Mapping investment environment by optimizing the forest bioenergy production plant locations

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Academic dissertation

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ABSTRACT

Finland's long-term climate and energy strategy is to become 'carbon neutral' by reducing greenhouse gas emissions (GHG), improving energy efficiency measures and increasing renewable energy production. Forests as a renewable energy resource offers opportunities to boost the bioeconomy, energy security and environmental benefits. This doctoral study aims to analyze the potential expansion of forest biomass based bioenergy production in Finland. Therefore, a spatially explicit techno-economic Mixed Integer Linear Programming (MILP) model was applied to optimize the potential new bioenergy plant locations by minimizing the full costs of the supply chain with respect to forest resources supply, industrial competition, and energy demand.

At first, the model was applied at regional level to optimize the methanol and Combined Heat and Power (CHP) production in Eastern Finland (Article I) to replace fossil fuel in transport and district heating supply with local forest and industrial biomass resources. Later in Article II, the model was further extended at national level to optimize the location of Fischer-Tropsch biodiesel production plants to meet the 2020 target of biofuel share in transport. In Article III, the opportunities to increase the share of forest chips through existing and new CHP investments to meet the 2020 target of forest chips consumption in heat and power production were studied. Article IV presents the survey-based approach in Poland to identify key societal parameters (e.g., willingness to biomass supply) that helps to optimize the future production plant locations taking into account of economic, environmental and societal aspects of the bioenergy value chain.

The results of this study provide valuable information to the investors with cost-optimal production plant locations (liquid biofuel and CHPs), optimal plant size with respect to economy of scale effects, choice of technology, feedstock resource allocation with import options, minimized cost of supply chain, income from by-product sales and CO_2 emission savings. The model results also provide insight on the dynamics of the feedstock flow between end users with respect to market uncertainties. The model parameter sensitivity analysis shown that the investment costs, conversion efficiency and heat price variations were the most plant influential parameters followed by feedstock cost, electricity price, subsidies, and transport cost. The variation of these parameters under uncertain market conditions favoured by unstable policies would cause serious challenges to promote the use of forest biomass in the future biofuel and CHP industries. Survey analysis helped to understand that willingness of feedstock suppliers (farmers or forest owners) would also play a vital role for the future success of biofuel or CHP industries. Therefore, formulation of socially inclusive policies are imperative for the future success of bioenergy industries with long-term market stability.

Keywords: biomass, liquid biofuel, CHP, optimization, supply chain, energy demand

ACKNOWLEDGEMENTS

"ஈன்ற பொழுதின் பெரிதுவக்கும் தன்மகனைச்.
சான்றோன் எனக்கேட்ட தாய்"

-Thiruvalluvar

LIST OF ORIGINAL ARTICLES

This thesis summary consists of following four research articles. Studies I, II and IV are peer reviewed scientific publications. Study III is a manuscript submitted to Bioenergy Research journal. The articles are reproduced in the thesis with the permission of publishers.

I.   Natarajan K., Leduc S., Pelkonen P., Tomppo E., Dotzauer E. (2012). Optimal Locations for Methanol and CHP Production in Eastern Finland. Bioenergy Research 2012;5:412–23.
doi:10.1007/s12155-011-9152-4.

II.   Natarajan K., Leduc S., Pelkonen P., Tomppo E., Dotzauer E. (2014). Optimal locations for second generation Fischer Tropsch biodiesel production in Finland. Renewable Energy 2014;62:319–30.
doi:10.1016/j.renene.2013.07.013.

III. Natarajan K., Leduc S., Pelkonen P., Tomppo E., Dotzauer E. (2018). New CHP Plant location optimization to increase the use of forest chips in Finland. (Manuscript).

IV.   Zyadin A., Natarajan K., Igliński B., Iglińska A., Kaczmarek A., Kajdanek J., Pappinen A., Pelkonen P. (2017). Farmers' willingness to supply biomass for energy generation: evidence from South and Central Poland. Biofuels 2017;8:421–30.
doi:10.1080/17597269.2016.1225647.

The author's contribution

Paavo Pelkonen, Sylvain Leduc and Karthikeyan Natarajan jointly developed the research ideas. For articles I-III, Karthikeya Natarajan was responsible for data collection, data processing, model simulation, results analysis and writing of the manuscripts. Karthikeyan Natarajan jointly developed the BeWhere Finland model (articles I-III) with Sylvain Leduc. Erkki Tomppo provided the biomass resource data for the model. For article IV, Karthikeyan Natarajan and Anas Zyadin carried out the field survey together with the Polish partners. Karthikeyan Natarajan and Anas Zyadin wrote the analysis and article jointly. All the co-authors contributed in improving the manuscript by their comments and suggestions.

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LIST OF ABBREVIATIONS

BECCS	Bioenergy with Carbon Capture and Storage
BIGCC	Biomass Integrated Gasification Combined Cycle
BTL	Biomass to Liquids
CHP	Combined Heat and Power
CAPEX	Capital Expenditure
DH	District Heating
ENS	Energy Source At Home
FIT	Feed in Tariff
FLP	Facility Location Problem
GHG	Green House Gas
GIS	Geographical Information System
HDD	Heating Degree Days
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
MACH	Machinery
MILP	Mixed Integer Linear Programming
MSW	Municipal Solid Wastes
NFI	National Forest Inventory
NGO	Non-Governmental Organizations
NREAP	National Renewable Energy Action Plan
OD	Origin-Destination
OPEX	Operational Expenditure
OR	Operation Research
PERC	Perceived Value of Farming
PPM	Parts Per Million
SNG	Synthetic Natural Gas

1. INTRODUCTION

1.1 Background and context

Climate Change pose a serious threat to our planet earth's ecosystem sustainability, people's livelihood and security because of rapidly melting glaciers, raising sea levels, varying precipitation levels and increasing global temperatures. The continued emissions of greenhouse gases (GHG) namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorinated gases (F-gases) into the atmosphere due to anthropic activities have attributed to the change in the earth's climate system. In 2017, the global average long-term atmospheric concentration of CO_2 measured at the Earth's surface was 405 ppm which was record high when compared to pre-industrial era (1750-1850) concentration of about 280 ppm. This elevated CO_2 concentration in the atmosphere has led to the increase in average global temperatures above pre-industrial levels by 0.85ºC (Blunden et al. 2018). Globally, the primary source of GHG emissions by economic sectors in 2010 were 25% electricity and heat production, 24% agriculture, forestry and other land use, 21% industries, 14% transportation, 6% buildings and 10% other energy sources (IPCC 2014). The latest United Nations Intergovernmental Panel on Climate Change (IPCC 2018) special report recommends that limiting the global warming to 1.5ºC above pre-industrial levels would bring enormous benefits to people and natural ecosystems ensuring a more sustainable and equitable society. To accomplish this goal, an unprecedented shift in energy systems and transport would be needed to confront the serious challenge of global climate change.

As it stands today, fossil fuels (coal, oil, natural gas) dominate the source of global primary energy supply by over 81% in 2017 (IEA 2018). Fossil fuels are non-renewable resources because if its once depleted then it cannot be replenished. The combustion of fossil fuels by humans release large quantities of CO_2 pollutants to the atmosphere causing climate change. On the other hand, renewable energy sources such as biomass, hydro, geothermal, wind and solar are naturally replenishable and they are often considered as "alternate energy" sources to fossil fuels because of their low carbon emission footprint. Renewable energy sources offer climate change mitigation opportunities but not without any environmental risks, for instance, loss of habitats due to rain forest deforestation for palm oil production in Indonesia or use of wood for energy from unsustainable forests. Traditionally, wood from the forests has been the primary source of energy for humankind since the time immemorial. Even today, more than 2 billion people in the world meet their primary energy needs (mainly cooking and heating) from wood fuels. For example, more than 70% of India's population are dependent on biomass for their energy needs.

In addition to its traditional use, the wood fuels are now being used in modern bioenergy applications to produce heat, power, liquid biofuels and other biochemicals. In 2017, renewable energy accounted 10% of global energy supply, of which bioenergy contributed around 50% of total renewable energy mix (IEA 2018). Among the renewables, the recent trends have shown that deployment of solar and wind capacity for power generation is growing unprecedented, which together accounted for 85% of all new capacity (167 GW) installations in 2017 (IRENA 2018). IEA 2018 forecasts that between 2018 and 2023, the modern bioenergy applications would still lead the growth of all renewables up to 30% mainly in heat and transport sector, though its role could be significantly boosted with better policy support and new technological innovations.

