Mechanical Engineering

Solutions for sustainable energy systems

Analyses of district heat optimization and microalgal biorefineries

Mikko Kouhia

Aalto University

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Abstract

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Abstract

Energy systems are in transition, as fossil fuels are phased out and variable renewable energy generation is introduced in increasing amounts into electricity networks. As the energy provision bears high environmental impacts, attention has to be paid into the sustainability of current and planned systems.

This dissertation investigates prospective technologies in the short and long term. District heat optimization and microalgal biorefineries are selected as the focus areas: the former represents current systems that are still mostly based on fossil and biomass combustion, and the latter an identified technology option to replace fossil fuels in the traffic sector.

Optimization and process modelling are employed in the analysis. District heat networks are investigated with optimization methods; the district heat network energy storage capabilities are addressed with economic optimization, and the inclusion of sustainability metrics in the design is evaluated with multicriteria optimization. Microalgal biofuel and bioproduct generation are investigated in integrated contexts with process modelling.

The results indicate that district heat system flexibility can be increased by letting the district heat supply temperature vary within given boundaries. This will reduce heat generation costs and facilitate increased variable renewable energy integration. Sustainability metrics can be included in the district heat supply design, to direct the heat supply into a more sustainable direction at the least possible cost.

The energy returns of various microalgal biofuel generation alternatives are compared with each other. Lipid extraction with algal residue utilization is identified as the likely best alternative. High-solids supercritical water gasification offers high energy returns, but the technology is still under development. A multi-product mill concept is reviewed, where lipids, fertilizer and methane are generated from waste activated sludge, ash and flue gas inputs, with microalgae cultivation in the process. This concept appears technically feasible. The results of this dissertation may be employed in a more efficient and environmentally sound district heat system design and operation.

The results also increase the understanding of microalgal biofuel and bioproduct concepts and help to direct further research efforts in enhancing the production economics.

Keywords district heat, biorefinery, optimization, modelling, microalgae, sustainability

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Tiivistelmä

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Tekijä
Mikko Kouhia

Väitöskirjan nimi
Ratkaisuja kestäviin energiajärjestelmiin: analyysejä kaukolämmön optimoinnista ja mikroleviä hyödyntävistä biojalostamoista

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Tiivistelmä

Energiajärjestelmät ovat murroksessa, kun fossiilisten polttoaineiden käyttöä vähennetään ja vaihtelevan uusiutuvan energian määrä lisääntyy sähköverkoissa. Yhteiskunnan energiahuollon ympäristövaikutukset ovat suuret, ja siksi nykyisten ja suunniteltujen järjestelmien kestävyyteen tulee kiinnittää huomiota.

Väitöskirjassa tarkastellaan mahdollisia teknologiaratkaisuja lyhyellä ja pitkällä aikavälillä. Kaukolämmön tuotannon optimointi ja mikroleviin perustuvat biojalostamot on valittu väitöskirjassa tapaustutkimusten kohteeksi. Kaukolämmön tuotanto edustaa nykyjärjestelmää, joka on edelleen vahvasti sidoksissa fossiilisten ja biopolttoaineiden polttamiseen; levistä jalostetut polttoaineet on tunnistettu mahdollisuudeksi korvata fossiilisia liikennepolttoaineita uusiutuvasti.

Tutkimus perustuu optimointiin ja prosessimallinnukseen. Kaukolämpöverkkoja tutkitaan erilaisilla optimointimenetelmillä: verkoston energianvarastointikykyä tutkitaan lyhyen aikavälin taloudellisella optimoinnilla, kun taas kestävyyskriteerien sisällyttämistä verkon lämpölaitosten rakentamispäätöksiin tutkitaan monimuuttujaoptimoinnilla. Mikroleviin perustuvia integroituja polttoaineiden ja biotuotteiden tuotantolaitoksia tutkitaan prosessimallinnuksen avulla.

Väitöskirjan tulokset osoittavat, että kaukolämmön tuotannon joustavuutta voidaan lisätä antamalla verkoston syöttöveden lämpötilan vaihdella vapaasti annettujen parametrien rajoissa. Joustavuuden hyödyntäminen alentaa lämmöntuotantokustannuksia ja mahdollistaa vaihtevien energiantuotantomuotojen integrointia järjestelmään enenevässä määrin. Väitöskirjassa osoitetaan, että kestävän kehityksen mittareita voidaan sisällyttää kaukolämpöverkoston suunnitteluun monimuuttujaoptimoinnin menetelmiä käyttämällä. Näin tekemällä on mahdollista parantaa järjestelmän kestävyttä alhaisimmin mahdollisin kustannuksin.

Tutkimuksessa vertaillaan erilaisia mikroleviin perustuvia polttoaineiden tuotantoketjuja perustuen ketjujen energiansaantoihin. Levien rasvahappojen erotus ja rasvahapoista erotetun biomassan jatkokäyttö tunnistetaan mahdollisesti parhaaksi vaihtoehdoksi. Ylikriittisessä vedessä kaasuttaminen korkean kuiva-ainepitoisuuden vallitessa tuottaa parhaimman energiansaannon, mutta tekniikka on vielä kehitysasteella vaihtoehtoihin verrattuna. Tutkimuksen viimeisessä osassa tarkastellaan integroitua leväbiojalostamoa, jossa rasvahappoja, lannoitetta ja metaania tuotetaan jätelietettä, tuhkaa ja savukaasuja hyödyntämällä. Tämä tuotantokonsepti näyttäytyy teknisesti mahdollisena.

Väitöskirjan tuloksia voi käyttää aiempaa tehokkaampien ja ympäristölle kestävämpien kaukolämpöjärjestelmien suunnittelussa ja ajossa. Tulokset myös lisäävät ymmärrystä mikroleviin perustuvista biopolttoaine- ja biotuotekonsepteista ja auttavat kohdentamaan tutkimusta tuotannon taloudellisuuden parantamiseksi.

Avainsanat kaukolämpö, biojalostamo, optimointi, mallinnus, mikrolevät, kestävyys

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Contents

List of publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Mikko Kouhia, Timo Laukkanen, Henrik Holmberg and Pekka Ahtila. District heat network as a short-term energy storage. *Energy*, volume 177, pages 293–303, April 2019.

II Mikko Kouhia, Timo Laukkanen, Henrik Holmberg and Pekka Ahtila. Evaluation of design objectives in district heating system design. *Energy*, volume 167, pages 369–378, January 2019.

III Mikko Kouhia, Henrik Holmberg, Matti Sonck and Pekka Ahtila. Energy analysis of algae-to-biofuel production chains integrated with a combined heat and power plant. *International Journal of Sustainable Engineering*, volume 12, no. 4, pages 281–290, November 2018.

IV Mikko Kouhia, Henrik Holmberg and Pekka Ahtila. Microalgae-utilizing biorefinery concept for pulp and paper industry: Converting secondary streams into value-added products. *Algal Research*, volume 10, pages 41–47, July 2015.

Author's contribution

Publication I: "District heat network as a short-term energy storage"

Mikko Kouhia is the primary author of the publication. The concept of the paper was planned by Kouhia and Ahtila. Kouhia developed the optimization model, analyzed the results and wrote the manuscript. Laukkanen provided advise on modelling. Laukkanen, Holmberg and Ahtila commented on the manuscript.

Publication II: "Evaluation of design objectives in district heating system design"

Mikko Kouhia is the primary author of the publication. Laukkanen provided an initial optimization model, which was improved and developed by Kouhia. Kouhia analyzed the results. Laukkanen wrote the first version of the introduction section, which was edited by Kouhia. Kouhia wrote other parts of the manuscript. Laukkanen, Holmberg and Ahtila provided advise and commented on the manuscript.

Publication III: "Energy analysis of algae-to-biofuel production chains integrated with a combined heat and power plant"

Mikko Kouhia is the primary author of the publication. Selection of the product pathways was done by Sonck and Kouhia. Kouhia developed the calculation model, analyzed the results and wrote the manuscript. Holmberg and Ahtila provided advise and commented on the manuscript.

Publication IV: "Microalgae-utilizing biorefinery concept for pulp and paper industry: Converting secondary streams into value-added products"

Mikko Kouhia is the primary author of the publication. Kouhia developed the calculation model, analyzed the results and wrote the manuscript. Holmberg and Ahtila provided advise and commented on the manuscript.

Abbreviations

CHP combined heat and power

DH district heat

EROEI energy return on energy input

GE gas engine

HOB heat-only boiler

HP heat pump

MILP mixed-integer linear programming

NLP nonlinear programming

PBR photobioreactor

PEF primary energy factor

SCWG supercritical water gasification

1. Introduction

1.1 Background

The energy systems are in transition: combustion-based processes in electricity generation, district heat provision and traffic face increasing requirements of sustainability, including climate and carbon neutrality. The scale of required change is large: for example in Finland, 49 % of district heat in 2017 was provided from fossil fuel combustion and 37 % from biomass combustion (Energiateollisuus ry, 2018), and the share of renewable energy in transport was only 8.4 % in 2016 (Eurostat, 2018). There is a growing pressure to reduce fossil fuel consumption and transition towards a more sustainable energy system.

Sustainability is most often grouped into three domains: environmental, economic and social sustainability. In the energy sector, the environmental sustainability problems include greenhouse gas emissions, impact on biodiversity, toxic emissions and hazardous waste. In this dissertation, energy systems are viewed from the two first sustainability aspects: how can the environmental sustainability of energy provision be increased, while taking into account economic criteria. Addressed solutions in this dissertation are mostly concerning fossil fuel replacement in short-term optimization and in the long term with systemic changes.

Energy sector transition implies increased use of variable renewable energy sources, such as wind and solar power. These mostly replace marginal electricity generation in the electricity grid, which most often is coal or natural gas (Olkkonen and Syri, 2016). The consumption of electricity in the heating sector is also currently increasing, as the number of heat pumps increases both in centralized and private heat provision solutions. Growing variability in electricity generation and increasing electricity demand imply that the demand for power balancing and energy storage solutions is on the rise. Energy storage systems can aid in balancing energy consumption and demand, thus reducing price variation, and enabling an increased amount of variable renewable energy in the system. Both energy system sustainability and price volatility are concerns that need to be addressed in energy system operation and development.

