumetric heat source in the region. Heat transfer in pipe stated as:

$$\rho A C_p u \cdot \nabla T = \nabla \cdot A k \nabla T + f_D \frac{\rho A}{2 d_h} |u|^3 + Q_{wall} \quad (3)$$

$$Q_{wall} = hZ(T_{ext} - T) \quad (4)$$

Where, u (m/s) is velocity, d_h (m) is hydraulic diameter, f_D is dimensionless Darcy friction factor, and A (m^2) is cross sectional area of the pipe. Where, Q_{wall} (W/m) is external heat transfer and Z (m) is wetted perimeter. A tetrahedral mesh created which consists of 119613 nodes and 60402 edge elements. Comsol software allows adding multiple physics interfaces on the geometry. In this case, Heat transfer in solids and Non-isothermal pipe flow interfaces used in the simulations, which produces output similar to conjugate heat transfer as oppose to computational fluid dynamics (CFD). The model should be validated with experimental measurements. Percentage error is calculated between experimental measurements and simulated calculations (TS23 and TS24). The percentage error expressed as:

$$\text{Error (\%)} = \frac{|T_{exp} - T_{sim}|}{T_{exp}} \times 100 \quad (5)$$

Where, T_{exp} ($^{\circ}\text{C}$) is experimental temperature and T_{sim} ($^{\circ}\text{C}$) is simulated temperature.

4. Results

This section presents results for both artificial neural network and BTES models. The accuracy of BTES charging and discharging modes estimated. Simulation of charging and discharging operation presented in the following section.

4.1. Accuracy of artificial neural network model

The accuracy of the models plotted in Fig. 3. The models predict the signal of charging and discharging operation and have higher accuracy on Train dataset compare to Test dataset. The Train dataset consists of all inputs and outputs parameters, while the Test dataset consists of unknown input parameters. The parameters shown in Table 1. Artificial neural network model trained with Train dataset where it learns the possible output. Test dataset then used to forecast the output with trained model. There is a 20% validation split, which means 20% of the dataset

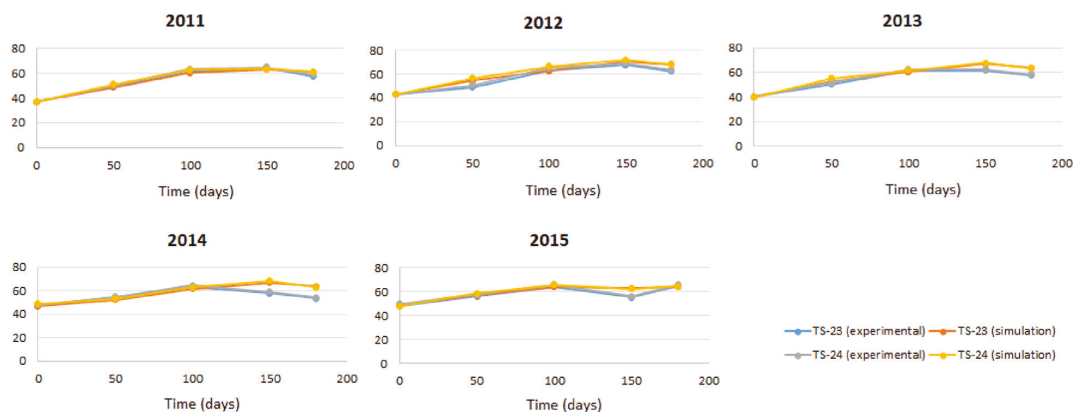


Fig. 4. Average daily surface temperature.

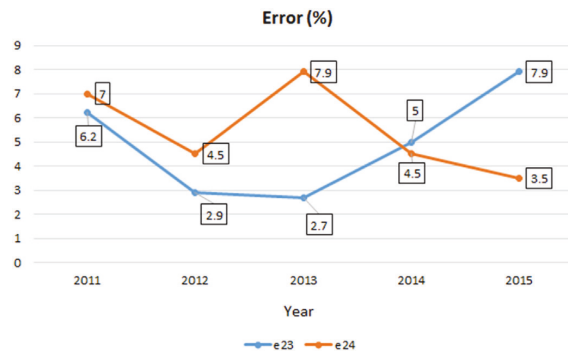


Fig. 5. Percentage error calculation between experimental measurements and simulation results.

separated for validation. The accuracy of the model elaborated as how well the model performs between known inputs and unknown inputs. Charging and discharging operations validated so that it can be used in other similar projects. Both charging and discharging models have an average accuracy over 95%.

4.2. Validating model of borehole thermal energy system

Five simulations conducted to validate the model for each year of charging operation. The collected dataset indicates six months (May–October) of charging operation performed every year. Experimental measurements are the surface temperature of the BTES. Average surface temperatures are always greater than zero ($^{\circ}\text{C}$) due to the charging strategy. In addition, charging operation starts if the reference temperature is stable. Fig. 4 shows the average daily surface temperature. The system description indicated that (TS22) was faulty. Therefore, TS-23 and TS-24 compared between simulation results and experimental measurements. TS is the temperature sensor measurements referring to the surface temperature of the BTES. There are six months of charging operation simulated during 2011–2015. The data indicates temperature measurement over 40°C at the beginning of the charging operation and surface temperature rose over 60°C by the end.

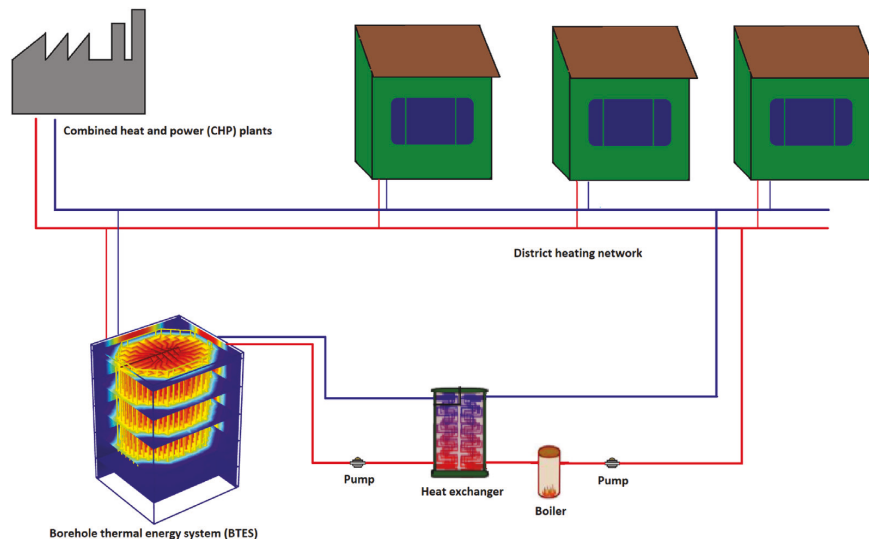


Fig. 6. Application of the proposed BTES. The excess heat from the CHP plants during summer time stored in the BTES and connected with the distribution network.

Fig. 5 presents percentage error calculation of charging operation during 2011–2015. The estimation conducted by considering average surface temperature measurements (TS-23 and TS-24). Errors (e23 and e24) represent percentage error between experimental measurement and simulation results. The minimum and maximum errors estimated at 2.54% and 7.8%. The average error between simulated and collected data calculated under 5%.

4.3. Limitations of the model

The model consists of 119613 plus 60402 number of degrees of freedom. High number of degrees of freedom have high latency. Computation of such complex model requires a lot of time to solve the parameters. The model was simplified by reducing the air temperature parameter. The insulation layer at the top and the soil layer were also not considered in the simulation. The input parameter (TS13) was converted into average daily temperature. The simulation was conducted in daily time steps, which reduces the time duration to solve the model compared to hourly simulation. Constant average volumetric flow rate was used instead of variable flow rate. The model was validated for only five months of charging operation instead of the whole year operation. Discharging operation mode could not be validated due to high fluctuation of heat demand during the entire year.