In Europe, European Union's Renewable Energy Directive 2009 mandated its member countries to achieve the minimum binding target of 20% renewable energy share in gross final energy consumption, and a 10% share of renewable energy in transport by 2020 (EC

2009). As a pursuant of this directive, EU member countries formulated their own national renewable energy action plans to meet the above targets by placing sectorial targets for electricity, heat and transport, feedstock resource consumption targets, selection of technological portfolios, strategic policy measures and needed support schemes. As a member country, Finland laid out its approaches in its National Renewable Energy Action Plan (NREAP) 2010 with an aim to achieve 38% (446.50 PJ) renewable energy share on final energy consumption, and 20% (25.20 PJ) renewable energy share in transport by 2020 (TEM 2010). The action plan considered that the domestic forest resources would play a vital role in increasing the share of renewables and therefore, a consumption target of 97.20 PJ forest chips by 2020 mainly in heat and power plants was set. Later in 2016, the national energy and climate strategy increased the targets on renewable energy share to 50% and biofuel share in transport to 30% by 2030 (TEM 2016) in line with EU's 2030 binding target of 27% renewable energy share in final energy consumption (EC 2014). In 2018, the original EU 2030 target of 27% was revised to 32% renewable share in final energy consumption to all member countries (EC 2018).

These policy targets and market transitions drove the Finnish forest and energy industries to seek new technological innovations to efficiently utilize the limited forest resources. Several industrial consortia such as UPM, Neste oil and Stora Enso, Metsäliitto and Vapo, and Fortum and Valmet worked together to develop the second-generation biomass to liquid (BTL) biofuel production technologies. Similarly, energy industries developed new technological solutions in cofiring wood chips with coal or peat, and small-scale district heating solutions. As a result, several new investments decisions were taken to build the second-generation liquid biofuel production plants across the country but however, only very few production plants have been realized so far.

Currently, liquid biofuels distribution target in Finland are met mainly from vegetable oils, tall oil from pulp mills, food industry wastes, bio-waste, sawmill residuals, imported palm oils and ethanol. On the other hand, since 2013 the total forest chips consumption in energy production remained unchanged (averaged around 58 PJ). The use of forest chips in heat only plants have increased steadily (14% increase in 2016 from 2015 level) whereas its use in CHPs have declined (6% decrease in 2016 from 2015) (Ylitalo 2016).

Figure 1 compares the targets and the actual share of liquid biofuel production (LVM 2017), and consumption of forest chips in Finland (LUKE 2018). The gaps in liquid biofuel and forest chips consumption target achievement is attributed to several reasons such as lack of new plant investments, changing policies, growing competition from other renewables
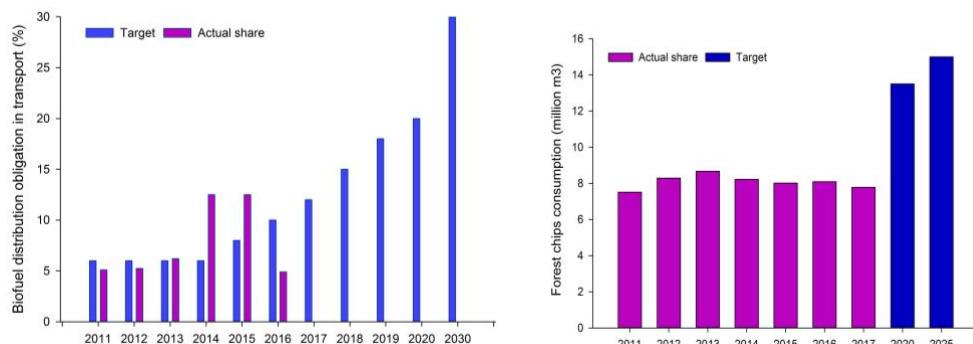
Figure 1. Yearly target and actual share of biofuels in transport (left) and forest chips consumption (right).

(e.g., wind), low CO_2 emission allowances, contradicting opinions and evidences on carbon neutrality of forest biomass, and public perception of wood fuels as energy source. The future deployment of liquid biofuel and forest chips use in energy would need the support of EU policies as Finland as an individual market offers smaller incentive to take on its own to develop and invest in new advanced technologies.

Finland is the second largest among the EU member countries to have a high renewable share (36% in 2017) in final energy consumption. In that, the wood fuels contributed about 27% of total primary energy consumption and remained one of the most important domestic individual energy resource followed by nuclear energy (27%), oil (23%), coal (9%), natural gas (5%), electricity import (5%), hydro power (4%), peat (4%), wind (1%), and other (4%) (OSF 2018). Since 1990, Finland has increased the use of wood fuels for energy by 137% while significantly reducing the use of imported fossil fuels. Furthermore, the net GHG emissions have fallen by 50% since 1990 (Bioenergia 2018). Forest biomass originating from sustainable managed forests can be considered "carbon neutral" if the forests are artificially or naturally regenerated after harvesting as the re-growing trees will re-sequester the carbon that were released during the conversion of forest biomass into energy. However, there is no clear consensus among scientists regarding the "carbon neutrality" of forest based bioenergy products as they are studied from different points of view with different methodologies approaches and parameter assumptions. Berndes et al. 2016 present an insight to the different views on forest biomass, carbon neutrality and climate change mitigation.

Finland as a pioneer in forest bioenergy utilizes forest biomass in an efficient and environment sustainable manner in modern energy applications (IRENA 2018). Importantly, the forest biomass comprises of mainly energy wood fractions obtained during pre-commercial thinning of young thinning wood, and logging residues and stumps obtained during final harvesting of round wood. In addition, industrial residuals such as sawmill by-products (wood chips, mill residuals), pulp mill by-products (black liquor) etc., are also used in energy production. It is also important to note that the stem wood is not directly used for energy and it is mainly used in the production of forest industry products such as wooden houses or furniture, which also has a long-term "carbon storage" potentials with climate benefits. Moreover, present Finland's annual harvesting levels (72.4 million m^3 in 2017) are lower than the calculated maximum sustainable felling potentials (85 million m^3) (LUKE 2018). However, as part of latest bioeconomy strategy, the government has plans to increase the annual harvesting up to 80 million cubic metres until the year 2025. This decision is in contrary to the latest IPCC 2018 report which calls for less forest harvesting as forests are important "carbon sinks" that can help to fight against climate change. A study reports that if government plans on increased harvesting would be realized, then the annual carbon capture of Finish forests would be reduced by half of 2013-2014 levels (27 million tons) (HS 2018). In 2017, about 60% of GHG emitted by Finland (excluding the emissions and removals of land use and forestry) were captured by forests of Finland (LUKE 2017). This may affect the Finland's ambition to become carbon neutral by 2030 or at latest 2045 as the balance between CO_2 production and carbon capture by natural sinks should be equal to zero.

Bioenergy with carbon capture and storage (BECCS) could provide one possible technological solution to overcome the CO_2 deficit created due to forest harvesting which is being studied in Finland and other Nordic countries. Lehtilä et al. 2016 estimated that potential deployment of BECCS could lower Finland CO_2 emissions by 15 Mt per year (5-8 Mt heat and power production, 4-7 Mt pulp and paper production and 3 Mt biorefinery production).

1.2 Research motivation

Large-scale bioenergy production plant investments are affected by many factors such as biomass availability, industrial competition, transport infrastructure, supply chain costs, capital investments, operation and maintenance costs, energy supply, market demand and prices. This requires also participation of different stakeholders such as farmers, forest owners, biomass traders, consumers, plant labours, industrial companies, financial institutions, and local organizations such as farmer or forest owner associations, local government departments and non-governmental organizations (NGOs). Moreover, lifetime of these production plants are over 25 years and any investments into it cannot be reversed once the plant is built. Therefore, a scientific approach to decision making on bioenergy plant investments is important to map the investment environment by carefully allocating the scarce natural resources. Operation Research (OR) offers such decision-making solutions through wide range of problem solving methods and tools for e.g., optimization, game theory, probability theory etc.

Optimization methods aim to find the best possible solution to a given problem. Determining new bioenergy plant investment location is a Facility Location Problem (FLP) and previously, several methods have been developed to solve the wide range of FLPs. For example, Noon et al. 2002, Panichellai and Gnansounou 2008, Perpina et al. 2009 and Zhang et al. 2011 applied GIS based techniques to locate bioenergy production plants. Dunnett et al. 2008, Rentizelas et al. 2009, Eksioglu et al. 2009, Zamboni et al. 2009, Huang et al. 2010, Dyken et al. 2010, and Kim et al. 2011 presented Mixed Integer Linear Programming (MILP) models to optimally design and located the biomass based conversion facilities. In last ten years, there has been an abundant studies on bioenergy plant supply chain optimization (Schmidt 2009, Akgul et al. 2011, Kallio et al. 2011, Mobini et al. 2011, Wetterlund 2012, Shabani and Sowlati 2013, Windisch et al. 2013, Cambero et al. 2014, Sukumara et al. 2014, Mesfun 2016, Schroder et al. 2019). The application of earlier optimization-modeling approaches contributed greatly to understand the importance of overall supply chain in bioenergy production. However, the optimization studies encompassing all the three dimensions economic, environment and societal aspects of the full bioenergy supply chain was rather limited. The previous studies focused on either supply side or demand side and in some cases both, but only then a particular aspect of the supply chain was considered. Cambero and Sowlati 2016 presented an interesting approach by including social benefits such as employment factor in their multi-objective optimization model by maximizing job creation, net present value and emission savings of forest-based biorefinery supply chain.