District heat may provide some balancing for the electricity system: depending on electricity price, the district heat load might be met with combined heat and power generation, producing electricity into the grid, or power-to-heat technologies, consuming electricity from the grid. The heat demand may also be shifted by employing the thermal inertia of the network and additional heat storages, thereby dispatching generation at the most favourable conditions. Described active regulation may be employed in balancing peaks in district heat consumption, and it has potential in cost saving and variable renewable energy integration.

In prior studies, the application of power-to-heat technologies has been considered to benefit variable renewable energy integration (Bloess et al., 2018; Kirkerud et al., 2017; Mathiesen and Lund, 2009). Heat pumps and thermal storages have also been identified to add flexibility to CHP plant operation, and the investment is often found profitable (Lund and Münster, 2006; Salpakari et al., 2016; Hast et al., 2017; Chen et al., 2015). The DH network heat capacity utilization has been included in some latest optimization studies (Zheng et al., 2018; Gu et al., 2017; Huang et al., 2018; Z. Li et al., 2016; J. Li et al., 2016). It has been found beneficial, but the analysis on an annual scale has not been presented.

Longer-term sustainability decisions are made in energy system design. The effect of district heat plant investment will span decades to the future, and therefore it is important to consider the district heat system sustainability during its design phase. Optimization methods may be employed in systems design, to produce information on the best solutions on the given criteria. Metrics such as primary energy consumption, carbon dioxide emissions, exergy efficiency and societal costs have already been employed in multicriteria energy system optimization (e.g. Østergaard, 2009; Buoro et al., 2013; Ahmadi et al., 2014). Primary exergy analysis — a combination of primary energy analysis and exergy analysis — has been suggested, to include the external effects in that are not typically included in exergy analysis (Laukkanen et al., 2016).

In order to replace fossil fuels in the traffic sector, various biofuels have emerged and new solutions are under investigation. Some, such as bioethanol from waste and biodiesel from palm oil, are already a part of the fuel supply as of now. Wood-based fuels are on the rise, and microalgae-based fuels have been proposed as a future option.

Microalgae cultivation for biomass generation has been studied due to their rapid growth rate, low land requirement and ability to consume non-potable water (Mata et al., 2010). Products such as biofuels and high-value extracts can be produced from microalgae (Koller et al., 2014), depending on the species. Biofuel generation has received significant attention during the last decades, but it has been also pointed out that biofuel production from algae is not yet commercially feasible (Barsanti and Gualtieri, 2018; Kenny and Flynn, 2017;

Beilen, 2010; Davis et al., 2011); current microalgal biotechnology companies focus on the high-value extractives (Barsanti and Gualtieri, 2018).

Process integration typically introduces a potential of cost reduction via e.g. shared sites, logistics and possibilities of heat and material integration. In microalgal biorefineries, integration concepts such as CO_2 sequestration from flue gases, nutrient recycling, and co-producing multiple energy products or higher value extractives are considered to be elemental to production economics (Su et al., 2017; Chisti, 2013). Despite the acknowledgement of integration necessity, most calculation studies are made for stand-alone plants, and not differentiating heat input levels or returns on electricity input.

1.2 Objectives and scope

The objective of this thesis is to explore possible solutions for enhancing the sustainability of biomass-based energy systems, while at the same time paying attention to energy, material, and/or cost efficiency. There are a plethora of options that might be considered, but in this thesis, two case frameworks are selected for further analysis: district heat optimization and microalgal biorefineries.

District heat represents an existing field where the majority of primary energy consumption is fossil or biomass-based. Here, short-term incremental benefits may be obtained with optimization methods. As the combined district heat consumption is large, even small improvements are of significant importance. Larger sustainability achievements might also be reached if the sustainability targets are increasingly taken into account in the system design.

On the other hand, microalgal biorefineries represent longer-term development possibilities in sustainable biofuel and material generation. By investigating the possible options, more information is acquired on the possibilities, restrictions and positioning in the future energy system.

The problem setting is partitioned into the following research questions, which are addressed in the mentioned publications:

1. How can the production economics of a district heat system be enhanced, if its energy storage capability is actively utilized via supply temperature optimization? (Publication I)

2. What are the effects of including sustainability metrics in district heat system plant selection, and how do different design objectives affect the optimal configuration? (Publication II)

3. Which microalgae-based biofuel process chains are energetically most feasible in an integrated context? (Publication III)

4. What is the technical potential of an integrated microalgal biorefinery concept combining methane, lipid and fertilizer generation? (Publication IV)

Each research question defines an area of research that has not yet been fully charted. The novelty of this research lies in the analysis of long-term effects and affecting factors in Publication I, analysis of supplementing design criteria and the trade-offs in Publication II, comparative analysis of process alternatives in an integrated context in Publication III, and presentation and validation of a novel process concept in Publication IV.

The system boundary in all studies is set at the district heat network or plant level. In some evaluations, when effects on global CO_2 emission or primary energy/exergy consumption are considered, the boundary is extended to include relevant parts of the surrounding energy system. Input values, such as commodity prices, are considered exogenous variables, thus they are not affected by the system under study.

1.3 Research process and dissertation structure

The research has been conducted in Aalto University during 2012–2019. Each publication is based on a separate study, which reflects the research process: Research for Publication IV is conducted in BioRefineTech research programme 2013–2014 and extends the author's Master's thesis. Publication III has its origins in commissioned work for Fortum Corporation in 2014, which was first presented in 23rd European Biomass Conference & Exhibition in 2015, and then extended into a journal publication. Research for Publication II is conducted in Efficient Energy Use programme 2016–2017, extending to 2018, and finally Publication I as an independent piece of research in 2018–2019 in the doctoral programme of Aalto University School of Engineering.

Table 1.1 illustrates the common methodology and topics in the publications. All publications are based on process modelling. Linear regression models are made for each research problem, with emphasis on optimization in Publications I and II. Process integration is elemental in Publications III and IV: the problem setting is dependent on CO_2, nutrients and heat provided by the surrounding plant. The biorefineries in Publications III and IV are integrated with a CHP plant and a pulp and paper mill, but the analyses are extendable to systems that provide the required interfaces to the microalgal biorefinery. The data for the case studies have mainly been collected from published scientific sources, with some information provided by the project partners.

Table 1.1. Employed methodology and common topics in publications. Symbol '●' indicates that the subject is elemental to the publication, '○' indicates that the subject is discussed.

Publication	I	II	III	IV
Process modelling	●	●	●	●
Optimization	●	●		
Process integration		○	●	●
District heat	●	●	○	
Combined heat and power	●	●	○	
Microalgae			●	●
Biofuels		○	●	●
CO_2 emissions		●	○	○

2. Methods

In this chapter, the main methods that are employed in individual publications are reviewed. More detailed descriptions of calculations are presented in the respective publications.

2.1 District heat supply optimization

In Publication I, a district heat (DH) control method is examined where the DH network heat storage capability is utilized by allowing the DH supply temperature to vary freely. The optimization control method is formulated as

$$\min C = \min \left(\sum_{t,u} C_{\text{variable},t,u} + \sum_{u} C_{\text{fixed},u} + \sum_{t} C_{\text{pumping},t} \right) , \qquad (2.1)$$

where C are total system costs and its components. Cost components are indexed with hourly time resolution t, and u stands for available units. Start-up and shut-down costs of plants are included in the variable costs, variable costs from possible idling of plants has been excluded.

The optimization control method is compared to a reference control method, where district heat supply temperature is determined as a function of ambient temperature. The optimization follows Equation (2.1) for both optimization and reference control methods, with added temperature constraints for the latter. As all other methodology is the same, a comparison can be made on the effects of the active temperature regulation.

District heat supply and return temperatures are linked to heat generation and consumption by approximating supply and return pipelines as energy buffers, as proposed by Lesko and Bujalski (2017):

$$T_{\text{S},t} = T_{\text{S},t-\Delta t} + \frac{\dot{m}_t \Delta t}{m_{\text{DHN,S}}} \left(T'_{\text{S},t} - T_{\text{S},t-\Delta t} \right) - k_{\text{X}} (T_{\text{S},t} - T_{\text{A},t}) \Delta t \qquad (2.2)$$

$$T_{\text{R},t} = T_{\text{R},t-\Delta t} + \frac{\dot{m}_t \Delta t}{m_{\text{DHN,R}}} \left(T'_{\text{R},t} - T_{\text{R},t-\Delta t} \right) - k_{\text{X}} (T_{\text{R},t} - T_{\text{A},t}) \Delta t \,. \qquad (2.3)$$

Here, the average supply temperature in the network T_{S} at time t is calculated from the average supply temperature at previous time step $t - \Delta t$, the supply temperature at plants T'_{S} and the ratio of supply water mass flow rate $\dot{m}_t$ to total mass of water in the supply pipeline $m_{\mathrm{DHN,S}}$, and heat loss to environment at ambient temperature T_{A} with linear loss coefficient k_{X}. Similar conditions apply for average return water temperature T_{R} and temperature of return water at the consumers T'_{R}, the mass of water in return pipes $m_{\mathrm{DHN,R}}$ being the same as in supply pipelines.

Modelling the district heat network is a balance between calculating the exact network state and computational complexity. The temperature model in Equations (2.2) and (2.3) simplifies the network to an extreme but allows for a quick approximation. In addition, with this method, detailed knowledge of network topology is not required to perform an indicative economic assessment. On the other extreme, a full network flow model such as in studies by Zheng et al. (2018), Gu et al. (2017), Huang et al. (2018), J. Li et al. (2016) and Z. Li et al. (2016) is able to reproduce the network state exactly, but the calculation for a long time span is intensive. A simpler model is selected for this study, as it should provide enough precision for conclusions from the heat source point of view (Lesko and Bujalski, 2017) and a less complex model allows rapid sensitivity evaluations.