5. Application of borehole thermal energy system in Finland

The municipality of Sodankylä, Finland planned to construct six small-scale CHP plants in order to reduce greenhouse gas emissions and support the local economy of the region. The plants are supposed to produce 4.3 MW of heat energy and contribute to the existing district heat production. These plants are wood-based replacing the use of peat energy source, eliminating the final significant fossil fuel use in the district heat production. The heat demand in the region during summer is significantly less than the winter. The preliminary study of the heat production and consumption indicates a surplus of heat production from June until August. The amount of heat surplus is high enough to investigate the opportunity of constructing heat storage system. The long-term benefit of heat storage construction outweighs the required initial investment. Earlier research reveals the contribution of BTES to utilize industrial heat (Guo et al., 2017; Xu et al., 2018). The stored heat energy

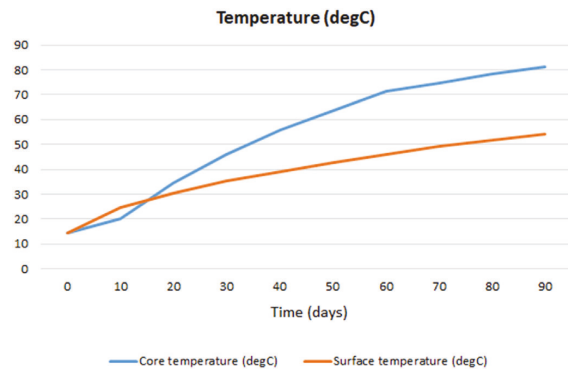


Fig. 7. Core and surface temperature of the BTES during charging operation.

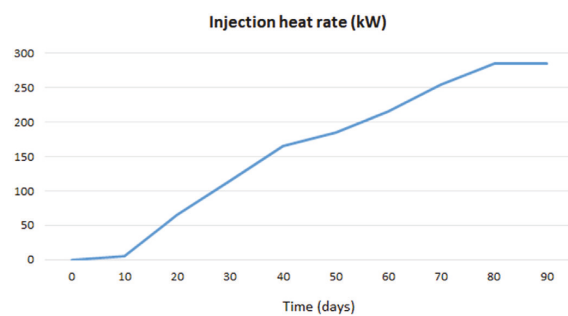


Fig. 8. Heat rate of charging operation.

contributes to the distribution network during the peak heat demand. The BTES can also be utilized in 4G decentralized district heating systems where the supply temperature is low. The efficiency of BTES reaches 90% in low supply temperature grid after a few years of charging (Guo et al., 2020). The benefits of using BTES in a low temperature small-scale district is significantly higher than a conventional district heating network.

5.1. Investigating the possibility of borehole thermal energy system installation

This section proposes an application of BTES with planned CHP plants. According to the preliminary analysis of the project, summer season (June–August) is reserved for service and maintenance. Data analysis of supply and demand of heat energy during summer season indicates a 1.53 MW surplus. This surplus heat energy can be stored in a BTES. Fig. 6 illustrates a possible BTES installation with CHP plants. The CHP plants delivers heat energy to the distribution network. In addition, the supply line can be extended to connect a BTES, which stores excess heat from the CHP plants. The BTES can discharge to the same supply line if needed or it can extend to other distribution network for new construction in the region. Next section simulates charging operation with excess heat. This evaluates the capacity of the BTES and required number of BTES to utilize 1.53 MW surplus heat energy during summer season.

5.2. Charging borehole thermal energy storage with excess heat

Initial temperature of the ground assumed to be 6 °C, carrier fluid has an average flowrate of 2 l/s, and constant supply temperature of 90 °C applied to the model. The simulation conducted for 90 days representing the summer season to deliver the available excess heat. One of the restrictions of using BTES is that it takes few years of charging operation to

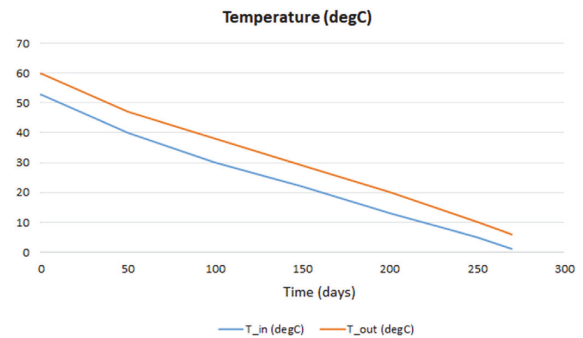


Fig. 9. Inlet and outlet temperature during discharging operation.

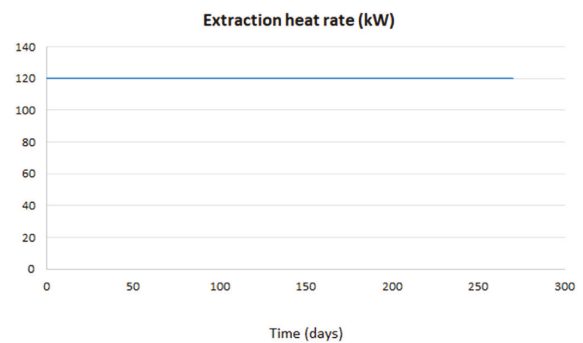


Fig. 10. Heat rate during discharging operation.

reach a desired temperature before it can be used for discharging operation. The simulation indicated that constant supply temperature from the district heating network insures the core temperature rise of 80 °C shown in Fig. 7. Core temperature (TS22.1-TS22.7) illustrated in Fig. 2. Surface temperature (TS23.1-TS23.7 and TS24.1-TS24.7) estimated at 50 °C at the end of the charging operation.

The energy stored calculated at 0.28 MW at the end of charging operation. Fig. 8 shows the heat rate of charging operation during summer season. The simulation reveals that there is a potential of five BTES of similar dimensions in order to utilize the total amount of excess heat energy from the CHP plants. If the BTES has an efficiency of 40% as estimated in the literature, it means that 86 kW of heat energy is readily available for distribution from each BTES.

5.3. Discharging borehole thermal energy system

Discharging operation investigated for short-term operation of the system. Simulation conducted with a constant heat rate of 60 kW. The initial temperature of the BTES considered to be 60 °C, which is the estimated temperature rise at the end of the charging period and suitable for discharging operation rest of the year. Inlet and outlet temperature evaluated with respect to the heat transfer between the heat exchanger pipes and the ground. The volumetric flow rate of the carrier fluid assumed at 2 l/s. The heat capacity of discharging operation is constant for the entire discharging period. The simulation period assumed at 270 days. Fig. 9 shows the inlet and outlet temperature during the discharging operation. The inlet and outlet temperature at the beginning of the simulation estimated at 50 °C and 60 °C respectively. The temperature dropped down to 1 °C and 6 °C at the end of operation.

The temperature gradually decreases over time with a constant heat extraction rate. At the end of the discharging operation, the average

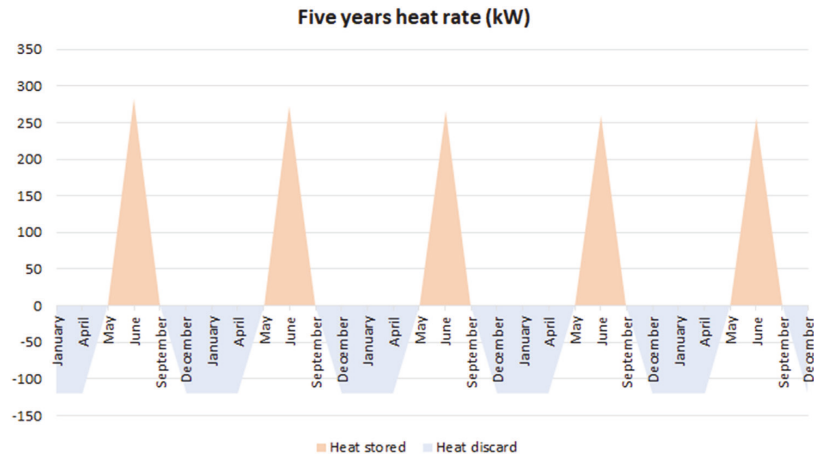


Fig. 11. Heat rate during five years of operation. Charging operation conducted during June–August while discharging took place during September–May.