In addition to social benefits such as job opportunities through new bioenergy plant investments, there are other social factors like willingness to supply biomass, perception and attitude towards biomass use in energy generation should be also considered (Zyadin et al 2015). My four year field level learnings to find new bioenergy investment opportunities in India and Poland through the "Sustainable Bioenergy Solutions of Tomorrow (BEST project, 2012-2016)" have helped me to understand the societal complexity and consequences that are critical for taking new bioenergy investment decisions. Integrating the societal aspects in the optimisation modeling framework (which is presently based on economic and environmental factors) would further enhance the decision making process and to address uncertainties of the biomass to bioenergy supply chain.

Finland as a pioneer in forest bioenergy production has both strong scientific knowledge and commercial plant operational experience. Earlier research studies in Finland have helped to create good information on biomass supply potential at national level (Tomppo et al. 2009, Tomppo et al. 2013), biomass supply chain economics (Kallio et al. 2011, Korpinen et al. 2013), biomass supply chain GHG emissions (Wihersaari M (2005), Kilpeläinen et al 2011,

Jäppinen et al. 2014a, Jäppinen et al. 2014b), and techno-economic assessment of biomass conversion technologies (McKeough P and Kurkela E 2008, Hurskainen M et al. 2016).The result findings from these earlier studies presented an opportunity in this doctoral work to prepare a systemic approach to make new bioenergy production plant investment decisions for investors in Finland. Furthermore, this doctoral study targets to overcome the gaps identified in the previous work and employ an optimization based decision support model that include full biomass supply chain taking into account of economic, and environmental aspects, and also identify the further possibility to include societal opportunities and challenges in the future model development.

1.3 Aim and objectives of the thesis

The overall aim is to map the investment environment by optimizing the forest bioenergy production plant locations and assess the forest bioeconomy based energy system. This doctoral work optimizes the location of second-generation liquid biofuel and CHP production plants in Finland. The analysis is based on employing a spatially explicit Mixed Integer Linear Programming (MILP) model to minimise the full cost of the supply chain with respect to the complexity of forest resource supply, existing industrial competition and energy demand. Along with this modeling work, the thesis discuss also the importance to open up a research avenue to perceive the complexity and necessity of a holistic approach, which covers several dimensions of sustainability.
Specifically, the objective of the thesis is

Policy and markets
- o To study the overall opportunities and potential expansion of second-generation liquid biofuel and CHP industries both at regional and national level.
- o To investigate the influence of policy instruments such as carbon tax on choice of technologies with respect to CO_2 emission reductions and fossil fuel substitutions.

Techno-economic assessment
- o To determine based on expected market development the optimal number, size and location of liquid biofuel production plants to meet the national 2020 target of biofuel share in traffic.
- o To determine based on expected market development the optimal number, size and location of CHP production plants to meet the national 2020 target of forest chips consumption in heat and power production.
- o To allocate the limited forest resources in a cost efficient and environmentally sustainable manner in future liquid biofuel and/or CHP production plants.
- o To map the optimal flow of woody feedstock and energy flow between existing forest and energy industries (sawmill, pulp mills, DH/CHPs, pellet plants).
- o To model the potential energy demand (and fossil transport dwelling heat) that can be supplied with future liquid biofuel or CHP production plants.
- o To study the impact of market variations (e.g., price, availability) on future liquid biofuel and CHP production plants.

Societal complexity and consequences
- o To study the effects of subsidies such as young thinning wood support and Feed In Tariff (FIT) on CHP production.
- o To identify the social factors that affects future investments such as willingness to supply biomass for energy generation.

1.4 Outline of thesis

An outline of this thesis is presented in Figure 2 to give the readers a better understanding on the summary of Articles (I-IV). Articles (I-III) are model-based studies and Article IV is a survey-based study.

INTRODUCTION
Background and context
Research motivation
Aim and objectives of the thesis

MATERIALS AND METHODS, AND RESULTS	
MODEL	**SURVEY**
Mode evolution & linkage between Article I-III	Survey linkage to the model (Article IV)
Model inputs: supply chain of optimization model	Survey inputs: study area & survey tool
MILP Optimization modeling	Methodology
Model Results	Survey Results

DISCUSSIONS
Discussion of both models and survey results

CONCLUSIONS
Main conclusions of the thesis and future work

Figure 2. Structure of the thesis.

2. MODEL

2.1 Model evolution and linkages between the articles (I-III)

Overview of the optimization model development and linkage between the articles (I-III) is presented in the Table 1. Article I presents the optimization model with regional level model inputs on forest resources, industrial competition, transportation by roadways and railways, full costs of the supply chain and energy demand. Article II presents the optimization model further developed to cover the entire Finland with biomass and biofuel import options. In addition, the model inputs were updated with the national forest inventory data, detailed transport network with terminal functions, and the results from a detailed energy demand model. Article III presents the latest optimization model with biomass cost variations by geographical regions. Furthermore, the demand for forest chips from the small-scale DH plants and fuelwood demand for domestic consumption was also incorporated to the model.

Table 1. Overview of the model development and linkage between the articles (I-III).

Article	Overview	Technology	Study area
I	- Optimization problem at regional level is defined for the investment of new production plants. - Regional level spatially explicit database on forest resources (NFI10 2004-2005), industrial competition, road and rail network, energy demand (heat and transport fuel) was created. - Costs of the full supply chain. - Techno-economic assessment of methanol and CHP production.	Methanol & CHP	Regional level (Eastern Finland)
II	- Optimization problem at national level is defined for the investment of new production plants. - National level spatially explicit model database contains updated information on forest resources (NFI11 2006-2010), industrial competition, detailed transport network with terminals, detailed energy demand model (dwelling heat and transport fuel), and new information on wood and biofuel imports. - Total Supply chain costs from Article I and the wood and biofuel import price. - Techno-economic assessment of FT-biodiesel production.	FT-biodiesel	National level (Finland)
III	- Optimization problem at national level is defined for the investment of new and retrofit production plants. - National level spatially explicit model database from Article II data + new information on fuelwood demand and small-scale district heating plant's demand on forest biomass. - Updated supply chain costs from Article II + the introduction of geographically explicit forest biomass cost variations and government support (subsidies for young thinning wood and feed in tariff biomass based electricity production). - Article I + updated techno-economic assessment of CHP production.	CHP	National level (Finland)

2.2 Model inputs: Supply chain of the bioenergy optimization model

The supply chain of the bioenergy optimization model includes a national level database (see Appendix 1) on domestic forest resources (saw wood, pulpwood, young thinning wood, logging residues, stumps), imports (wood and biofuel), industrial demand and supply from sawmills, pulp and paper mills, pellet factories, DH/CHPs, detailed road and rail transportation network with terminals, state of the art bioenergy technologies (methanol, FT-biodiesel, CHP), costs and CO_2 emissions of the whole supply chain, existing energy demand (dwelling heat and transport fuel). A conceptual overview of the supply chain of the bioenergy optimization model is presented in Figure 3.

A complete flow of feedstock and energy products between different existing end users has been included in the model. New flow of feedstock supply to the bioenergy plant is considered only when there exists a feedstock supply potential after meeting the existing users demand. The energy produced from the bioenergy production plant is assumed to substitute the existing fossil fuel based energy system.