The optimization problem is solved with a sliding time window method, extending the method by Fang and Lahdelma (2016). Figure 2.1 depicts the algorithm: a ten-day schedule is first made for plant start-ups and shutdowns with a mixed-integer linear programming (MILP) model, where district heat temperatures are excluded. The scheduling for the first 48 hours is employed in a nonlinear programming (NLP) model, where DH network temperatures and the storage effect are then included. Then, the first 24 hours are extracted, time windows shifted 24 hours forward, and the process is repeated. Different solution windows were tested: extending the NLP model horizon past 48 hours did not affect the results. 10 days was selected as the MILP model horizon length to accommodate longer-term decisions such as CHP plant start-ups and shut-downs, but when forecasts would be employed as model inputs, credible weather forecasts could be still obtained.

The sliding time window method enables the division of annual runtime examination to smaller optimization blocks. Decisions on a longer-term i.e. CHP plant shutdowns are solved first and then the network temperatures and exact plant operation are solved on a shorter time span. This reflects the operating decisions that are made in system operation, and the separation of MILP and NLP models reduces the computational difficulty. However, the sliding window implementation may lead to only locally optimal solutions, as the plant commitment is fixed before storage optimization and the possibility of runtime extension from storage utilization is not factored in.

Storage optimization benefits under various circumstances are the key focus area in this study. Therefore sensitivity analyses to various key parameters are performed, such as maximum allowed temperature gradient, CHP plant para-

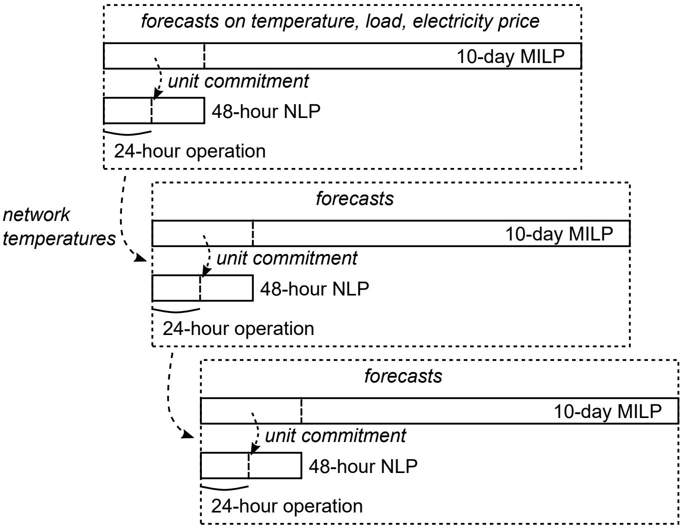

Figure 2.1. Sliding time window optimization method for district heat system operation, depicted in the time domain. Modified from Publication I Figure 3.

meters and electricity prices. In addition, the effects of heat pump installation are studied in detail.

2.2 District heat plant multicriteria optimization

In Publication II, the inclusion of sustainability metrics in district heat system design is addressed via individual and multiobjective optimization. The district heat consumption is simplified by dividing the load duration curve into periods that have constant heat demand. Figure 2.2 displays the simplification into periods: in Publication II, seven periods are selected to represent the heat consumption curve. Five different objectives are investigated:

$$\min f_1 = -\left(\sum_{i,p} C_{\mathrm{sales},i,p} - \sum_{i,p} C_{\mathrm{input},i,p} - \sum_{i,p} C_{\mathrm{CO_2},i,p} - \sum_{i} C_{\mathrm{invest},i}\right) \tag{2.4}$$

$$\min f_2 = \sum_{i,p} \left(\dot{B}_{\mathrm{in},i,p} - \dot{B}_{\mathrm{out},i,p}\right) t_p \tag{2.5}$$

$$\min f_3 = \sum_{i,p} \left(m_{\mathrm{CO_2,direct},i,p} + m_{\mathrm{CO_2,indirect},i,p} - \left(P_{\mathrm{out},i,p} - P_{\mathrm{in},i,p}\right) t_p \, g_{\mathrm{m}}\right) \tag{2.6}$$

$$\min f_4 = \frac{\sum_{i,p} E_{\mathrm{pri},i,p}}{\sum_{i,p} Q_{\mathrm{DH},p} \, t_p} \tag{2.7}$$

$$\min f_5 = \frac{\sum_{i,p} B_{\mathrm{pri},i,p}}{\sum_{i,p} \dot{B}_{\mathrm{DH},p} \, t_p} \, . \tag{2.8}$$

In these equations, index p is period index and i district heat provision technology; t_p is the duration of a given period.

The first objective function f_1 maximizes profits by deducting feedstock, carbon dioxide and annualized investment costs C from product sale income. Objective f_2 minimizes combined exergy losses $\dot{B}$ in all heat providing units. Third objective f_3 minimizes fossil carbon dioxide emissions in the system: direct and indirect emissions from district heat provision are calculated, and the net electricity output P to the surrounding network is replacing marginal electricity consumption that has emission intensity g_{m}. Final two objectives f_4 and f_5 are similar in form, f_4 for minimizing district heat primary energy factor and f_5 for district primary exergy (PeXa) factor. Here, numerators E_{pri} and B_{pri} stand for primary energy and exergy consumption, and denominators are total heat and exergy consumption in district heat provision, respectively.

The objective functions are selected to represent business as usual (profit), popular climate metrics (CO_2 emissions), metrics employed in plant efficiency analysis (exergy losses) and global metrics (primary energy/exergy consumption). District heat primary exergy (PeXa) factor is a novel metric proposed by Laukkanen et al. (2016); the usefulness of primary exergy in energy system analysis is also under evaluation in Publication II.

Individual objectives are combined for multicriteria optimization with compromise programming method (see e.g. Stanley Lee and R. J. Li, 1993). In this method, additional objective function distance variable δ is minimized:

$$\min L_{\infty} = \delta \, , \tag{2.9}$$

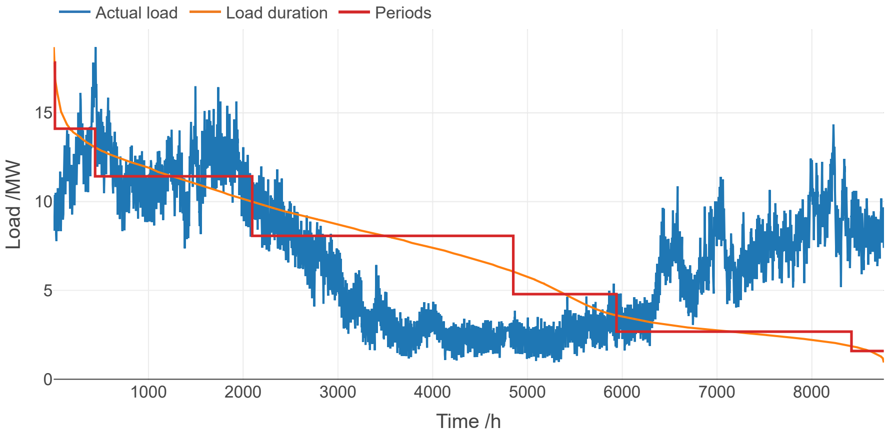

Figure 2.2. Division of heat load into periods. Modified from Publication II Figure 1.

where objective functions f_k constrain distance δ:

$$w_k \frac{f_k - f_{k,\mathrm{min}}}{f_{k,\mathrm{max}} - f_{k,\mathrm{min}}} \leq \delta \quad \forall k \, . \tag{2.10}$$

In Equation (2.10), the objective function minimum and maximum values $f_{k,\mathrm{min}}$ and $f_{k,\mathrm{max}}$ are calculated from independent minimization runs for all f_k. The objective weighing factors w_k are varied so, that weights $w_k \in [0,1]$ and $\sum_k w_k = 1$. This optimization produces a set of Pareto-optimal solutions, in which no objective can be increased without harming the others. The solutions all represent optimal configurations, given the implied preferences between the design objectives.

A mixed integer linear problem (MILP) is formed for a case study district heat network. In the problem setting, there are no existing plants and different district heat units can be installed: gas engines, biomass combined heat and power (CHP) plants and heat only boilers (HOBs), gas HOBs, heat pumps and a synthetic natural gas generation plant can be built. Figure 2.3 displays the plant superstructure employed in the problem. The results thus communicate that which plants will be commenced with different design criteria, and how the criteria selection and weighting will affect the outcome measured on other metrics.

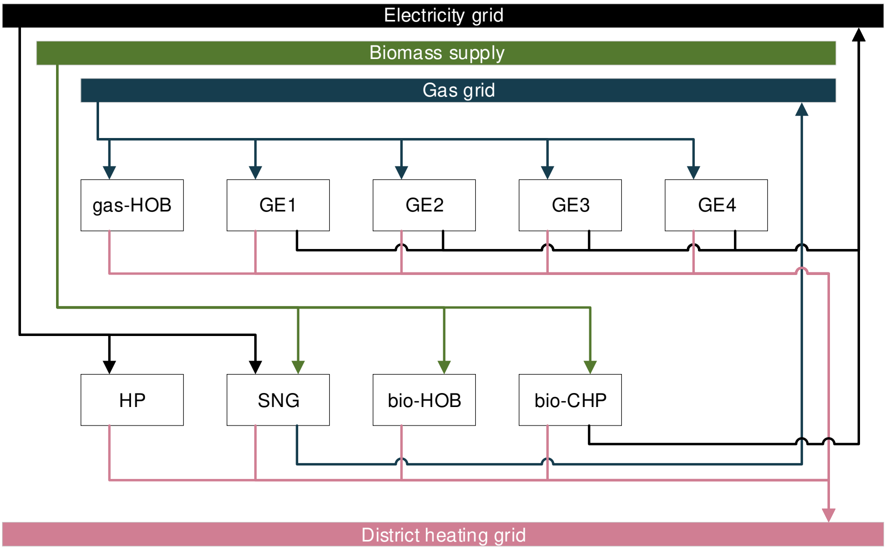

Figure 2.3. The superstructure of possible plants in the studied energy system. HOB stands for heat-only boiler, GE gas engine, HP heat pump, CHP combined heat and power, and SNG synthetic natural gas. Modified from Publication II Figure 2.