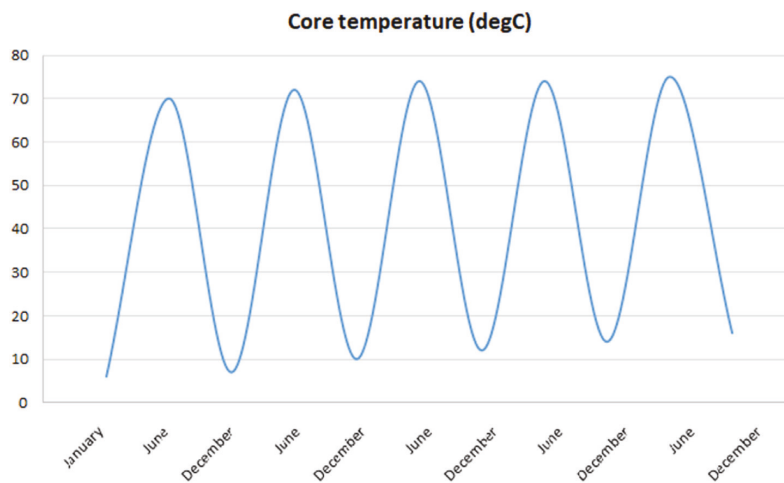


Fig. 12. Average core temperature of the BTES during five years operation.

temperature core estimated at 10 °C. The discharged heat rate is constant at 120 kW illustrated in Fig. 10. In practical scenario, the rate of heat extraction varies with time. If the heat rate of extraction is less than the assumed estimate, the temperature of the BTES will result higher than the calculation. Similarly, if the heat rate of extraction is higher than the assumed estimate, the temperature of the BTES will result lower than the calculation. The point of consideration is to acquire a balance between charging and discharging operation. So that, the BTES can be used for a long period. Another point of consideration is that the temperature of the BTES at the end of the charging operation should not be very high because higher temperature will significantly intensify the heat loss from the BTES. The temperature of the BTES at the end of the discharging operation should not be very low because the lower the temperature of the ground, the longer time it will take to charge at the optimal temperature at the end of the charging season.

5.4. Five years operation of heat storage

In order to evaluate the short-term feasibility of BTES with the

proposed mode of operation, the heat injection and extraction forecast in Fig. 11. The heat extraction during the five years operation kept constant which represent the maximum amount of heat extracted for the proposed model. On the other hand, the heat injection during five years operation decreases with time, which represents the temperature increase in the BTES. The plot also shows the duration of heat injection (June–August) and heat extraction (September–May). The heat extraction can be increased, once the heat injection rate is decreased significantly after number of years of operation. The plot depicts a clear representation of the amount of heat rate injected or extracted.

The core temperature illustrated in Fig. 12. Temperature rose to 70 °C at the end of the charging operation of year one. The temperature dropped down to 10 °C at the end of the discharging operation of year one. After five years of operation, the temperature estimated slightly less than 20 °C. It shows the potential to increase the heat extraction rate to balance the operation. The temperature after four years of operation was estimated to be over 70 °C. It shows that heat loss is significantly high which can be optimized by decreasing the injection heat rate.

5.5. Discussion

Charging and discharging operations revealed adequate information on application of heat storage. The model can be connected to the CHP plants storing the released excess heat. The stored heat estimated 0.28 kW, which does not utilize the entire excess heat released from the plants. Additional five BTES is recommended with similar configuration to store surplus heat. These heat storages is beneficial investment because stored heat can be used during winter season to the existing supply network. The heat storage can also be used to deliver heat to remote buildings. Another possible application is a centralized 4G low temperature heating network for new construction. The system can resemble DLSC project with an interchangeable heat source. The DLSC project used fan coils for space heating where the carrier fluid circulated from storage tank to district network at an average temperature of 37 °C. Similar configuration can be taken with floor heating in new residential buildings in the region. The DLSC study concluded that the investment was economically challenging even with the subsidy. The major cost of such system is due to the installation of solar heat collectors. The proposed model combined with excess heat from the CHP plants makes the system economically beneficial.

6. Conclusion

This study focuses on modelling 3D borehole thermal energy system with a possible applications in Sodankylä, Finland. The municipality of Sodankylä is planning the construction of six new CHP plants. Only two of the plants operate during summer season and the rest are shutdown for maintenance, which results in 1.53 MW of excess heat. The excess heat can be stored in a heat storage which is useful during peak winter season. A BTES model created to store excess heat from CHP plants. The configuration parameters of the model were similar to the DLSC project. Experimental dataset of DLSC system was used to validate the BTES model. The accuracy of the model was estimated at 95%. An artificial neural network was created to simulate the modes of operation (charging/discharging). The accuracy was calculated to be 97%. The model could be used in different heat storage applications. The stored excess heat estimated at 0.28 MW during charging operation. Simulations revealed that there is a potential of five BTES installation with similar configuration to utilize the entire excess heat. The capacity of the BTES projected between 285 kW and 250 kW during five years operation.

Ethics approval and consent to participate

Not applicable.

Availability of data and materials

Data that is relevant to the manuscript presented in the text and figures.

Consent for publication

The authors declare full contribution towards the Manuscript. The author edited the manuscript and approved of the final manuscript.

Declaration of competing interest

The authors do not intend to compete and declare no competing interests.

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Article

Modelling Sustainable Industrial Symbiosis

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Abstract: Industrial symbiosis networks conventionally provide economic and environmental benefits to participating industries. However, most studies have failed to quantify waste management solutions and identify network connections in addition to methodological variation of assessments. This study provides a comprehensive model to conduct sustainable study of industrial symbiosis, which includes identification of network connections, life cycle assessment of materials, economic assessment, and environmental performance using standard guidelines from the literature. Additionally, a case study of industrial symbiosis network from Sodankylä region of Finland is implemented. Results projected an estimated life cycle cost of €115.20 million. The symbiotic environment would save €6.42 million in waste management cost to the business participants in addition to the projected environmental impact of 0.95 million tonne of CO₂, 339.80 tonne of CH₄, and 18.20 tonne of N₂O. The potential of further cost saving with presented optimal assessment in the current architecture is forecast at €0.63 million every year.

Keywords: industrial symbiosis; life cycle assessment; life cycle cost assessment; environmental assessment



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1. Introduction

Industrial symbiosis (IS) can be understood as a platform for material exchange among business collaborators with the objectives of sustainability and waste reduction. The proposition of European commission to turn political commitment into legal obligation requires businesses to implement circular economic model by utilizing the resources efficiently [1]. This encourages businesses to focus on eco-innovative practices and strengthen corporate responsibility towards sustainability by means of maximizing energy efficiency, optimizing raw material use, and create value from waste [2,3]. Furthermore, businesses are encouraged to conduct decision-making based on sustainable environmental performance indicators and social implications of industrial products [4–6]. Such objectives were achieved by collaborative platforms such as industrial symbiosis, where industries share knowledge and expertise to device best practices for sustainable ecosystem [7,8]. IS networks allow synergetic relations among companies to fulfill the environmental regulations of a region, in addition to coordination that achieves cost savings for industrial participants which otherwise would not have been possible [9–11]. Furthermore, from the perspective of industrial ecology, industrial symbiosis demands radical implementation of sustainable business processes [12]. However, the methodological approach is focused on technical aspect, innovative growth strategy, and implementing digitalized environment [13,14].