2.2.1 Forests and industrial resources supply

The model input on the feedstock supply potential for bioenergy production includes spatially explicit information on the domestic forest resources, industrial by-products and wood imports (Figure 4). For the estimation of forest resources, LUKE (earlier METLA) conducted a Multi-Source National Forest Inventory (MS-NFI) covering the entire country once in every two years. The MS-NFI10 (2004-2005) and MS-NFI11 (2006-2010) data were used in the Article I and Article (II-III) respectively. The MS-NFI data included in the model analysis are estimated using field measurements, satellite imagery, and digital map data (Tomppo et al. 2009, Tomppo et al. 2013). For the model input, map form predictions were used to assess the potential of forest resource supply by feedstock assortments such as saw wood, pulpwood, thinning wood, logging residues and stumps.
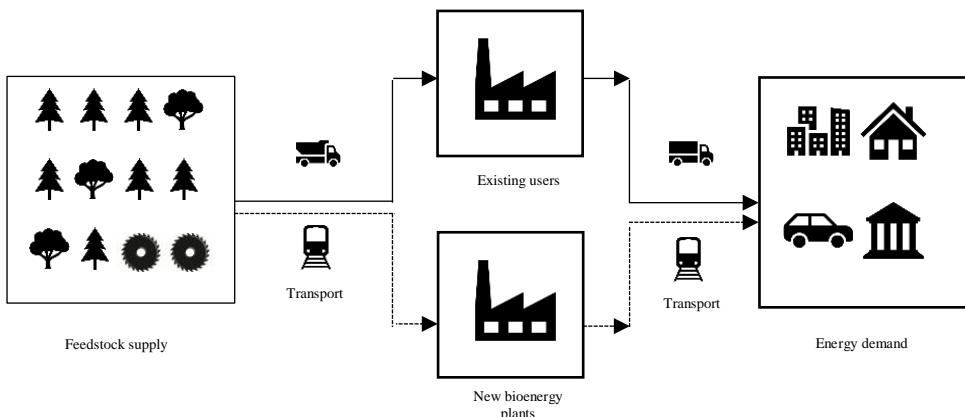
Figure 3. Conceptual overview of supply chain of the bioenergy optimization model.
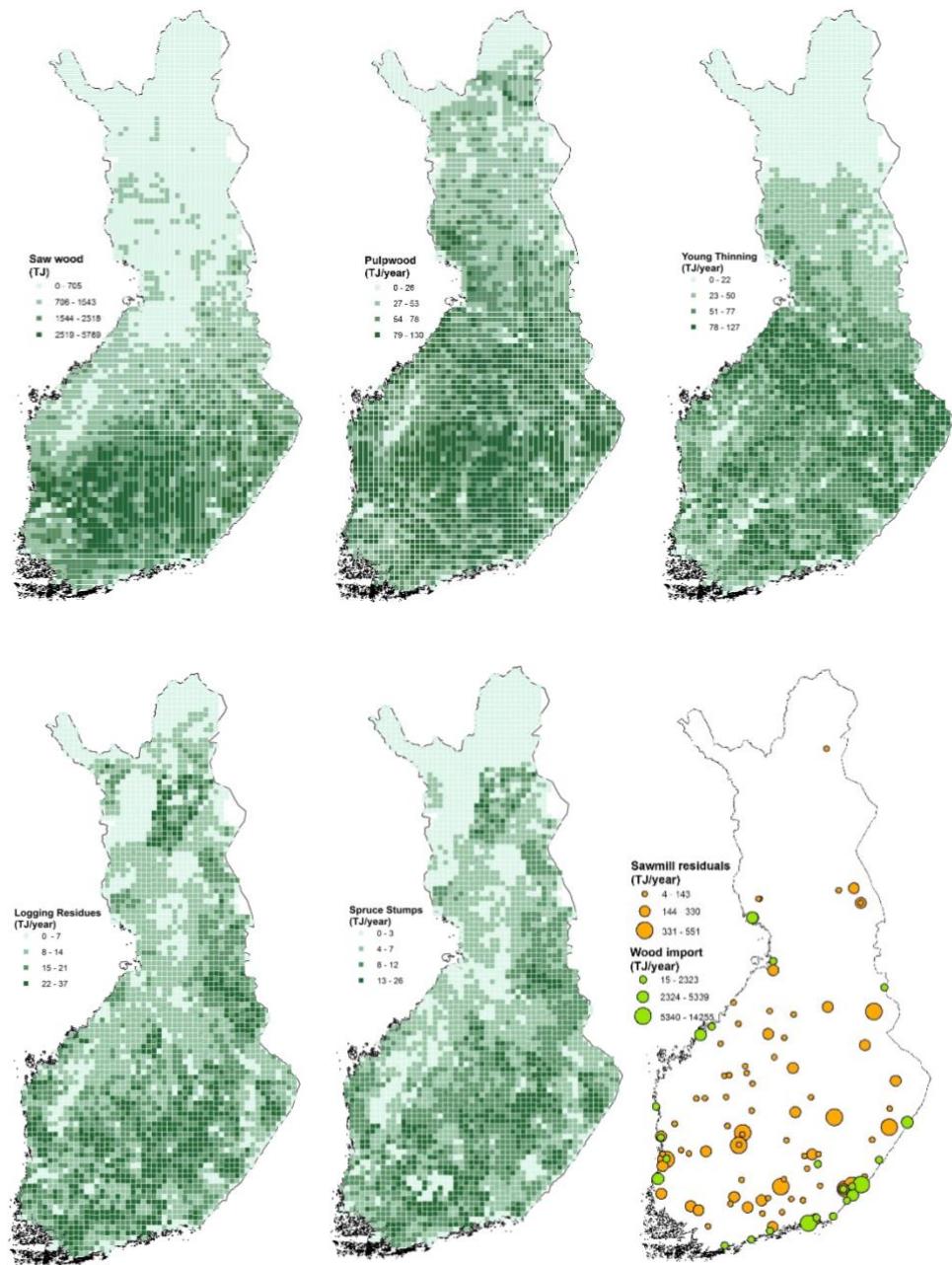
Figure 4. Spatial distribution of feedstock supply resources. Saw wood (upper left), pulpwood (upper middle), young thinning wood (upper right), logging residues (lower left), spruce stumps (lower middle) and sawmill residuals (lower right). Saw wood is presented in total growing stock volume while other feedstock assortments were assumed available for bioenergy production (hence potential feedstock supply has been calculated per year).

For round wood assortments such as saw wood and pulpwood supply, a municipal level inventory result containing total volume estimated by tree species (pine, spruce, birch and other) from the forestland and poorly productive land available for wood production were applied in the model analysis. The flow of saw wood to sawmill and pulpwood to pulp mills depends on the annual harvesting level. In the model input, neither saw wood nor pulpwood was assumed available for either liquid biofuel or energy production. For biomass estimation (young thinning wood, logging residues and spruce stumps), tree level of biomass estimates were calculated first for sample trees using the models developed by (Repola et al. 2007, Repola 2008, Repola 2009) and then for tally trees in a similar manner as the volumes. To estimate the young thinning wood supply, stands in which first commercial thinning was proposed for the first five year period or on which pre-commercial thinning was proposed were selected. In such stands, only field plots with extraction possibility of 28-43% of above ground biomass were considered. Regional guidelines for thinning regimes for dominant tree species pine, spruce and birch on most common site fertility classes (mesic forests and sub-xeric forests) were employed. The dominant tree species was selected using stand level data from the stand including the plot. To estimate logging residues and stump supply, the biomass estimates from mature forests that include branches, foliage, stem residuals, and stumps and large roots by tree species group were calculated. Then the technical supply potential was calculated in each 10km by 10 km grid cell using the proportion of land available for wood supply, share of mature and thinning stands (development class), annual harvesting level (2009 base year), and ecological constraints (only spruce stumps are lifted and 70% of logging residues can be collected). In total, 3,307 grid cells covering the entire country with forest resource supply potential by feedstock assortments were used as model inputs.

The industrial by-products such as sawmill residuals were also added to the model feedstock supply input data. The sawmill database of Finland contains spatial location and production capacity of sawmills (Sawmill 2012). To estimate the sawmill residuals supply, material and energy balance equations developed by (Heinimö et al. 2005) were applied to calculate the proportion of saw wood by-products productions (wood chips, sawdust and bark). Noteworthy is that annual availability of sawmill residuals is proportional to the saw wood production which directly depends on the annual round wood harvesting. The annual wood import volume to Finland varies by year, and this model input data uses wood volume imported during 2010 as the base year (METLA 2011, FTA 2011).

2.2.2 Competition from household and industries on forests and industrial resources

The mapping of wood flow from forests to households and industries is needed to optimize the resource allocation for future bioenergy production plants. The utilization of forest resources between forest industrial clusters are high in Finland and therefore, one or more industrial users may have to compete on the same feedstock resources to meet the plant's raw material requirement. In Article I-III, sawmill's demand for saw wood, pulp mill's demand for pulp wood and sawmill woodchips, pellet factory's demand for sawmill residuals, and DH/CHP's demand for forest chips and sawmill residuals were modelled using location, installed production capacity, and plant conversion efficiency by each industrial type. In the latest work in Article III, fuelwood consumption at household level for each municipality in Finland has been calculated. In addition, Article III presents an updated analysis on the forest chips and sawmill residuals demand in both small-scale DH plants, and large-scale DH/CHP plants. Furthermore, forest chips and industrial residuals demand for liquid biofuel production in the existing and planned sites have been taken in to account as well in the