2.3 Microalgal biorefinery modelling

In Publications III and IV, microalgal biorefineries are investigated with mass and energy balances. Figures 2.4 and 2.5 display the considered configurations in the publications. In all systems, algae are cultivated, then dewatered to appropriate solids content for the post-processing pathway and then processed further. Selection of algal species is left outside the scope of the work: a general algae composition is assumed as the starting point.

Different cultivation methods are analyzed: in Publication III open ponds and photobioreactors are investigated, with or without the addition of artificial lighting. Here, a limited area is given for algal cultivation and thus growth rates are limiting annual product generation. In Publication IV, cultivation in photobioreactors is considered, and the reactors are dimensioned for peak algal productivity, thus using all available nutrient flow in the feedstock at peak growth. In both cases, annual output will vary based on algal growth rate, which again depends on the irradiance levels. Results of Publication III are calculated on annual average growth rates, whereas in Publication IV daily averages are employed and thus information on the production variance is acquired.

The process alternatives in Publication III (displayed in Figure 2.4) produce energy carriers that may be used as traffic fuels; combustion of algal biomass is calculated as a reference. The other options are biodiesel generation via lipid extraction, where the lipid-extracted algal residue is processed to either methane or ethanol; and thermal gasification of microalgae and synthesis of product gas to Fischer–Tropsch biodiesel or methane. Lipid extraction is currently the most investigated microalgal biofuel option, whereas supercritical water gasification

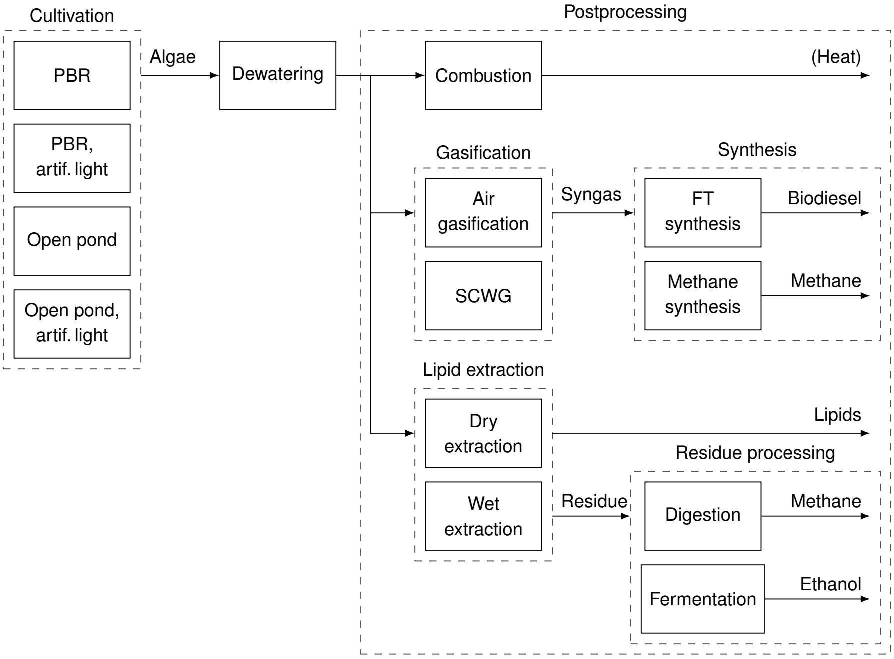

Figure 2.4. The superstructure of evaluated biorefinery processes in Publication III. Vertically stacked processes or pathways in dashed rectangles are considered as alternatives to each other.

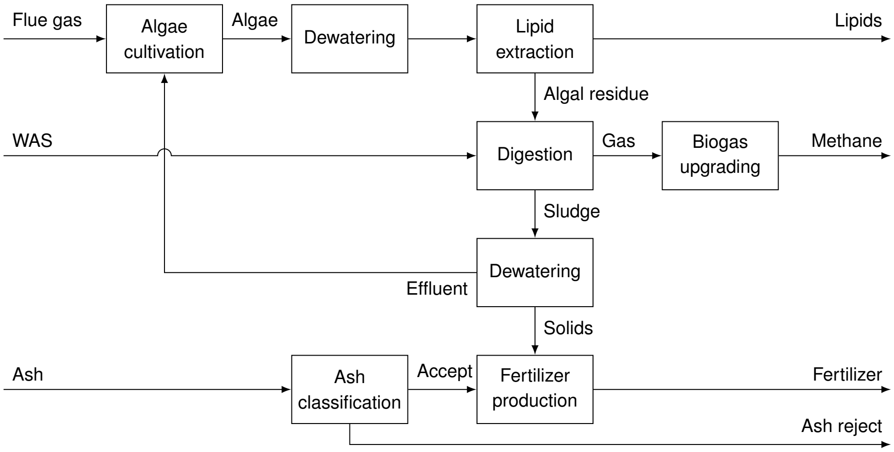

Figure 2.5. Evaluated biorefinery configuration in Publication IV: flue gas, waste activated sludge (WAS) and ash are consumed in lipid, methane and fertilizer production while employing algae in the conversion process. Modified from Publication IV Figure 1.

is identified as a possible technology option that is not yet on a commercial scale (Caputo et al., 2016). Input materials to algae cultivation are carbon dioxide from a municipal combined heat and power plant, and nutrients from municipal wastewater handling.

Process scheme in Publication IV (Figure 2.5) represents an integrated concept, where lipids, methane and fertilizer are produced from waste activated sludge, ash and flue gas, with microalgae cultivation inside in the process. All inputs are waste or secondary streams from a pulp and paper mill, and thus the mill potentially benefits from creating a utility to those streams — disposing of the sludge or ash at a landfill would for example imply costs that can be avoided.

Integration and generation of multiple products are elemental to the analyzed processes in both publications. Both systems include energy carriers as the bulk product; the biorefinery in Publication IV also includes ω-3 fatty acids as higher value co-products. Both systems can be generalized to other integrated contexts if the input materials are provided.

All process units are in mass and energy balance, thus

$$\sum \dot{m}_{\text{in}} - \sum \dot{m}_{\text{out}} = 0 \tag{2.11}$$

$$\sum Q_{\text{in}} - \sum Q_{\text{out}} = 0\,, \tag{2.12}$$

where $\dot{m}$ is mass flow rate and Q energy flow rate. For most units, a conversion rate or energy consumption is specified that is characteristic to the process in question. The employed values represent average values that are achievable with current technology — these parameters and their application are discussed in the respective publications. Lower bounds for sensitivity analysis in Publication III represent values that might be expected in near future. Gasification processes in Publication III are first modelled in Aspen software to acquire the specific productivities and energy consumption values, and these parameters are then employed in mass and energy balance calculations, conducted with Python code. Sensitivity to initial parameters is performed in both publications by varying the input values separately and recording the effect on the system.

3. Results

The results in this chapter are ordered in accordance to research questions 1–4 on page 17.

3.1 District heat network as an energy storage

In Publication I, a district heat (DH) control strategy is examined, where DH supply temperature is optimized for minimum operational costs. This control strategy actively utilizes the heat capacity of the network, thus employing its energy storage capability. Applying the optimization control method results in lower district heat generation costs than with the reference method, in all examined conditions. In the case study, approximately 2 % cost savings are achieved, without investments to new district heat generation units.

With the proposed optimization strategy, the network storage effect is dominantly employed to increase the operation of those plants that have the lowest variable costs. In the case study this results in the reduction of heat-only boiler operation and combined heat and power plant (CHP) condensing mode operation, while at the same time increasing full load operation of CHP, and heat pumps if they are present. Energy consumption in pumping is reduced, while heat losses are increased in comparison to the reference control method.

Largest benefit from the supply temperature optimization and heat capacity utilization arises when there is a large difference in DH generation costs between available plants. In Publication I case study, the CHP plant most often has lowest marginal generation costs, and thus supply temperature optimization leads to higher utilization of the CHP plant in comparison to the other units. Figure 3.1 displays where the cost savings of control method change originate on annual average: greatest benefits are received from increased CHP electricity sales and lower pumping costs.

Figure 3.2 displays the main effects of the optimization control scheme for a sample period in the case study. The district heat supply temperature increases when the heat input exceeds heat demand plus losses and reduces when the input is lower than the consumption and losses. Where the heat demand allows,

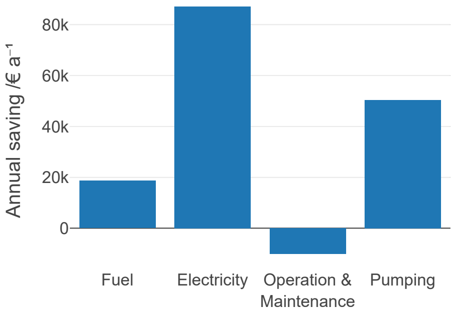

Figure 3.1. Annual benefits from supply temperature optimization: difference of economic outcomes between the optimization and reference control schemes in Publication I case study.

the CHP plant is operated near or at full load. The heat storage level of the network is increased to allow higher CHP production during low consumption and decreased to reduce heat-only boiler utilization at peak consumption hours. The district heat supply temperature is typically higher than the reference supply temperature, to enable flexibility actions.

The optimization control strategy and investment to a heat pump direct the district heat system operation towards a similar outcome: both reduce heat-only boiler operation and alter CHP operation under part load. Aforementioned actions are however not competing, but complementary to each other. Figure 3.3 displays the operation in a case study system with 20 MW heat pump included, for the same sample time period as in Figure 3.2. The main effect of the heat pump inclusion is in replacing heat generation from biomass heat only boilers, and replacement of CHP condensing mode operation during the summer. In addition, heat pumps are often employed to charge the network during low load and low electricity cost.