Present approach of industrial symbiosis network assessment comes from either industrial ecological or technical studies. Both disciplines rightly quantify the necessary components to analyze the system such as environmental and economic parameters [15,16], life cycle assessment [17–19], and recycling network [20–22]. However, businesses require further transformation in the business model to implement sustainable practice [23]. This study combines both IS network approaches from ecological and technical studies and presents a model of sustainable industrial symbiosis. The aim is to evaluate the sustainability of IS network by calculating life cycle assessment (LCA), environmental impact, life

cycle costs of products and waste management. The method offers a comprehensive tool to assess the performance of IS network and possible improvement in the existing state of the system. The proposed tool also identifies IS network connections (possible resource sharing) among industrial practitioners to ease the process of material exchange in addition to providing the total quantity of material flow, produce cost, waste management cost, and cost reduction in the IS network. Furthermore, the approach combines the methodological consideration from business and technical perspectives with respect to standard guidelines of life cycle assessment.

2. Materials and Methods

2.1. Literature Review

Sustainable development is key to achieve universal peace and freedom. The United Nation's 2030 agenda for transforming the world emphasized on the sustainable development, which consists of three pillars: economic, environmental, and social sustainability [24]. The document further highlighted the importance of regional discussions, peer learning, and sharing best practices to achieve the given targets. In the spirit of aligning the regional business development with United Nation's sustainable development goals, businesses must be able to show willingness to cooperate with governmental or non-governmental bodies under synergetic environment to improve economic, environmental, and social impact. Recent study reveals that synergetic relationships directly influence the social well-being, affordable, and clean energy [25]. Businesses are not only encouraged for sustainable production but also liable for sustainable supply and distribution chains [26,27]. These targets can be achieved entirely by industrial collaboration and shared platform.

The analysis of industrial symbiosis (IS) appeared in management [28], and technical [29] literature in the past. Both emphasized on the benefits of shared resources in IS network. There are limitations of material exchange among industrial participants in the absence of agreed rules [30]. Therefore, identifying all products and by-products in a symbiotic environment must be conducted by standard guidelines [31,32]. Conventional assessment methods of symbiotic network includes life cycle assessment [33–35], environmental impact accounting [36–38], recycling and waste utilization [39], and comparison with few reference scenarios [40]. The focus has always been to reduce the environmental impact of IS network in business sectors such as, chemical industry [41], energy industry [42], and steel industry [43].

Previous studies lack clarity and comprehensive methodological aspect in addition to quantify waste management and identify material exchange in IS network. The literature primarily focused on either quantification of life cycle assessment (LCA) or accounting of environmental impact. However, the benefits of waste utilization and waste management should be emphasized. This study compiles a comprehensive method of conducting sustainable assessment of industrial symbiosis. The method combines both management and technical methodologies including cradle-to-gate approach LCA [44,45], environmental impact calculation, waste management accounting, and optimization assessment [46] of IS network.

2.2. Model

This study presents a sustainability model of an industrial symbiosis (IS). The model is applicable to any symbiotic environment considering business sector, system's boundaries and material exchanges identified appropriately to existing symbiosis or new business development. Figure 1 illustrates the model of sustainable symbiosis environment. Three sections articulate input data (collected from either business participants or literature studies), modelling (identifies material exchange, quantifies boundaries, and optimizes environmental impact), and result (reports of economic, environmental, and optimization). The following sections elaborate input data required to identify and estimate material flow in the system.

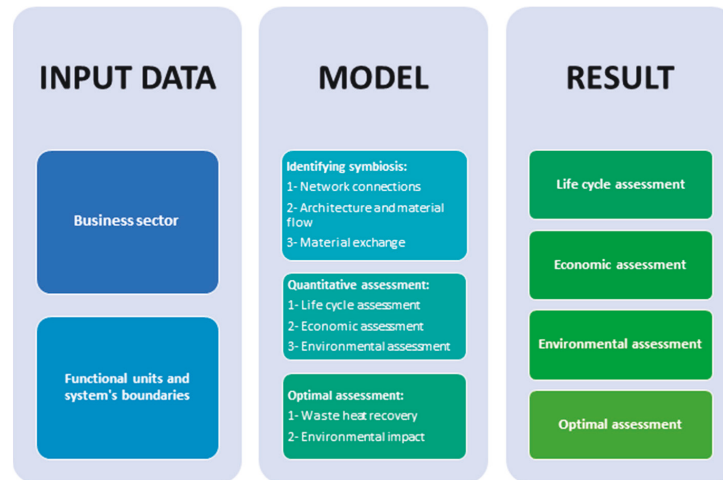


Figure 1. Sustainability model of industrial symbiosis.

Input data is categorized by business sector, functional units, and system boundaries. The model uses given data to identify synergies, material exchange, and quantify symbiotic activities. Business sector reveals type of assessment selected for IS. The model considers cradle-to-gate boundaries assessment. This includes input (energy, raw material, and water consumption) and output (products\by-products, wastewater, solid waste, and losses). The functional units of an IS are the main products of business participants [45].

Identification of materials exchange among participants consists of connection from one industry to other. Domenech and Davies (2011) [8] showed the construction of IS network matrix. The architecture of the symbiotic environment outlines material flow between industries. Once the network identified in IS, material exchange are visible. Quantifying symbiosis consists of three important sub-sections. Life cycle assessment of materials in IS estimates total amount of energy, raw materials, water, products, wastewater, and solid waste of all participating industries. These parameters are represented as, Equations (1)–(6):

$$E_{IS} = \sum_{t=1}^T \sum_{i=1}^n E_n \quad (1)$$

$$W_{IS} = \sum_{t=1}^T \sum_{i=1}^n W_n \quad (2)$$

$$M_{IS} = \sum_{t=1}^T \sum_{i=1}^n M_n \quad (3)$$

$$P_{IS} = \sum_{t=1}^T \sum_{i=1}^n P_n \quad (4)$$

$$SW_{IS} = \sum_{t=1}^T \sum_{i=1}^n SW_n \quad (5)$$

$$WW_{IS} = \sum_{t=1}^T \sum_{i=1}^n WW_n \quad (6)$$

where IS represents industrial symbiosis estimation; E is energy consumption; W is water consumption; M raw material consumption; P is product produced; SW is solid waste produced; WW is wastewater produced; T is number of assessment years ($T = 20$); n

is number of industries participating in the symbiosis. These parameters are essential to estimate the performance and sustainable production of a symbiotic environment. Economic assessment of materials further divided into two sections. The first is life cycle cost (LCC_{IS}) of all material produced in the IS. The life cycle cost of production in symbiosis is expressed as, Equation (7) [47]:

$$LCC_{IS} = \sum_{t=1}^T \sum_{a=1}^n (C_p(1+e)^{-1}) \quad (7)$$

where C_p is the production cost; LCC_{IS} is life cycle cost; e is the discount rate ($e = 1.5\%$); n is the number of participating industries. The production cost (C_p) includes the costs of input fuel, energy consumption, feedstock, raw material, and labour. The economic assessment is divided into two sections: The life cycle cost of products, and the life cycle cost of waste management. The life cycle cost of waste management can be further characterized [48]: economic life cycle cost (LCC_{eco}); environmental life cycle cost (LCC_{env}); and societal life cycle cost (LCC_{soc}). The life cycle cost of waste management is formulated as, Equations (8)–(10) [49]:

$$LCC_{eco} = \sum_{t=1}^T \sum_{i=1}^n [W_i(UBC_i + UT_i)] \quad (8)$$

$$LCC_{env} = \sum_{t=1}^T \sum_{i=1}^n [W_i(UBC_i + UT_i + UAT_i)] \quad (9)$$

$$LCC_{soc} = \sum_{t=1}^T \sum_{i=1}^n [W_i(UBC_i * NTF + UEC_i)] \quad (10)$$

where n is the number of participating industries; i is the unit cost activity; UBC_i is the budget cost of unit activity (waste management activity); W_i is the quantity of input waste (waste input for waste management); UT_i is the unit transfer of activity (waste collection or transportation cost for waste management). NTF is the net tax factor (shadow price of marketed goods); UAT_i is the unit anticipated transfer of activity (anticipated cost increase in future); UEC_i is the unit externality cost of the activity (unintended cost). The third section of economic assessment consists of environmental calculation. The environmental evaluation of each industry includes estimating the environmental impact of each products [35]. Environmental assessment of IS is expressed as Equations (11)–(13):

$$CO_{2IS} = \sum_{t=1}^T \sum_{i=1}^n CO_{2n} \quad (11)$$

$$CH_{4IS} = \sum_{t=1}^T \sum_{i=1}^n CH_{4n} \quad (12)$$

$$N_2O_{IS} = \sum_{t=1}^T \sum_{i=1}^n N_2O_n \quad (13)$$

where CO_2 is the carbon dioxide emissions from each industry; CH_4 is methane emissions; N_2O is nitrous oxide emissions. The agriculture sector has a standard product-specific carbon footprint, which is taken into account. Methane and nitrous oxide emissions from the agricultural sector are negligible because biowaste and wastewater are collected by the waste management and wastewater treatment departments. The major source of emissions is the energy sector. The environmental assessment does not include carbon monoxide and variations of nitrogen oxide due to technological factors of CHP plants, which eliminate these parameters by oxidation in the middle of the process. The study only portrays the standard emissions parameters that are provided in the previous literature and are according to the standard guidelines of intergovernmental panel on climate change (IPCC). The last

sub-section of modelling symbiosis includes optimization. Optimal symbiotic environment consists of waste heat recovery and reducing environmental impact of the products. The environmental impact of industries reduce by participation in symbiosis activities [29]. These activities include optimizing energy consumption and waste management with IS framework. Afshari et al. (2020) [46] showed design optimization of IS by carefully characterizing energy supply and demand, and considering variation between residential and industrial users. Cost of waste heat is expressed as, Equation (14):

$$Z = \sum_{i=1}^n (C_{waste\ heat} + C_{tax}) \quad (14)$$

where, Z is cost saved in optimal symbiotic environment; C_{waste_heat} is cost of waste heat or excess heat; C_{tax} cost of carbon tax. The optimal assessment represents potential of cost saving by waste heat recovery and applied carbon tax on fossil fuel, only applicable on the energy industry. The potential to store waste heat from power plants could significantly reduce the total cost of energy production. The variation of energy consumption between summer and winter season create imbalance in the energy production, which can be rectified by recovering the excess heat during summer season. Equation 14 estimates the cost of waste heat from power plants, which could be stored in a heat storage and utilized during the winter season. The cost of carbon tax also taken into consideration, which is applicable on fossil fuels. The carbon tax can be avoided by replacing the fossil fuels with renewable fuel. The optimal assessment could be nullified if power plants do not produce excess heat and only consume renewable fuel during the year.

3. Results

3.1. Case Study

This section presents implementation of the model on an industrial symbiosis case study from Finland. The municipality of Sodankylä planned to establish new businesses to boost the regional economy. These businesses must show the potential of sustainability and circular economy. There are two business sectors engaging in the activity. The first is energy sector and the second is agriculture sector. The business sectors expected to create symbiotic environment to reduce waste products and boost the ecosystem in the region.

There are five new business development planned for Sodankylä. The existing energy distributor of the region will also participate in the activity. The municipality is looking into the possibility of constructing a fish farm, a greenhouse farm and an insect farm. Several combined heat and power (CHP) plants are also under consideration to distribute energy to the new development in the area. Furthermore, a biogas reactor is to be constructed to collect biomass from the local businesses. The municipality is responsible for facilitating material exchange among the six businesses, in addition to maintaining the department of waste management and wastewater treatment in the region.

The existing main power plant distributes an annual average of 9.92 MW heat to the region. The plant consumes Peat, woodchip, and heavy oil fuels. External suppliers supply the primary electricity and input fuels. There are six CHP plants proposed to distribute 4.3 MW of heat for the new business development. The plants also produce biochar to be distributed to the local and global markets. A modern greenhouse farm is proposed, based on the rooftop greenhouse in [50]. A 5000 m² farm construction expected to produce a yield of 70 kg/m² of tomatoes initially. The farm is capable of accommodating potted plants and salad leaves as well. A conventional fish farm is under consideration with a 70 t per year capacity of whitefish production. The regional farms can produce either trout or whitefish. An innovative insect farm concept is considered to supply fish feedstock in the region. A combination of six insect farms, each with an area of 50 m² would supply 4.2 t of *Hermetia illucens*, which is further processed to produce feedstock. A biogas reactor of 500 m³ capacity would be an essential business for the region to collect biomass from agricultural sector in addition to other local businesses. The reactor produces 203,250 m³ methane per year, with a calculated density of 0.72 kg/m³. The biogas reactor includes biogas upgrading to intensify

the production of methane gas (bio methane). The case study is further elaborated in [51,52]. The waste and wastewater release from industries collected by the regional department of waste management and wastewater treatment.

3.2. Implementation

The input data was collected from the Natural Resource Institute Finland. Biogas reactor and greenhouse farm data based on the literature presented in [50,52]. The business sector can be characterized as:

- Three energy businesses (energy sector)
- Three agriculture businesses (agriculture sector)

The functional unit and system's boundaries are presented in Table 1.

Table 1. Yearly consumption and production of businesses.

Parameter	Main Power Plant	CHP Plants	Greenhouse Farm	Fish Farm	Insect Farms	Biogas Reactor
Functional unit	Heat, electricity	Heat	Tomatoes	White fish	Feed stock	Biogas
Energy (MWh)	1840 ¹	3372 ¹	4380 ³	501 ¹	17 ²	2216.28 ⁴
Water (m ³)	-	-	6132 ³	35,040 ¹	218.57 ²	-
Material (t)	54,686.60 ¹	8574 ¹	560 ³	82.43 ¹	40 ²	2742.5 ⁴
Product	86,899 ¹ (MWh)	27,900 ¹ (MWh)	350 ³ (t)	70 ¹ (t)	1.43 ² (t)	2505.22 ⁴ (t)
Waste water (m ³)	-	-	-	31,010.40 ¹	216.30 ²	-
Solid waste (t)	8230.70 ¹	-	213.50 ³	437.12 ¹	25.26 ²	-

¹—Estimations by Natural Resource Institute Finland; ²—Estimation based on [53]; ³—Estimation based on [50]; ⁴—Estimation based on [52].

The lifecycle assessment combines input consumption and output production of the businesses involved in the system. Figure 2 illustrates the amount of material flow in the system to produce the estimated products. Equations (1)–(6) were used to calculate the quantity of materials. Material in the system consists of input fuels for both CHP plants and main power plant, input fish for the fish farm, tomato plants for the greenhouse farm, and eggs for the insect farm. Most of the biogas raw material is expected to come from the participants, however, external suppliers also provide bio-waste to the biogas reactor as well as to all participants. The byproducts of industries are added in the estimated production because of the available market in the region. Energy industries in the symbiotic system do not require added fresh water other than that provided by the district water supplier as opposed to the agriculture businesses. The fish farm consumes most of the supplied fresh water; the greenhouse farm is the second biggest consumer of fresh water and the insect farm has the third biggest water consumption in the system. Similarly, wastewater and solid waste are anticipated to be released intensely from the agriculture businesses, respectively.