Article III model input. Figure 5 presents the annual wood demand of Finnish households and industries from forests and other industrial resources.
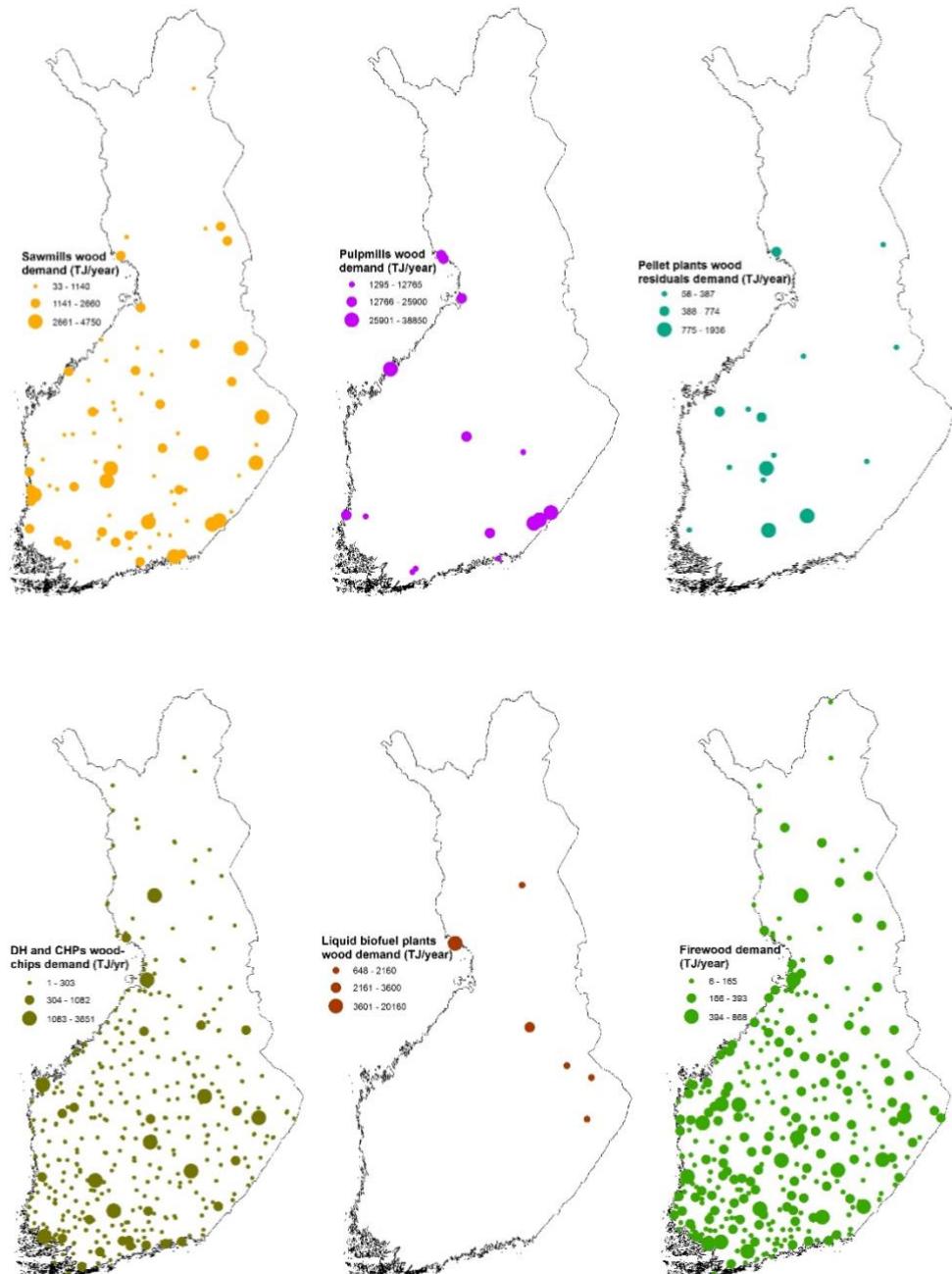
Figure 5. Spatial distribution of industrial wood and household firewood demand. Feedstock demand for; Saw mills (upper left), pulp mills (upper middle), pellet factory (upper right), DH/CHPs (lower left), liquid biofuels (lower middle) and household firewood (lower right)

2.2.3 Energy demand

The spatial distribution of energy demand densities is essential to model the location and size of the bioenergy production plants to substitute the existing fossil based district heating and vehicle transport. In the model, heat and transport fuel demand for 315 municipalities has been calculated (Figure 6). In Article I, a simple formula was employed to calculate the energy demand as a function of per capita energy consumption and population density in Eastern Finland. In Article II, the energy demand methodology (model equations are presented in Article II) was developed with detailed analysis on dwelling heat demand and transport fuel demand. A dwelling heat demand model was constructed for three building types and nine different age class from 1920 to 2010 (attached houses, apartment houses and detached houses) (SF 2012). At first, total dwelling area in each city for building type and age class was calculated as a function of number of buildings and average dwelling floor area. Then, the specific net heat demand for each specific building type and age class was estimated using the specific heat loss and heating degree-days (HDD). Subsequently, the total dwelling heat demand was calculated using the total dwelling area and specific net head demand for each building type and age class. Finally, the net heat demand representing additional heat that can be supplied through biodiesel production plants was estimated by subtracting the existing district heating supply from the total dwelling heat demand.

To calculate the transport diesel demand in each municipality, 2011 vehicle stock data from TRAFI (TraFi 2012) in each municipality was used as a function of number of diesel vehicles, average annual transportation distance and average fuel consumption per km by vehicle type. In Article III, the heat demand model developed in Article II was further extended to include nine more building types including commercial buildings, office spaces, institutional buildings, assembly buildings, education buildings, industrial buildings, warehouses, traffic and other buildings. This heat model was then also updated with the existing forest biomass based heat supply from small-scale DH plants (<3MW) and large scale DH/CHPs.
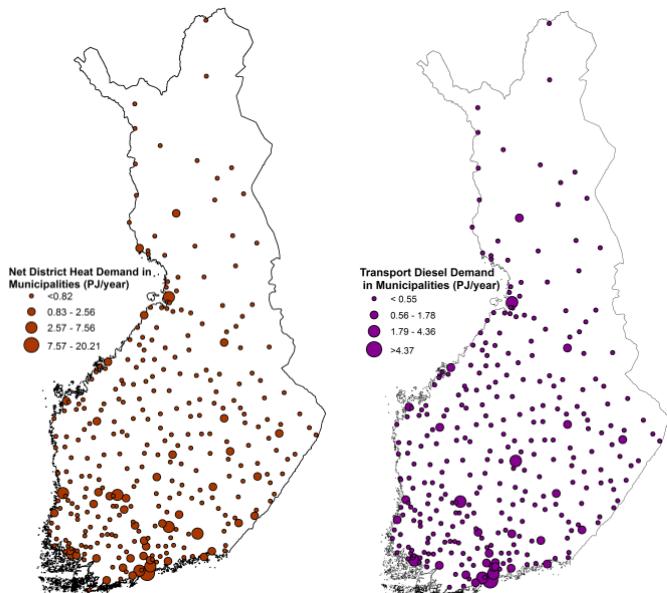
Figure 6. Spatial distribution of energy demand densities in Finland. Net DH demand (left) and total transport diesel demand (right)

2.2.4 Transport network

A commercial scale bioenergy production system demands huge amount of feedstock input for producing energy for the end users. This requires feedstock to be procured from longer distances. Similarly, the biofuel produced at the plant has to be delivered to the gas stations at longer distances. Roadways, railways or waterways can transport both feedstock and biofuel. The choice of transportation method usually depends on the distance and infrastructure availability. In Article I and II, two modes of transportation, both roadways by truck and railways by train were used to transport the feedstock from the supply points to the production plant locations, and liquid biofuel from the production plants to the gas stations. In Article II, railway terminals were included in the transport network, so that first the feedstock will be transported by road from the supply points to the nearest terminal, and then delivered to the production plant by train covering longer transportation distance. In Article III, only truck transportation was considered. Figure 7 presents the transport network of roadways and railways with terminals used in the model analysis. For the model input, a transport network model based on Origin-Destination (OD) matrix was constructed in ArcGIS to measure the truck and train transportation distance between supply and demand points. The distance measured is then used in the transport cost calculations as given in the equation 1.

$$C = a + b.d \qquad (1)$$

Where $'C'$ is the cost of transportation by truck or train, 'a' represents fixed costs (distance independent) which include loading and unloading costs, $'b'$ represents variable costs (distance dependent) which include driver costs, fuel costs, margin, administrative, and maintenance costs and 'd' represents the actual transport distance travelled (in km).
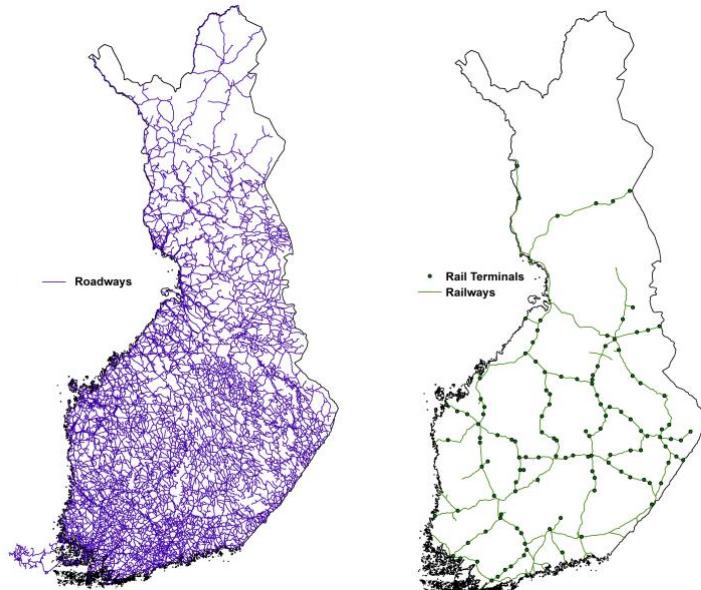
Figure 7. Transport network of Finland used in the model analysis. Road network (left) and rail network with terminals (right)

2.2.5 Costs of the supply chain

The supply chain costs of the technology studied in Article (I-III) is presented in Figure (8-10). The costs presented in Figures 8-10 are reference model parameter inputs. A techno-economic assessment for methanol, FT-biodiesel and CHP technology was included in the model analysis. In Article I and II, only heat price had geographically explicit price variations while other costs of the supply chain were assumed fixed for the entire study area. The total biomass conversion efficiency of the methanol and CHP production plant were assumed at 66% (55% methanol and 11% heat) (Leduc et al. 2008, Leduc et al. 2009, Leduc et al. 2010, Hamelinck et al. 2001) and 90% (55% heat and 35% electricity) (Dornburg et al. 2001, Craig et al. 1996, Marbe et al. 2004) respectively.