The optimization control method also has a positive effect on the analyzed system, if a heat pump is included. In comparison to the reference control method, the full load operation of both CHP and heat pump are increased in the case study. The heat pump benefits from low electricity prices, and therefore it can, for example, absorb variable renewable energy production peaks into the district heating network. The implementation of the optimization control scheme further allows the storage capability of the network to be utilized, and for example, the DH supply temperature increased above reference supply temperature curve at times of such variable renewable energy (VRE) absorbing actions. Sensitivity analysis in Publication I indicates that the optimization control method is especially useful in a system with both CHP and heat pumps, when electricity price volatility increases.

The general results and conclusions on the control scheme differences should be transferable to all district heat systems. The exact outcome and differences between reference and optimization control scheme are specific to each district

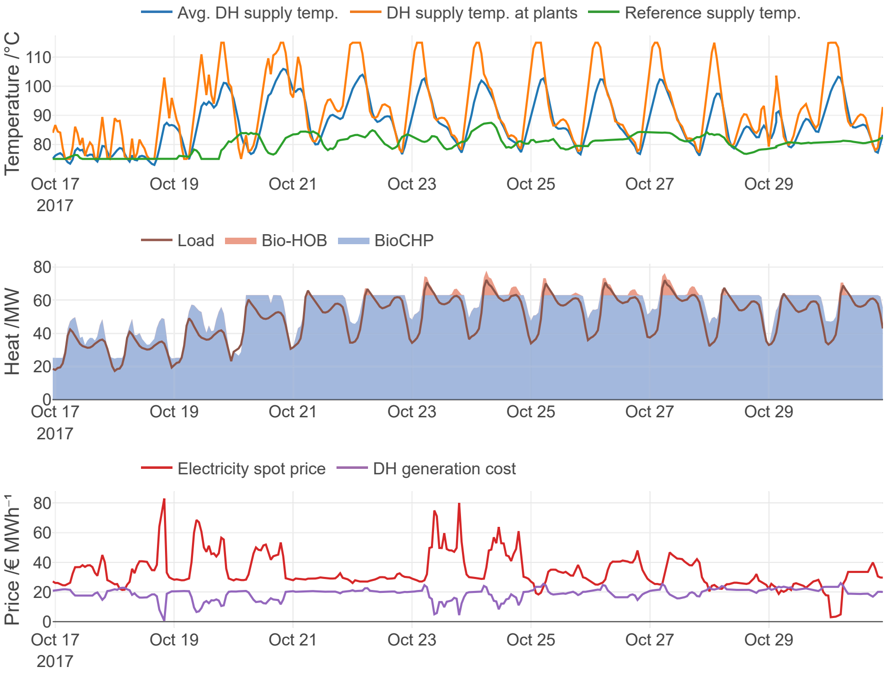

Figure 3.2. Operation of Publication I case study district heat network under optimization control scheme, for a sample period.

Figure 3.3. Operation of Publication I case study district heat network under optimization control scheme, for a sample period, with 20 MW installed heat pump capacity.

heat system, and they depend on the system characteristics, input parameters and available plants. As the model reduces the network into buffers, the exact implications on particular networks, such as minimum supply temperature at network locations, cannot be addressed. A full flow model of the district heat network is required to include those factors. The optimization methodology itself can be applied in any district heat system.

Based on the Publication I study, it can be concluded that the active utilization of district heat network energy storage capability results in price reduction over the traditional district heat temperature control method. The optimization method employs the added flexibility to increase operational hours of those plants, whose variable costs are the lowest. Greatest cost savings are to be expected within systems that have a large generation cost difference between district heat supply units. With the improved storage utilization, power-to-heat technologies can help absorb variable renewable energy in the DH network more effectively than with the reference method.

3.2 Sustainability metrics in district heat system design

In Publication II, a district heat network is optimized for five different design objectives and combinations of those. Optimizing for different design objectives yields diverse results: Table 3.1 displays the solutions that are recorded in the case study individual optimizations, and a summary of their benefits and disadvantages.

The business-as-usual design case, optimizing for maximum profit, results in a combination of a heat pump and a gas-fired heat-only boiler (HOB). Under given economic circumstances, for example heat and power co-generation is not economically feasible — the electricity price is low and the investment cost of such a small biomass combined heat and power (CHP) plant is too high. As examined in Publication II, optimizing for maximum profit is sensitive to commodity price variation and relatively small changes in electricity and biomass price levels may change the optimal plant configuration. Thus, there is always uncertainty regarding future prices and possible policy changes that should somehow be taken into account in a responsible investment decision.

Minimizing global CO_2 emissions in the case study results in a district heat system with biomass-fired CHP plant and heat only boiler. This outcome is a result of the common assumption that biomass usage is CO_2 neutral, and of produced electricity replacing market electricity that has higher CO_2 emissions. The result has a negative annual profit, but lower primary energy consumption than in the case when optimizing for maximum profit. Designing a district heat system to only minimize global carbon dioxide emissions is effective in the goal, but the CO_2 removal costs at this extreme are high. In addition, the assumption on biomass CO_2 neutrality is not always valid, and in the design of

Table 3.1. Optimal district heat provision systems in Publication II, optimizing only one design objective in a case study. More detailed report of the case study outcomes is presented in Publication II Table 4.

Objective	Heat supply	Benefits / disadvantages
max. profit	heat pump, gas-HOB	+ lowest cost – sensitive to price variation
min. fossil CO_2	bio-CHP, bio-HOB	+ lowest global CO_2 – sustainability of sourced biomass?
min. exergy losses	heat pump	+ low losses in the system – excludes global effects
min. primary energy / min. primary exergy	gas engines	+ minimal global consumption – sensitive to grid electricity PEF

a large biomass system, the indirect emissions and other environmental effects of biomass consumption should be considered very carefully.

Minimizing exergy losses in the case study results in a system where heat is provided with heat pumps only. Coincidentally, the optimization outcome also has a positive annual profit. Despite the goal of minimizing exergy losses, this system has high primary energy and exergy consumption. The conflict is due to system boundary setting: exergy loss minimization within the DH network does not take external effects into account. The heat pumps are able to generate district heat with lower exergy losses in comparison to other alternatives, but the generation of imported electricity increases the global primary energy and exergy consumption. Due to this exclusion of systemic effects, minimizing exergy losses in district heat provision cannot be considered a satisfactory criterion for system sustainability.

Minimizing district heat primary energy or exergy factors share the same outcome in the case study: heat is provided with gas engines, and the generated electricity is exported. This electricity replaces marginal electricity generation in the electricity grid, with less primary energy/exergy consumption. There is little variation between the two design objectives in the case study because the energy and exergy content of the commodities are very similar. Differences can be expected to arise if a system has low exergy content inputs. The two metrics can be considered a valid system sustainability indicator, but they are sensitive to primary energy/exergy factors (PEF) in the electricity system due to the allocation method of electricity consumption or production. The primary energy and exergy consumption in the case study is significantly lower with given design objectives than when optimizing for minimal exergy losses. Employing primary energy and exergy factors in the design includes systemic effects by default, and therefore the metrics can be considered to represent global sustainability better than aiming to minimize local exergy losses.

The different design objectives are combined in Publication II with multicriteria optimization. The results indicate that designing for minimum district heat primary energy factor or primary exergy factor produce highly correlating results, thus aiming at similar solutions. Hence, in a system resembling the case study, it is not sensible to have both metrics as design objectives at the same time — they would directing towards the same solution. The multi-objective optimization also displays that the minimization of exergy losses and district heat primary exergy factor are conflicting objectives, having a high negative correlation in the results.

Figure 3.4 displays so-called Pareto-optimal solutions to the multicriteria optimization problem: all points represent a solution where one single objective cannot be improved without weakening the others. There it is visible, how the generation unit combinations obtained by individual objective optimization are rarely repeated when other design factors are weighed in. On the contrary, unit combinations obtained by weighted design criteria are more flexible and found optimal under several other design conditions. It can be also identified that profit maximization, CO_2 minimization and primary energy factor minimization are all conflicting objectives with each other.

When balancing profits to CO_2 emissions, such solutions are preferred where biomass CHP, biomass HOB, and possibly gas HOB and heat pump are employed. Similar systems are suggested when balancing profits to primary energy factor: combinations of CHP, gas HOB, heat pump and gas engines are prominent. Based on case study analysis, combinations of aforementioned units adapt to support most evaluated design objectives — installed capacity of the units varying depending on employed objective function weights. When profit maximization has a major role in the investment decision and other criteria have minor weights, CHP typically takes care of the base load and peak power is provided by HOBs, with possible heat pump addition.

The qualitative evaluation of design objectives in Publication II should be transferable to other district heat systems whose plant output can be regulated. The modelling of the study excludes the effect of variable electricity production forms, such as wind and solar power generation. The modelling by load duration curve also excludes time-variability of parameters such as hourly variation in prices and marginal electricity generation technology in the system. The case-specific results — optimal plant configuration and numeric outcome — are dependent on the initial assumptions, load duration curve and its simplification to periods. The publication examines such an installation, where all units are designed at the same time. The district heat plants are more typically planned one at a time when the district heat network is expanded or an existing plant is replaced. The evaluation methodology may be extended to these situations, either to set global targets or by fixing earlier plants and then finding the best-supplementing units according to selected criteria. In addition, the trade-offs between different sustainability metrics may be analyzed with optimization models such as the one presented in the dissertation.