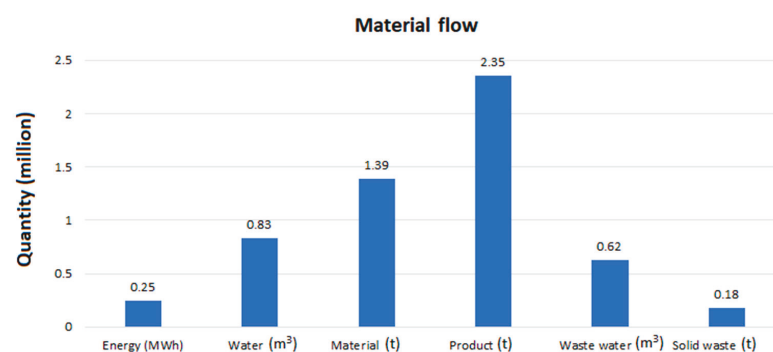


Figure 2. Life cycle assessment of symbiotic environment in Sodankylä.

3.2.1. Identifying Symbiosis

This section combines all the information required to identify material exchange among the participants in the system. The municipality of Sodankylä is the coordinating authority in the network. Table 2 presents network connections among participants. A “1” in the table indicates possible material exchange; “0” shows no exchange. The department of waste management and wastewater treatment do not recognize in the table. The IS network matrix implies three possible exchange among industries. The first is energy including heat and electricity, the second is bio-waste consist of sludge and energy crops, and the third is recyclable waste including fertilizer and biochar. In addition, there may be some non-recyclable waste including fly ash, inorganic waste, and residual waste.

Table 2. IS network matrix [51].

Industry	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

Figure 3 presents the architecture and material flow of the IS network. The acting authority of the network is the regional municipality. The department of waste management and wastewater treatment is under municipality’s control. An external supplier supplies primary energy to the main power plant. The primary energy of CHP plants is supplied by the main power plant. The CHP plants supply energy to all new developments in the region. The raw materials and input fuels come from non-regional businesses, unrecognized in the architecture. Furthermore, fresh water is supplied by the municipal water plant. The synergetic relations among the business participants shows the circular economy model, where resources are shared among industries and cost savings are achieved due to business development in the whole region. Quantified benefits of waste management in the symbiotic environment are presented in the next section. Figure 4 shows the material exchanges among collaborators. Identified materials available for exchange among the participants are divided into three sub-groups. The division helps articulate the exchange between respective businesses. Material exchange includes heat, electricity, bio-waste (sludge, energy crop), and recyclable waste (biochar, fertilizers). The energy supplied by the CHP plants for all new businesses. Bio-waste comes from the agriculture sector, including the fish and greenhouse farms. Biochar and fertilizer products are produced by the CHP plants and biogas reactor.

3.2.2. Quantitative Assessment

The economic assessment consists of life cycle cost (LCC) of all products and waste management of all businesses. The costs include the cost of raw materials, water consumption, and energy consumption of all businesses illustrated in Table 3. The waste management is characterized in three cost categories: economic cost; environmental cost; and societal cost. The cost of waste is estimated separately to show the reduced life cycle cost under IS network. Table 4 presents the cost of waste management of all businesses.

The costs are divided so that the municipality could offer incentives to business participants in return for cost savings for waste management and material exchange. In a non-symbiotic environment, the cost of waste management added to the life cycle cost respectively. The combined life cycle cost is forecasted at €115.2 million. The biggest cost of the product is the energy produced by main power plant and CHP plants. Fish and tomatoes are the third and fourth biggest cost in the system. The cost of the insect farm may vary depending on the production rate of *Hermetia illucens*, which is the input feed to the secondary process of insect farming producing feedstock. Figure 5 depicts the life cycle cost of all products in the system. Equation (7) was used to estimate the life cycle cost of products.

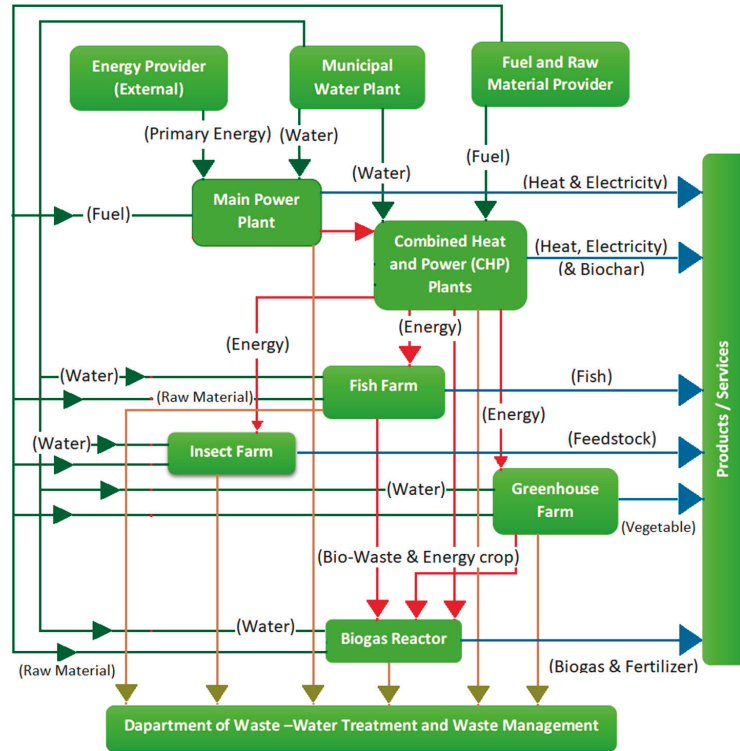


Figure 3. The architecture and material flow of industrial symbiosis in Sodankylä. Green color represents the input; blue color depicts the output and red color reflects the material exchange.

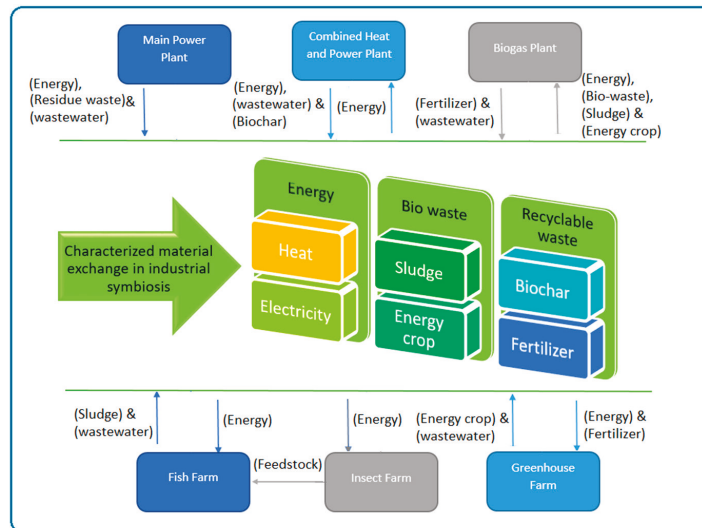


Figure 4. Identifying material exchange in IS network.

Table 3. Life cycle cost parameters of products.

Parameter	Cost of Material (€/year)	Cost of Water Consumption (€/year)	Cost of Energy Consumption (€/year)
Main Power Plant	1.80 ¹ million	-	73.60 ¹ thousand
CHP Plants	0.78 ¹ million	-	0.13 ¹ million
Greenhouse Farm	0.40 ³ million	6.99 ³ thousand	0.20 ³ million
Fish Farm	0.78 ¹ million	40 ¹ thousand	16.67 ¹ million
Insect Farms	12 ¹ thousand	0.25 ¹ thousand	0.68 ¹ thousand
Biogas Feactor	2.40 ² thousand	-	88 ² thousand

¹—Estimations of Natural Resource Institute Finland; ²—Estimations based on [53]; ³—Estimations based on [50].

Table 4. Life cycle cost of waste management.