In Article II, in addition to domestic forest resources, wood import was included in the feedstock supply chain. Geographically explicit pulpwood and heat prices were included while other costs were assumed fixed for entire Finland. The total feedstock conversion efficiency of FT-biodiesel production plant was assumed at 57.2% (45% biodiesel, 5.8% heat and 6.4% electricity) (Van et al. 2009, Mckeough et al. 54).

In Article III, both feedstock supply costs from forests and heat prices were presented spatial explicitly in the model while other costs are assumed constant for the entire region. The total conversion efficiency of the CHP production plant was assumed at 85% (58.6% heat and 26.4% electricity) (Hurskainen et al. 2016). In real world, the above cost assumptions of the supply chain are subjected to changes with respect to market uncertainties. Therefore, sensitivity analyses were carried out in each paper to study the influence of cost parameter changes on the future bioenergy production.

2.2.6 CO_2 emissions

CO_2 emissions during different parts of the supply chain from feedstock procurement to energy conversion at the production plant was accounted in the model. In addition, model considers also the offset emissions by liquid biofuel, heat, and electricity supplied from the bioenergy production plants using the emission factors and amount of fossil energy displaced. The emission factors were calculated based on the country's energy mix data (SF 2012). The calculated emission factors based on the primary energy consumption for heat, electricity, fossil diesel, and fossil gasoline were 0.119 t_{CO2}/GJ, 0.131 t_{CO2}/GJ, 0.073 t_{CO2}/GJ, and 0.30 t_{CO2}/GJ. In Article I-II, emissions during the conversion of second-generation feedstock to bioenergy were assumed carbon neutral, as it can sequestrate naturally again, when forest is replanted after harvesting. In Article III, the full CO_2 emissions of the whole supply chain was included in the model including wood production, forest operations (thinning, harvesting, forwarding), transport, biomass to energy conversion at the CHP plant, and fossil fuel based energy displacement by bioenergy.
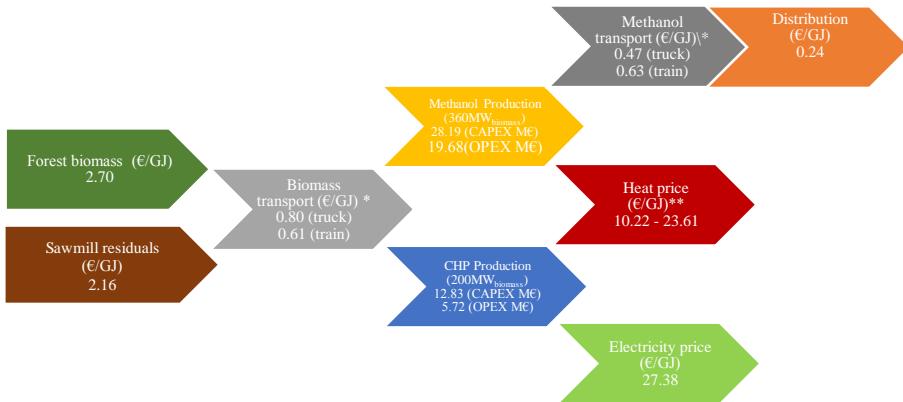
Figure 8. Article I model inputs on the costs of methanol and CHP production plant supply chain. * for 100 km transport distance. ** heat price varies geographically
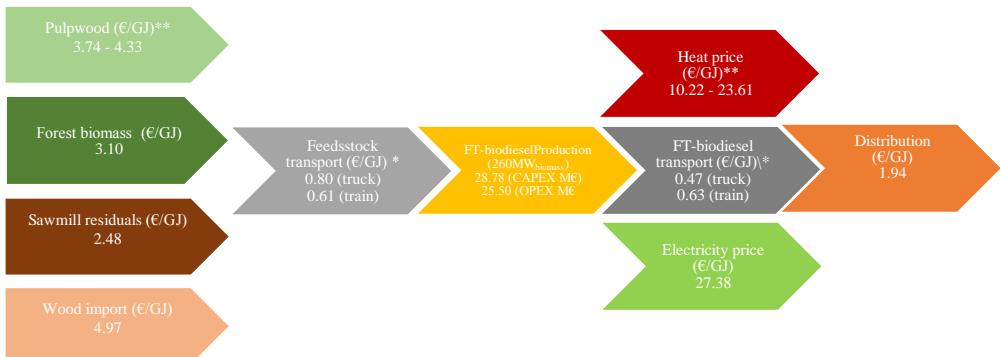
Figure 9. Article II model inputs on the costs of FT-biodiesel production plant supply chain. * for 100 km transport distance. ** pulpwood and heat price varies geographically
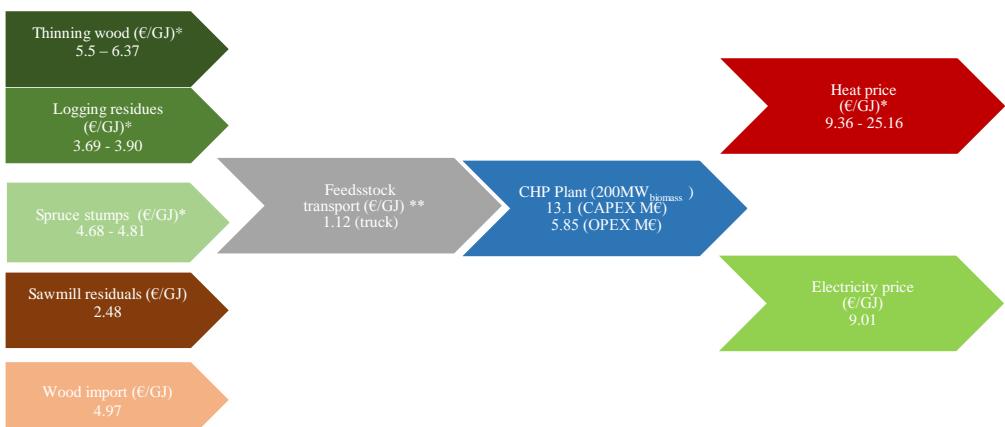
Figure 10. Article III model inputs on the costs of CHP production plant supply chain. *costs varies geographically, ** for 100 km transport distance

2.3 MILP optimization modelling

A MILP model (Wolsey L. 1998) can solve different types of FLPs. BeWhere, a MILP optimization model (Leduc 2009) developed at International Institute of Applied System Analysis (IIASA), Austria has been further developed in this study to optimize the forest based bioenergy production in Finland. BeWhere optimizes the allocation of renewable energy systems from the local (Xylia et al. 2017), regional (Leduc et al. 2010, Patrizio et al. 2015), national (Leduc et al. 2008, Leduc et al. 2009, Schmidt et al. 2010, Khatiwada D et al. al. 2016) or European level (Wetterlund et al. 2013).

The BeWhere Finland model optimizes production plant locations, size and choice of bioenergy technology that should be built either at regional (Article I) or national level (Article II-III) by minimizing the total costs of the supply chain with subjected to constraints as given in the equation (2)

$$C_{total} = C_{supply\ chain} + E_{supply\ chain} \times C_{CO2} \tag{2}$$

Where $'C_{total}'$ is the total supply chain cost, $'C_{supply\ chain}'$ is the costs of the supply chain, $'E_{supply\ chain}'$ is the CO_2 emissions of the supply chain and $'C_{CO2}'$ is the carbon tax for CO_2 emissions.

The supply chain costs $C_{supply\ chain}$ include:
- Feedstock supply: harvesting, comminution and collection costs by wood assortments (young thinning wood, logging residues, stumps, sawmill residuals, pulpwood, sawn wood, wood import)
- Transportation: cost of feedstock transportation from supply site to future production plants and existing industrial users like DH/CHPs, liquid biofuel plants, pellet industries, sawmills, pulp and paper mills), and cost of liquid biofuels transportation (methanol or FT-biodiesel) from plant production sites or import points to gas stations by either truck only or truck and train combinations.
- Bioenergy technology: methanol, FT-biodiesel, or CHP plant installation and production costs
- Distribution costs at the gas stations
- Income from heat and electricity sales
- Government subsidies for young thinning wood and feed in tariff (FIT) for biomass based electricity production
- Price of fossil fuel (transport, peat)

The supply chain emissions $E_{supply\ chain}$ include:
- CO_2 emissions of feedstock procurement during wood production, forest operations, comminution and storage
- CO_2 emissions from transport of feedstock and liquid biofuels by either truck only (Article III) or truck and train combinations
- CO_2 emissions from energy conversion at the production plant
- Offset emissions from displaced fossil transport fuel, heat and electricity

The model constraints are classified in to
- Supply constraints: It includes the amount of feedstock supplied to future plants and existing industries are restricted by the availability of feedstock from the forests,

industries, and imports under different fuel assortments. In other words, feedstock demand from the future and existing uses cannot exceed its availability. At the same time, the existing demand for feedstock in small-scale housing, small and large scale DH/CHPs, and liquid biofuel plants must be first met before supplying to the future bioenergy production plants. Therefore, the model considers that the future production plants can be set up only if surplus feedstock is available for supply.