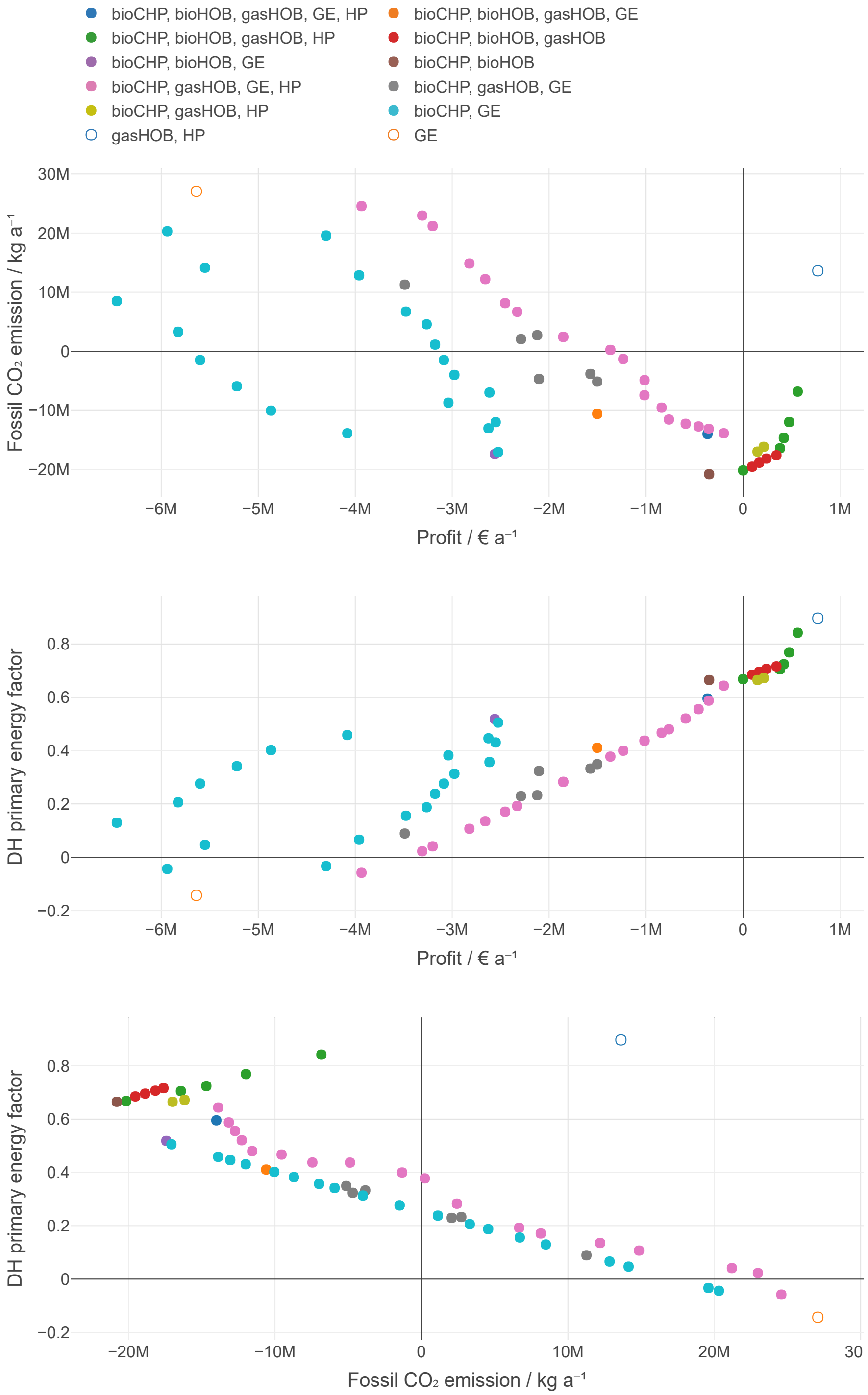

Figure 3.4. Pareto-efficient solutions from multi-objective optimization, grouped by district heat generation unit combination in each solution. Displayed are solutions that have weights on profit, CO_2 emissions and primary energy consumption — see Publication II Figure 5 for solutions having weight on local exergy loss minimization or primary exergy factor minimization. 10 % step in objective function weights are employed in this figure.

Based on the Publication II study, it can be concluded that multicriteria optimization offers a way to incorporate sustainability metrics in district heat system plant selection. Optimizing for a single metric can provide target values or other information that can be employed in network development, but the systems may be expensive or otherwise unreasonable. However, including the sustainability metrics as minor weights to profit optimization results in flexible systems that direct towards the sustainability targets at minimum cost. Based on the study, a combination of profit maximization, global CO_2 emission minimization and district heat primary energy/exergy factor minimization can result in district heat systems that are still economical but internalize environmental effects to some extent. Primary exergy or PeXa method (Laukkanen et al., 2016) appears a valid analysis tool: because of externality inclusion, it is more suitable to system design in comparison to the sum of exergy losses in processes. However, when energy and exergy content of input streams of the analyzed system are close to each other, the primary exergy analysis does not present benefits in comparison to primary energy analysis.

3.3 Energy analysis of microalgae-to-biofuel production chains

In Publication III, various microalgae-to-biofuel production pathways are analyzed in a context, where heat, CO_2 and nutrients are provided at a low cost from a combined heat and power plant and a waste water treatment plant located nearby. The energy outputs from analyzed post-processing pathways are displayed in Figure 3.5: energy outputs relative to algae input are somewhat similar to each other, lowest being 77 % of the algae higher heating value, 22 MJ/kg.

Most differences between process pathways arise in energy consumption in algae cultivation and post-processing. Figure 3.6 presents the total heat and electricity consumption for the investigated pathways, in open pond cultivation.

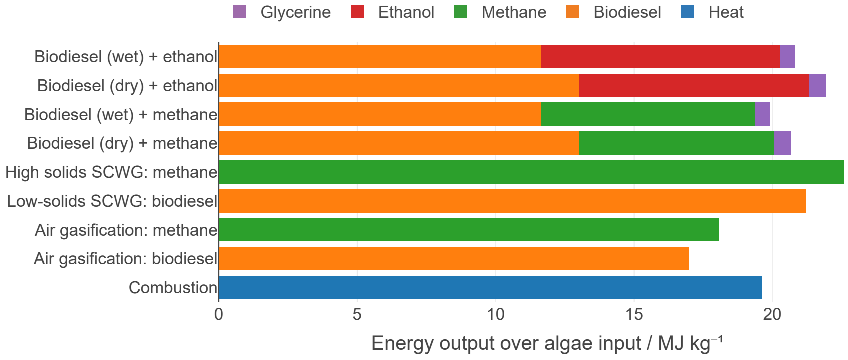

Figure 3.5. Energy output from different product pathways in Publication III. Modified from Publication III Figure 3.

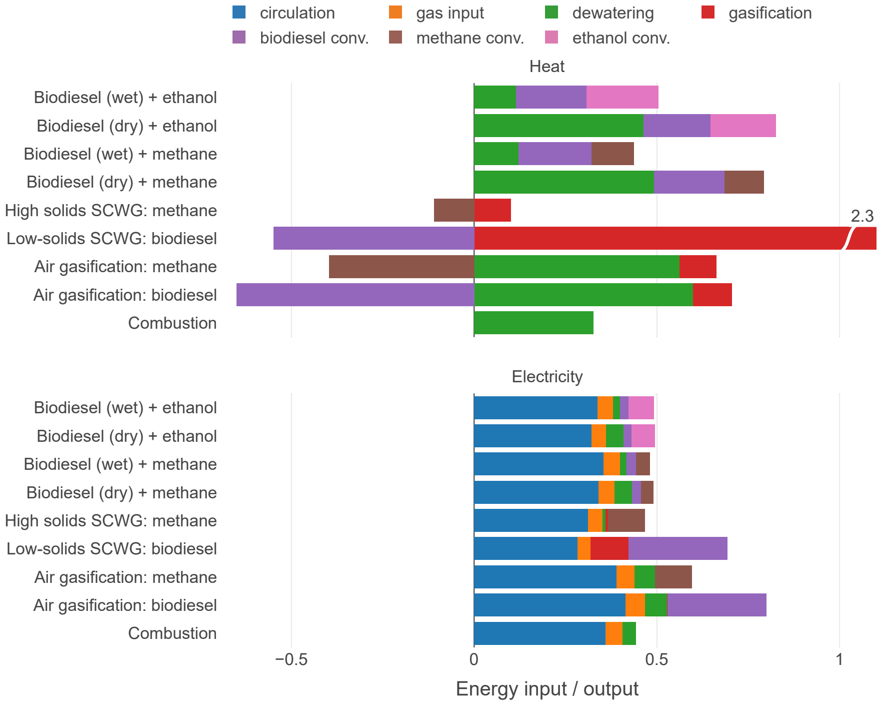

Figure 3.6. Heat and electricity consumption in different pathways, from open pond cultivation without artificial lighting. Negative heat consumption is heat generation in gas reforming reactions. Modified from Publication III Figure 5.

In most pathways, growth medium circulation in algae cultivation is the largest single electricity consumer, and algae drying accounts for most heat consumption — the heat consumption in drying can be more than 50 % of the energy in end products. This is in alignment with previous research, where these two steps are classified as major challenges in microalgal bioproduct commercialization (e.g. Milledge and Heaven, 2013).

The electricity consumption in cultivation depends on the cultivation method: results in Figure 3.6 are based on open pond cultivation, which is commonly studied and often employed in current cultivation plants. Sensitivity analysis in Publication III shows that the electricity requirement in cultivation is the most important parameter affecting the energy efficiency of the whole system in all process options, followed by algae areal growth rate. This highlights that regardless of the energy conversion pathway, algae cultivation method has the most importance to energy efficiency of production, and special attention is required to minimize electricity consumption in cultivation. Photobioreactors are also investigated as cultivation options, but the electricity consumption of photobioreactors in the study is significantly higher than in open ponds, and thus they are not preferred if energy carriers are produced. The possibility of increasing production with artificial lighting is also investigated, but it is not sensible in energy carrier production: only a few per cent of input electricity is

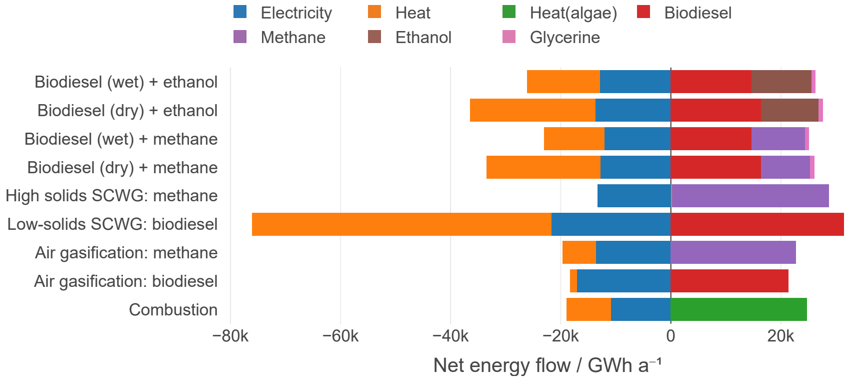

Figure 3.7. Energy balances for biofuel pathways in open pond cultivation. The heat flow is displayed as input/output separated for combustion, and as a net value for the other processes. Modified from Publication III Figure 6.

converted to algae chemical energy. The total energy consumption and energy balances in Figures 3.6 and 3.7 are thus reported only for the energetically most feasible case, with open pond cultivation in ambient conditions.