Industry	Waste Type	Waste Product/by-Product (t/year)	Waste Handling Cost
Fish Farm	Economic	438 ¹	2 ¹ (€/t)
	Environmental	31,063 ¹	1000 ² (€)
	Societal	438 ¹	1 ³ (€/t)
Greenhouse Farm	Economic	154.35 ⁴	1.50 ³ (€/t)
	Environmental	-	1000 ² (€)
	Societal	154.35 ³	2 ³ (€/t)
Main power Plant	Economic	8230.69 ¹	1.50 ³ (€/t)
	Environmental	24,682.11 ⁵	35 ⁷ (€/t)
	Societal	8230.69 ¹	6 ³ (€/t)
CHP Plant	Economic	-	-
	Environmental	1019 ⁵	5 ³ (€/t)
	Societal	-	-
Biogas Reactor	Economic	2500 ⁶	1.50 ³ (€/t)
	Environmental	402.50 ^{5&6}	5 ⁵ (€/t)
	Societal	2500 ⁶	5 ³ (€/t)
Insect Farm	Economic	20.95 ⁸	2 ¹ (€/t)
	Environmental	216.30 ⁸	1.82 ¹ (€/t)
	Societal	20.95 ⁸	5 ³ (€/t)

¹—Estimations of Natural Resource Institute Finland; ²—Estimations of Sodankylä Municipality [54]; ³—Estimations based on [53]; ⁴—Estimation based on [50]; ⁵—Estimations based on global warming potential of energy sources [55]; ⁶—Estimations based on [52]; ⁷—Estimations based on taxing energy use 2019 [56]; ⁸—Estimations based on [53].

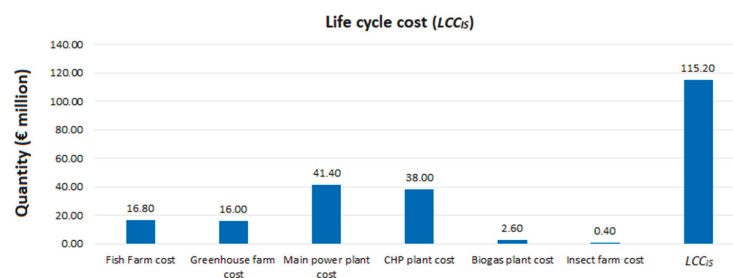
**Figure 5.** Life cycle cost of products in symbiotic environment in Sodankylä.

Figure 6 illustrates the waste management cost of business participants. Equations (8)–(10) were used to calculate the life cycle cost of waste management. The combined life cycle cost of waste management is forecast to be €6.42 million. The cost further divided into economic cost, environmental cost, and societal cost. The economic cost of the system estimated at €0.34 million, which is smallest among the division. A majority of the economic

cost is generated at the main power plant because of fly ash collection and transfer. The biogas reactor is the second biggest economic cost because of the transport cost of fertilizers. Environmental and societal costs are the biggest in the system. Carbon taxes on fossil fuels are expected to generate significant costs. By replacing the input fuels of the main power plant, the environmental cost and societal cost can be reduced.

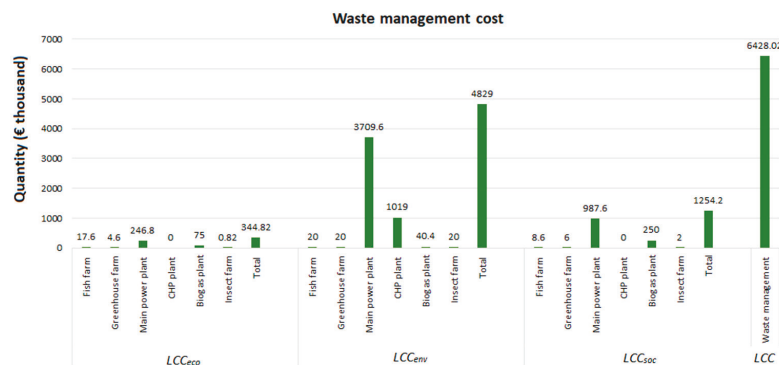


Figure 6. Life cycle cost of waste management in symbiotic environment in Sodankylä.

The environmental assessment data consists of the carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions from all the business participants in the symbiosis. The emission factors of energy sector collected from the Intergovernmental Panel on Climate Change (IPCC), fish farm emissions from were collected from the Natural Resource Institute Finland, and emissions from the greenhouse and insect farm were acquired from the literature. Table 5 presents the amount of environmental impact produced by all the businesses. The IPCC presented variety of emission factors based on input fuel types and the capacity of the plants. The methane emission for mixed fuel (fossil and biomass) has three capacity ranges. Methane emissions are the highest for plants with a capacity smaller than 1 MW, emissions are marginal for 1–5 MW capacity, and the smallest methane emissions are for 5–50 MW capacity. The nitrous oxide emissions for mixed fuel depends on the type of boiler rather than the capacity of the plant. The circulating fluidized bed configuration has the highest nitrous oxide emissions, a bubbling fluidized bed has marginal emissions, and grate combustion systems have the lowest nitrous oxide emissions. Nitrous oxide and methane emissions from Peat And Woodchip input fuels are similar to those of mixed fuels.

Table 5. Yearly environmental impact of businesses.

Parameter	Main Power Plant	CHP Plants	Greenhouse Farm	Fish Farm	Insect Farms	Biogas Reactor
CO ₂ (t)	30,880.94 ¹	14,861.76 ¹	595 ⁴	1309 ²	0.21 ³	-
CH ₄ (t)	15.64 ¹	1.35 ¹	-	-	216.30 ³	-
N ₂ O (t)	0.62 ¹	0.27 ¹	-	-	25.26 ³	0.014 ¹

¹—Intergovernmental panel on climate change [57]; ²—Estimations of Natural resource institute Finland; ³—Estimations based on [58];
⁴—Estimations based on [50].

Figure 7 shows the environmental impact of the system. Equations (11)–(13) were used to estimate the environmental impact of the system. The combined carbon dioxide emission estimated at 0.95 million t. The main power plant is the source of majority of the carbon emissions projected at 30,000 t every year. The estimated carbon emissions from CHP plants is over 14,000 t every year. Carbon emissions from the fish farm and greenhouse farm are calculated at 13,000 and 590 t every year. The insect farm and biogas reactor release the smallest amount of carbon dioxide. Methane and nitrous oxide emissions

are approximately zero from the biogas reactor and agriculture businesses. The methane emissions from the main power plant and CHP plants are projected at 15.64 and 1.35 t every year. The nitrous oxide emissions from the main power plant and CHP plants are forecasted at 0.62 and 0.27 tonne every year.

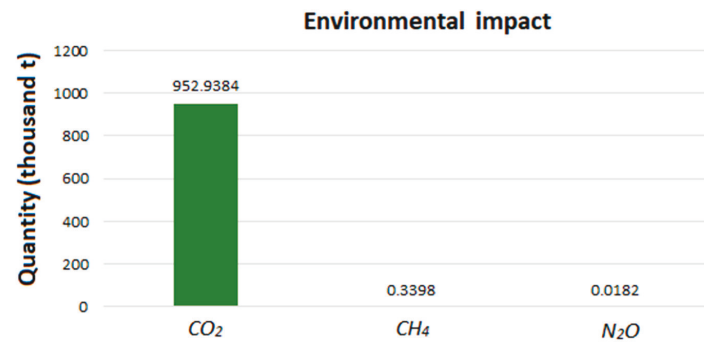


Figure 7. Environmental assessment of symbiotic environment in Sodankylä.

3.2.3. Optimal Assessment

An optimal assessment was conducted to reduce the cost of products and the environmental impact of the system. The cost saving potential can be assessed by analyzing the energy supply and demand of the region. A power plant is expected to operate at full load to use the optimal amount of fuel during all seasons. Energy consumption in the region is reduced significantly. Therefore, four CHP plants must shut down during the summer season. The CHP plants still produce excess heat during summer, which can be stored in a heat storage system. The stored heat can be utilized during the winter season when energy demand is at a peak. Storing excess heat reduces significantly the cost in the life cycle cost assessment. There is another possibility of reducing the environmental impact and life cycle cost by replacing the fossil fuels used to produce energy in the main power plant. Energy production from input fuels such as peat and heavy oil adds significant carbon tax costs. The carbon tax can be entirely eliminated by adopting renewable fuels available in the region such as woodchips or wood pellets. Table 6 shows the parameters of the optimal assessment.