- Plant constraints: The model uses energy balance equations of different bioenergy technologies to convert the feedstock into bioenergy (methanol, FT-biodiesel, heat and power) through plant conversion efficiency. In addition, the capacity constraints restrict the plants not to produce energy more than its own capacity.

- Energy demand constraints: It implies that the heat energy produced at the production plant should meet the heat demand from the heat density regions within 20 km of heat transportation distance. Similarly, vehicle fuel demand constraint which considers competition between liquid biofuels and fossil fuels is defined for each demand regions. The regions where the heat or biofuel is not supplied with future production plants will be met by existing fossil fuel based supply source.

Hence, the above facility location problem is solved in the optimization software GAMS 22.7 using CPLEX solver (GAMS 2010). The model simulation considers one-year period of plant operation. The model selects the least costly pathway from one set of feedstock supply points to a specific future plant location and further to a set of energy demand points. The scheme of the model is presented in Figure 11. A continuous variable is associated to each arc, representing the delivery of feedstock, and bioenergy produced at the plant (methanol or FT-biodiesel, and heat). Binary variables are associated to the plant nodes, modelling when the current plant is in operation. The model output gives the optimal solution that includes information on policy and markets (what is the share of fossil fuel that can be substituted with bioenergy? what could be the suitable choice of technology with respect to policy instruments e.g., carbon tax? how the market uncertainty could influence on the future bioenergy production?) and techno-economic assessment (how many production plants need to be built? what could be the optimal production plant size? where they can be located?, how much feedstock could be allocated to the production plants and from where it can be taken?, where is the potential energy demand regions and to where the produced energy/liquid biofuels could be sold? and the minimized costs of the full supply chain).

2.4 Scenario formulations

Scenarios were formulated to study what if situations would occur, and what impacts that would bring to the future bioenergy production? This is important as the parameter value assumptions in the model may change with respect to future market conditions. For model simulations in (Article I-III), one baseline scenario which reflects the current market condition was defined as a reference case, and several other scenarios were formulated by varying the key selected parameters (or combination of one or two parameters) to reflect the dynamic market conditions as presented in the table 2. To select the key parameters, several random model runs were made first to identify which parameter has the most influence on the plant production. The final formulated scenarios are then added to the model for optimization.

Costs and emissions of the supply chain

Feedstock	Feedstock transport	Production plant	biofuel transport	Distribution
·stumpage ·harvesting ·forwarding ·chipping ·storage	·truck ·train	·investment ·operation & maintenance ·interest rate	·truck ·train	·gas station

Feedstock supply
- ·forest chips
- ·sawmill residuals
- ·fuel wood
- ·pulpwood
- ·saw wood
- ·wood import

Existing uses
- ·DH/CHPs
- ·small scale heating
- ·pellet factories
- ·pulp & paper mills
- ·sawmills
- ·liquid biofuels

Transport network
- ·road
  (Origin-destination)
- ·rail
  (Origin-terminal-destination)

Candidate sites
- ·feedstock supply
- ·energy demand
- ·pulp & paper mills
- ·existing CHPs
- ·ports

Energy demand
- ·transport fuel
- ·dwelling heat

Optimization modeling

Feedstock supply — Bioenergy plants — Gas Stations

Heat demand

Feedstock transport

Energy delivery

Parameters
- ·biofuel yield
- ·heat yield
- ·electricity yield
- ·emission factor

Constraints
- ·feedstock supply
- ·production plant
- ·energy demand

Other costs
- ·fossil fuel
- ·subsidy/incentives
- ·CO_2 price
- ·heat price
- ·electricity price

Model results

1. plant number
2. optimal location
3. size
4. choice of technology
5. feedstock supply area
6. feedstock share
7. biofuel sold
8. heat sold
9. electricity sold
10. minimized costs of supply chain
    a. feedstock
    b. transport
    c. production
    d. distribution
11. bioenergy cost
12. plant income
13. CO_2 emissions
14. biofuel blending
15. biofuel import

Figure 11. Scheme of the MILP optimization model.

Table 2. Scenario formulation in Article (I-III) based on model parameter variations.

Key parameters studied	Unit	Article I	Article II	Article III
Feedstock supply	%	±50	±50	±30
Industrial competition	%	±50	±50	as per target
Energy demand	%	+25	-	-
Import (wood, biofuel)	%	-	-50	-
Feedstock costs	%	±50	±50	±30
Transport costs	%	+50	±50	±30
Plant investment	%	-	±50	±30
Plant Size	%	±30	±50	-
Plant conversion efficiency	%	+25	+30	-
Heat price	%	±50	±50	±30
Electricity price	%	-	±50	±30
Carbon tax	€/t$_{CO_2}$	up to 220	up to 100	6.5
Subsidy (FIT vs CO_2)	%	-	-	±30

2.5 Model results

2.5.1 Diffusion of methanol and CHP technologies at regional level (Article I)

At first, the model was developed at regional level to determine the optimal production plant locations for second generation methanol and CHP production, and also to determine the preferred choice of technology between the two to utilize the limited local forest biomass resource with respect to economy and environment. The model assumptions were to replace 100% gasoline transport fuel with methanol production and to substitute fossil-based district heating supply with biomass based BIGCC CHP production in Eastern Finland. The model results indicated that two methanol production plants of 360 $MW_{feedstock}$ and 8 CHP plants of 125 $MW_{feedstock}$ could be newly built to meet the local transport fuel and heat demand. The promising locations for the methanol and CHP production plants based on 12 scenario model simulations are given in the figure 12.
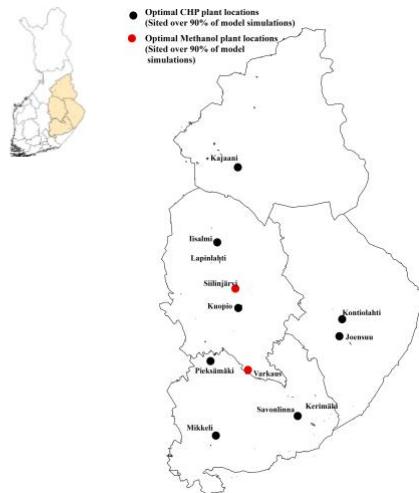
Figure 12. Cost optimal locations for methanol and CHP plants in Eastern Finland.
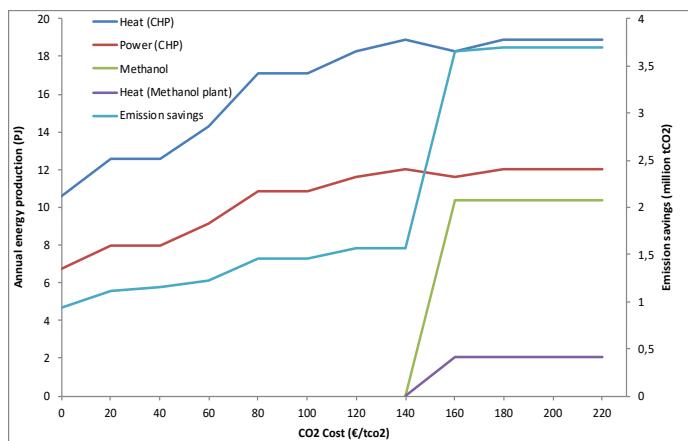
Figure 13. CO_2 cost influence on the diffusion of methanol and CHP production technology.

To determine the choice of technology between the methanol and CHP production, CO_2 cost coupled with seasonal heat demand variations was introduced into the model. Figure 13 presents the influence of CO_2 cost on the technologies, energy production and emission savings. The CO_2 cost input increased the competitiveness of forest biomass based energy generation in Eastern Finland. At low CO_2 cost levels, CHP technology was the preferred choice of technology. A technological transition point at 145 €/t_{co2} CO_2 cost was observed when the technology selection shifted from CHPs to methanol production. Noteworthy is that the emission saving potential also increased with methanol technology selection.

2.5.2 New liquid biofuel production planning strategy for achieving 10% biofuel share in transport by 2020 (Article II)

To meet the 2020 targets of 10% biofuel share in transport, 29 scenarios totaling 145 model runs were simulated to find the cost optimal second-generation FT-biodiesel plant locations in Finland. The model results indicate that five FT-biodiesel production plants of 390 $MW_{feedstock}$ plant size would meet the proposed targets. The cost optimal locations chosen over 90% of the times out of total model scenario simulations is presented in Figure 14.