Large energy consumption, as exhibited by Figure 3.6, can be prohibitively costly. Therefore processes with high heat load should be avoided, or the heat should be of low cost. Heat requirement in dewatering depends mostly on the required moisture content before algae post-processing. The moisture content before post-processing is low for supercritical water gasification (SCWG) and wet lipid extraction, and thus little if any thermal drying is required in those pathways. Digestion, fermentation and drying processes can utilize heat at a low temperature, which in most cases can be procured as secondary heat at low cost. On the contrary, especially supercritical water gasification requires high temperature. Supercritical water gasification has large heat consumption at low solids content because large volumes of water in the microalgal broth require heating before gasification. Therefore, in energy efficiency perspective supercritical gasification seems to be best performed at higher solids content.

Annual energy balances for the considered biofuel pathways in Publication III case study are displayed in Figure 3.7, for open pond cultivation in natural lighting. It is evident that for the evaluated processes, differences in energy consumption are more significant than variations in energy outputs. Figure 3.8 shows the energy return on energy input (EROEI) and energy return on electricity input ($\mathrm{EROEI_{el}}$) for the processes, accompanied with Publication III sensitivity analysis results for parameter changes with the greatest effect.

For most pathways, EROEI > 1 and the energy output is greater than energy inputs, except for low solids content SCWG, and dry route biodiesel pathways. Energy returns can be greater than inputs because the solar energy input is excluded and only the human inputs included. Greatest energy returns are from high-solids content SCWG, followed by combustion, and air gasification pathways. If the consumed heat is from secondary sources, comparison on

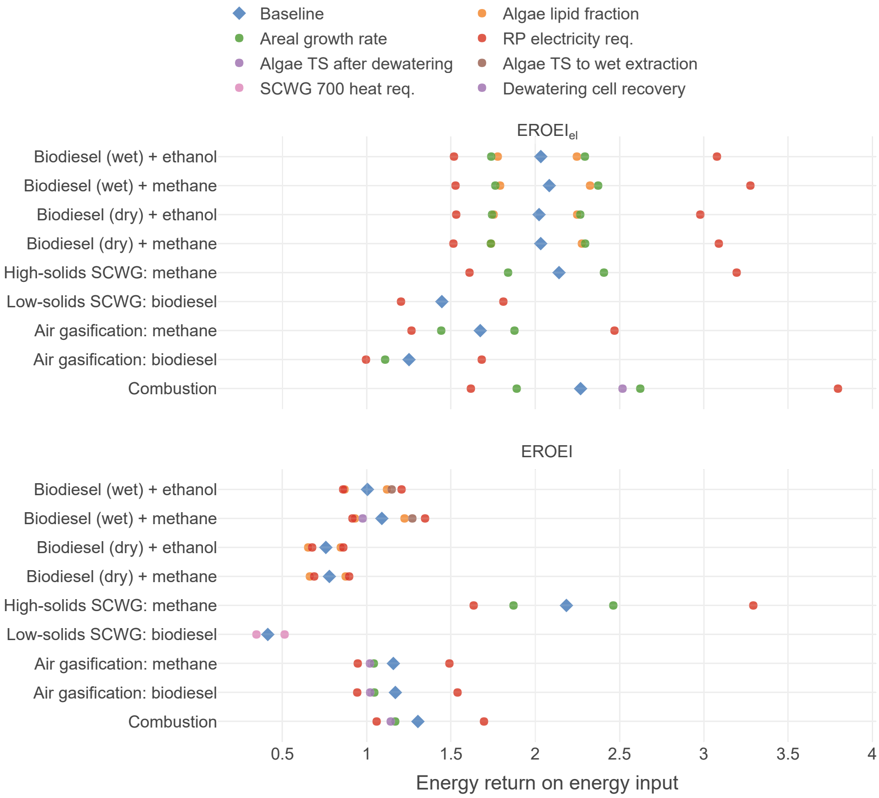

Figure 3.8. Sensitivity to key parameter variation. Energy returns on energy input are displayed in such case modifications, where a certain parameter is changed and others remain constant. Variance of parameters is presented in Publication III Table 4. For clarity, only those data points are shown where parameter adjustment results in EROEI/$_{el}$ change of greater than equal to 10 %. Modified from Publication III Figure 7.

EROEI_{el} may provide relevant information. For high-solids SCWG, combustion, and lipid extraction pathways, energy returns on electricity input are 2 to 2.3. When heat can be accessed at low cost, these options may be favourable. Still, in terms of input/output energy ratios, they hardly compete with other biofuels whose EROEI are around a value of 2 to 5 (Hall et al., 2014).

The energy returns are very sensitive to some input parameters, as identified by Figure 3.8. Therefore technological development and careful estimation of process technology is crucial to investment decisions. In addition, selecting the algal species that supports the chosen pathway will be still required — it was left outside the scope of this thesis. The relative order of investigated pathways is not much affected by input parameter variation since the largest differences arise from cultivation parameters. High-solids supercritical water gasification seems most favourable alternative with regards to energy returns — low solids content supercritical water gasification being the least favourable. It is important to note that supercritical water gasification technology is in small-scale prototyping phase, and no large-scale installations exist. Therefore this technology has to be considered as a potential future solution. The results on supercritical water gasification in Publication III are based on simulations rather than on experiments, and thus experiments are required. The extreme results highlight that if supercritical water gasification options are investigated further, an emphasis is to be placed on operating conditions' effect on production economics.

Biodiesel extraction pathways are amongst those options that have the lowest energy returns on energy input in the case study. However, since the technology is quite mature and the process equipment simple, the biodiesel extraction pathways might be one of the best overall options when investment and other factors are weighed in. Wet lipid extraction is preferred over more conventional dry extraction, but energy returns are not largely different whether the lipid-extracted algal matter is digested to form methane, or fermented to ethanol. The required temperature level of consumed heat in biodiesel pathways is low or medium, which enables the utilization of secondary heat sources via process integration. The energy return on electricity input for biodiesel pathways is among the highest of the investigated options, which is relevant if the heat can be provided of low cost.

The biofuel pathway comparison in Publication III can be generalized to systems where algal productivity levels are the same. In more productive locations, the specific energy consumption in cultivation is lower than presented. The comparison of post-processing options is extendable to other circumstances, within the given initial values. The gasification and reforming processes are calculated to reach the equilibrium state. However, the gas composition will most likely not reach the equilibrium, and the yields of the desired components in an actual process are likely to be lower than in the presented computational analysis.

Based on the Publication III study, a process alternative where algae undergo supercritical water gasification and product gas methanation is energetically the most favourable. Due to technology readiness and expected costs, lipid extraction pathways are speculated to be more economic and relevant in the near future. The presented research on microalgal biofuel production chains agrees with prior studies that large energy consumption in microalgae cultivation and dewatering are the main factors that cause low energy returns from the production pathways. Even in integrated contexts, where secondary heat could potentially be exploited, the energy returns on electricity input are only slightly above a value of 2 — considerably less than more conventional biofuel options. This is mostly due to high energy demand in cultivation; cultivation technology also induces the greatest variance to energy returns and therefore it is crucial to seek ways to reduce its energy consumption. Even though investment and other aspects of production economics were excluded from the study, the outcome suggests that producing only energy carriers from microalgae can hardly be economically competitive with other options.

3.4 Microalgae biorefinery concept evaluation

In Publication IV, an integrated biorefinery concept is evaluated, where microalgae are cultivated and then methane, lipids and fertilizer are generated as products. The process is shown in Figure 2.5. Figure 3.9 displays the calculated production for a sample year: algae growth and thus lipid production varies largely over the year due to variation in natural irradiance. Methane production has lower variation, having approximately 60 % loading rate in winter, and fertilizer production is the most stable at approximately 80 % load in winter. Despite amount variation, product composition stays constant over the year. The nutrient ratios in the case study fertilizer are similar to ratios in organic fertilizers in the market, but the absolute amounts are slightly lower.

The analysis in Publication IV indicates that recycling of lipid-extracted algal matter to digestion is important to the process and increases yields of all products significantly. At dimensioned capacity, the nutrient recycling increases algal growth by 42 %, methane production by 64 % and fertilizer production by 24 %. When the algal residue is recycled, the phosphorus and nitrogen in algal protein are returned to digestion, after which they provide more nutrients for algal cultivation and eventually end up in the fertilizer.