Table 6. Optimal parameters.

Parameter	Value	Cost
Excess Heat	1.53 MW	55 (€/MWh)
Fossil Fuel Emission	18,000 tCO ₂	25 (€/tCO ₂)

The stored heat is utilized during the winter season. The cost of heat recovery from CHP plants is projected at €0.18 million every year. Fossil fuels can be replaced with renewable fuels available in the region. The carbon tax cost is estimated at €0.45 million every year. The combined cost savings in the system is forecasted at €0.63 million every year in the current system. Figure 8 illustrates the optimal assessment of the system. Equation (14) was used to estimate the potential cost savings.

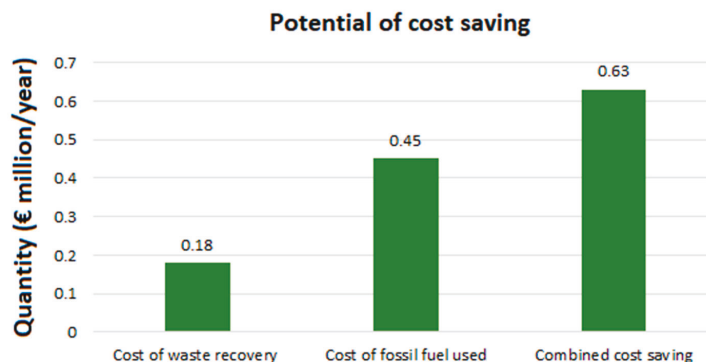


Figure 8. Optimal assessment of symbiotic environment in Sodankylä.

4. Discussion

The research methodologies published in the past assessing industrial symbiosis network lack a complete set of evaluation elements in both management and technical studies. The approach presented in this study has therefore addressed a combined set of methods from both disciplines fulfilling the life cycle assessment guidelines. However, there are limitations in the presented approach depending on the selected data and business sector participants. The following sections provide a discussion on the strengths and limitations of the method, including the choices made in the methodology and its implications for future research and industries involved in the IS network.

4.1. System's Boundary

Previous life cycle assessment studies of IS networks aimed at reducing raw material consumption, environmental consumption and increase production. Aissani et al. [40] argued for characterizing four reference scenarios to compare the impact of each aim of the IS network. The approach taken in this paper eliminates the necessity of creating hypothetical scenarios to reduce the complexity due to number of exchanges and evaluation of the data that may not be usable with respect to the standard guidelines [31]. Many previous studies did not characterize the business sector of industrial participants as it determines the possible exchange in IS network. Suh and Hupples [35] emphasized keeping a life cycle inventory of the system's boundaries to conduct IS network assessment. This study acquired similar data configuration of each participating industry in addition to quantified solid waste and wastewater release to reflect the sustainable feature of the IS network. Previous studies failed to present the waste management aspect of IS networks. However, waste management of the IS network estimated to provide a coherent strategy for waste management and water conservation to all participants as suggested by [30].

4.2. Implementation and Results

The method provided in this study combines various approaches to identify material exchanges, quantify material flows and optimize energy production in a IS network. It is recommended that either the maximum or average value of the system's boundary be used to avoid the sensitivity analysis of the system. The comprehensiveness of the proposed methodology eliminates the need for reference scenarios as well. In the case of uncertain data from a company, new results can be acquired swiftly. In the absence of agreed rules on assessment [30], the model provides a complete life cycle, environmental, and waste management assessment of the system. This approach presents a complete set of information about a IS network to optimize material exchanges for industrial participants.

The industrial symbiosis network implemented in this study had a limited number of products and exchanges, which simplified the process of identification of network connections. The limitations on multiple number of products and exchanges are minimal with the

presented approach. However, the complexity of exchanges may increase with respect to quantifying transportation and waste collection in addition to environmental assessment.

Quantification of a IS network is influenced by the amount of material flow in the system, economy of industries, and environmental impact produced. The economy of industries suggest either a linear or a circular model. The case study presented in this study shows a circular economy example from the Sodankylä region of Finland where new business developments are planned. Nevertheless, a linear economic model may show variations in the quantitative assessment. Businesses could transform into a circular economic model by participating in an existing network or cooperating with a local municipality as is standard practice in Finland, which shows cost variation for waste management solutions. It is recommended that the location of the industry and logistics of any waste management solution be carefully selected to limit the constraints on economic and environmental assessment of the system. The location of the industries is also an important factor to conduct optimal assessment as it determines the energy distribution costs for the energy sector. The excess energy and seasonal variation were taken into consideration in this study as suggested in [46].

The applicability of an optimal assessment may be questioned in this study. The method highlights cost savings from carbon taxes by implementing renewable fuels. In the case of a renewable energy business, an optimal assessment would be excluded from the method. Application of a 50/50 method is avoided for material exchange in the proposed method. Martin et al. [45] argued for the necessity of intermediate processes for fair distribution exchange and classification of materials as waste. This approach assumes a reduction of raw material consumption, which is not necessarily the case for participants in addition to the quality of exchanged materials, suggesting a further analysis of material properties. Instead, economic assessment of products and waste products is recommended in this study to reduce the complexity of the calculations and providing a monetary platform for material exchange.

4.3. Use of the Method on Other System

The method presented in this study was designed to provide a complete sustainable assessment of a industrial symbiosis network. The highlights of the approach included identifying a symbiotic network for a possible material exchange among industrial participants, quantifying life cycle assessments of materials in addition to economic and environmental estimations. However, the approach may not be able to answer all the research questions of IS networks. The approach is best suited for calculating sustainable assessments of new business development with a circular economy orientation in addition to a quantitative analysis of a system's boundaries in energy and agriculture business sectors. The approach is less suited for business sectors such as aviation and chemical plants because of their different environmental assessment and circular economy considerations. However, identifying network connection in this approach may be used for all business sectors, see e.g., [36,37] for quantitative assessment of a chemical business sector.

The approach presented in this study has been applied to a planned IS network for the Sodankylä region of Finland. The identification of network connections to highlight possible material exchanges was conducted based on previous studies. Quantitative analyses of the IS network including life cycle assessment, life cycle cost of products and waste management, and environmental assessment were evaluated based on the standard guidelines of life cycle assessment acquired from various studies. However, the credibility and future improvements of the presented approach require implementation of other case studies.

5. Conclusions

The study presented a comprehensive model of sustainable industrial symbiosis, which included identification of a IS network, architecture and material exchanges among business participants, quantified life cycle assessments, life cycle costs of products and waste management, environmental impacts, and possible optimal assessment in the network. The approach compiled identification parameters from ecological studies and quantification

parameters from technical studies to articulate a complete set of methods in one model in accordance with the standard guidelines of the life cycle assessment literature. The model was implemented on a case study from Sodankylä, Finland. The case study consisted of six new industrial collaborators aiming to achieve a circular economy and sustainability in the region. Results indicated a €6.42 million cost savings in waste management with the presented IS network architecture. In a linear economic model, this cost would simply be added to the cost of product development of each industry. Further cost reductions included €0.63 million every year for carbon taxes and waste recovery. The environmental impact could significantly be reduced by replacing the fossil fuels with renewable energy fuels such as woodchips, which are available in the region. The approach not only helped create network connection but also estimated a life cycle assessment, life cycle cost of products and waste management, environmental impact, and potential cost savings in the IS network. However, further validation is required for the constructed approach. The model only applied on a simplified case study with one product from each industry. Identification of network connection would result in complex architecture where companies have more than one product.

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