Table 3.2 summarizes the annual production and displays the effect of plant location for a similarly dimensioned plant; algal growth in the selected locations are also shown in Figure 3.10. Site selection has a direct consequence to algal growth and lipid generation but has less significance to methane and fertilizer output. If only maximal production is considered, the plant performs best in conditions with most constant irradiation. When product generation varies, so does also the input material utilization: in Finnish conditions, annual nutrient

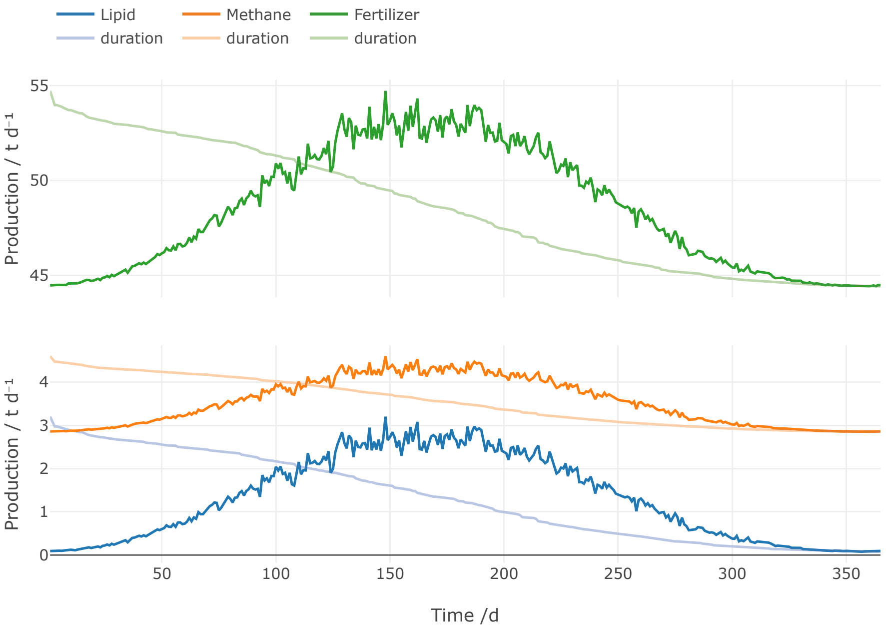

Figure 3.9. Annual variation in biorefinery product generation. Production duration curves display the average plant load. They and are formed by sorting the daily production. Modified from Publication IV Figure 4.

intake from supplied wastewaters is only 47 % of plant maximum capacity, whereas in Brazilian installation the peak capacity factor would be 79 %.

If constant nutrient removal would be required, from e.g. waste management perspective, a plant operating with phototrophic microalgae would therefore not be adequate. Complementing or alternative processes could be devised, such as nutrient precipitation in times of low algal growth, or change of algal species to one that could utilize carbohydrates as their energy source instead of light. Artificial lighting is also an option, but as shown in Publication III, the energy conversion rate of algae is still so low that the sales value of products needs to be significantly higher than electricity cost.

Algal strain selection is one of the key aspects of a successful biorefinery implementation since it has an effect on e.g. the growth rate, ability to consume nutrients in the digestion effluent, and the content and amounts of desired end products. Another crucial factor is the input material to digestion: its properties will have a direct effect on the algal growth, methane generation, and the fertilizer composition. If trace components such as toxins or heavy metals are present in the feed, it is important to ensure that these are not conveyed to lipids or fertilizer.

The process concept in Publication IV can be extended to other process industry and wastewater treatment plants that share the same interfaces as in the case study: carbon dioxide, heat, ash and waste activated sludge. The product properties and yields will depend on the algal species and their properties.

Table 3.2. Annual biorefinery production and input material consumption in selected locations. Modified from Publication IV Table 4.

Country City	Finland Helsinki	Germany Stuttgart	China Shanghai	Brazil São Paulo
Annual production, 10^3 kg/a				
• lipids	475	546	662	806
• methane	1360	1400	1470	1550
• fertilizer	17700	17900	18300	18800
Ratio of annual consumption to plant maximum capacity, %				
• ash	89	91	93	95
• digestion effluent	47	57	70	79

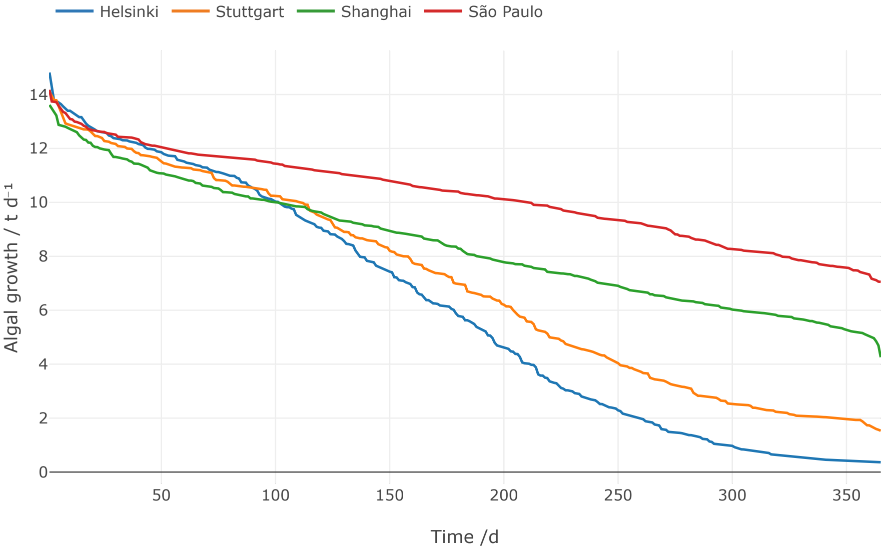

Figure 3.10. Annual algal growth duration curves in four selected locations. Modified from Publication IV Figure 5.

Therefore, each implementation requires laboratory tests in order to find out the appropriate model parameters and to evaluate implementation details such as the algal species and the growth conditions.

Based on the Publication IV study, presented biorefinery process appears technically viable. Nutrients are efficiently circulated for algae cultivation and finally utilized in a combined fertilizer. The integration with the pulp and paper mill provides required input material and possible sources for low-level heat for algae cultivation and processing. Lipid production varies largely with natural irradiance, but methane and fertilizer generation are more stable. Nutrient content in the fertilizer is close to currently available organic fertilizers. Process concepts such as the one presented may bring additional benefits to microalgal biomass and product generation: having a more diverse product palette with some higher-value products can potentially be beneficial to the production economics.

4. Concluding remarks

4.1 Contribution of the thesis

In this dissertation, four viewpoints to sustainable energy systems are presented. Each included publication addresses a separate research question presented in Section 1.2. The answers that are contemplated in Chapter 3 can be summarized as follows:

1. Supply temperature optimization in a district heat network adds flexibility into the system, which reduces heat generation costs and adds possibilities of variable renewable energy integration.

2. Multiobjective optimization can be employed to target sustainability goals at the least possible cost when designing district heat supply solutions. Including supplementing metrics in design also results in solutions that are less sensitive towards changes in economic parameters, in comparison to pure economic optimization.

3. Producing biofuels from microalgae is energetically most feasible of the investigated alternatives with lipid extraction pathways, where lipid-extracted residue is utilized, or with high-solids supercritical water gasification. Energy returns from all pathways are low and the results are highly sensitive to process unit energy consumption, especially in cultivation and dewatering stages.

4. Presented microalgal biorefinery concept appears technically viable. The location has a large effect on lipid productivity, but fertilizer and methane generation is more stable over the year.

The findings address the environmental and economic sustainability of energy systems by proposing ways, in which the systems can be operated and designed more cost-effectively and more environmentally sound, and researching into opportunities of reducing the dependence on fossil fuels.

Optimization and process modelling plays a key role in analyzing the sustainability of industrial systems and the performance of sustainability actions. Optimization tools reveal the best outcome on the selected metrics, and then decisions and practical solutions can be made knowing the technical optima. Process modelling may be employed in feasibility studies to reveal general insights on the systems and highlight the areas having the highest importance on the sustainability outcomes. Based on the studies, integrated process concepts are relevant in increasing material and energy recycling, and thereby process integration has potential in improving the environmental performance of industrial systems.

The results on district heat and the presented optimization methods can be directly utilized by district heat companies in their control systems, and when extending or designing heat supply networks. Municipal decision-makers also benefit from knowledge on the trade-offs between economic and sustainability goals, and other information obtained from the multicriteria model. The dissertation also increases the understanding of microalgal biofuel options and help companies and research institutions direct their efforts in enhancing production economics.

4.2 Reliability and validity

The analyses in this dissertation are based on case studies and are thereby affected by their initial assumptions, modelling choices and system boundaries. The effects of these factors are addressed in respective publications, where the possibilities of generalization are also discussed.

The general methodology selection that is presented in Table 1.1 performs well in the studies. All studies employ linear simplifications, which capture the major characteristics of the processes and thus enable conclusions on a general scale. More detailed models and verifications may be required, when exact subprocesses and equipment are selected and detailed knowledge on system operations are demanded. All studies include sensitivity analyses to investigate the effect of input data variance to the results.

4.3 Recommendations for further research

The presented research covers some earlier research gaps but also gives rise to more research topics that could be undertaken.

In district heat framework, the extent of district heat networks' effect to variable renewable energy integration is worth analyzing. This study identified that optimization control schemes have a role in it, but quantification of effects and the identification of incentives requires more attention. More broadly, the analysis of district heat networks' role in sustainable energy systems is a relevant topic for the Nordic countries and should be analyzed carefully. A thorough analysis of sustainability metrics' effect and relevance to variable renewable energy integration is also of high interest.

In microalgal biorefineries, creating solutions to reduce energy consumption in cultivation and harvesting is of high importance. Integrated process concepts that can employ secondary resources and produce more than one marketable product appear as a relevant possibility for microalgal product generation. Research into concepts that are adapted to local conditions will be helpful to identify possible opportunities for sustainable bioproduct generation. The economic analysis of modelled process concepts is a crucial step towards possible pilot projects.

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Errata

Publication II

Equation 1 First term in first line of summation should be corrected $P_p c_{\mathrm{el,in}} \rightarrow P_{\mathrm{out},p} c_{\mathrm{el,out}}$; first term of second line should be corrected $P_p c_{\mathrm{el,out}} \rightarrow P_{\mathrm{in},p} c_{\mathrm{el,in}}$. The results are not affected by this typesetting error.

Figure 2 A connector is missing between the biomass supply and SNG plant.

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