Model solutions on five FT-biodiesel production plants produced each 5.04 PJ of biodiesel to meet the 2020 target of 10% (25.2 PJ) biofuel share in transport. All five-production plants together used about 56 PJ of forest biomass and sawmill residuals for FT-biodiesel conversion. For the base scenario S0 (which reflects the present market conditions), model allocated mostly energywood (51.10 PJ) as primary feedstock input to the plants then followed by sawmill residuals (4.90 PJ).
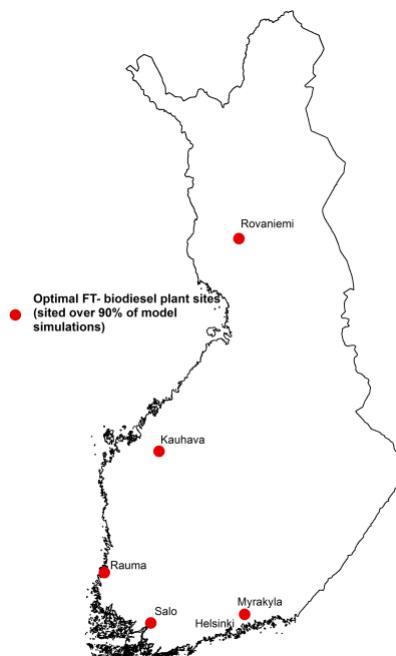
Figure 14. Cost optimal FT-biodiesel production plant locations for new investment opportunities in Finland.

The model results also presents the competition for feedstock resources between different end users. For instance, the model simulation on future market price variation of feedstock between energywood and pulpwood have shown profound influence on the share of feedstock utilized at the production plants (Figure 15). On the other hand, the industrial by-product such as sawmill residuals price variations have shown minimum effect on the feedstock consumption as there was a cap on the maximum supply potential of sawmill residuals at 4.90 PJ. However, either 50% increase in forest harvesting or 50% decrease in existing industrial demand from pellet industries can increase the sawmill residual supply share up to 20% and 16% respectively.

The average cost of FT-biodiesel available at the gas station for distribution was estimated as 22.43 €/GJ$_{biodiesel}$ excluding taxes, incentives or additional income. The share of supply chain cost distribution for all the five production plants was calculated as 26% feedstock supply (24% energywood, 2% sawmill residuals), 7% feedstock transport, 57% production, 1% biofuel transport, and 9% distribution. An additional income from the heat and electricity sales would help to reduce the total costs of the supply chain by 20%.
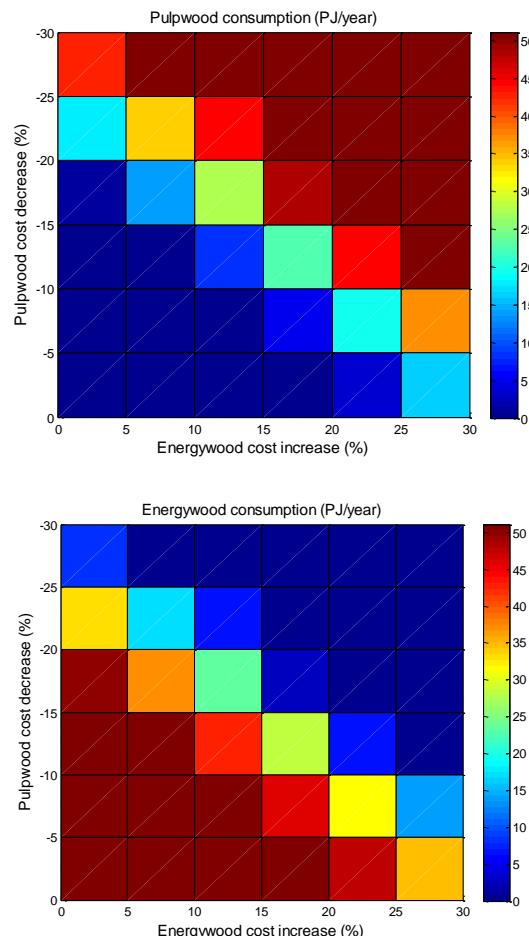
Figure 15. Influence of feedstock cost variations on the pulpwood consumption (top) and energywood consumption (bottom) for FT-biodiesel production plants.

2.5.3 New cogeneration production strategy for achieving 2020 target of forest chips consumption (Article III)

Model results provide different decision making options to meet the 2020 target of forest chips use through new CHP production plant investments, CHP and liquid biofuel investments together, cofiring (coal and forest chips) in existing coal powered plants, and peat fuel substitution with forest chips in existing DH/CHP plants. In Figure 16, the potential use of forest chips in each selected option is presented. The present forest chips consumption in existing DH/CHPs and small house heating contributes approximately 59% of 2020 target of forest chips consumption. In a business as usual scenario, model optimizes ten CHP production plants that could tap the remaining 41% (39.60 PJ) forest chips potential for heat and electricity production. When planned pipeline investments in liquid biofuel production taken into account 22% (21.6 PJ), five CHPs of different plant sizes were built to consume the balance 19% (18 PJ) of the forest chips target. When 15% cofiring was introduced in three coal powered plants (minimum 2000 GWh coal consumption), the total share of forest chips contribution from the existing plants increased to 71% (69.5 PJ), and hence, there was a potential to install seven CHP plants to use 29% (27.7 PJ) of the 2020 target.
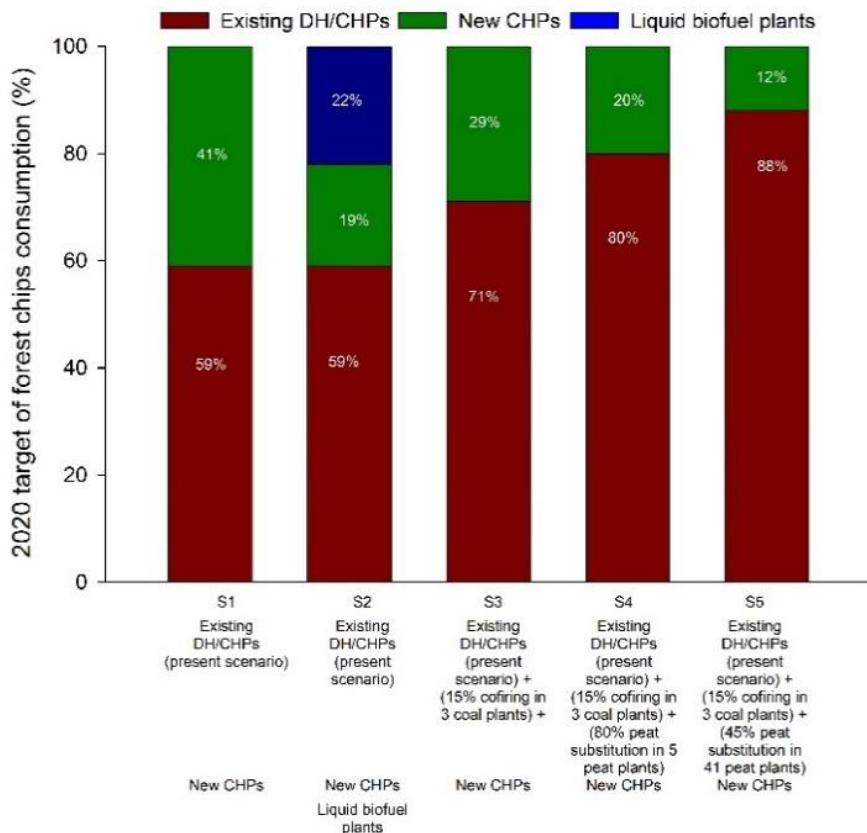
Figure 16. Contribution of forest chips consumption to 2020 target between existing coal and peat based DH/CHP plants, liquid biofuel plants, and potential new CHP plants.

Similarly, 15% cofiring and 80% peat fuel displacement (minimum 650 GWh peat use in 5 plants) in the existing plants would increase the present consumption of forest chips contribution to 80% (77.4PJ) of the total forest chips target. In such situation, five CHP plants were setup to utilize the remaining 20% (19.8 PJ) of forest chips. Furthermore, when 45% peat substitution with forest chips was considered in 41 existing DH/CHPs (minimum 50 GWh peat use in 41plants) together with 15% cofiring in three coal plants, only three new CHP investments would be then needed. In such a scenario, the existing industries can increase their present share of forest chips target by almost 88% (85.3 PJ) while new CHPs can consume about 12% (11.9 PJ) of forest chips target for heat and power production. The results show that future investments in CHP becomes imperative.

Out of 16 Scenarios (65 model runs), the model determined ten CHP plant (200 $MW_{feedstock}$ plant size) locations selected over 90% of the total model run simulations is presented in the Figure 17. The chosen existing coal and peat based DH/CHP plant sites to model the cofiring and peat fuel displacement with forest chips is also included in Figure 17.
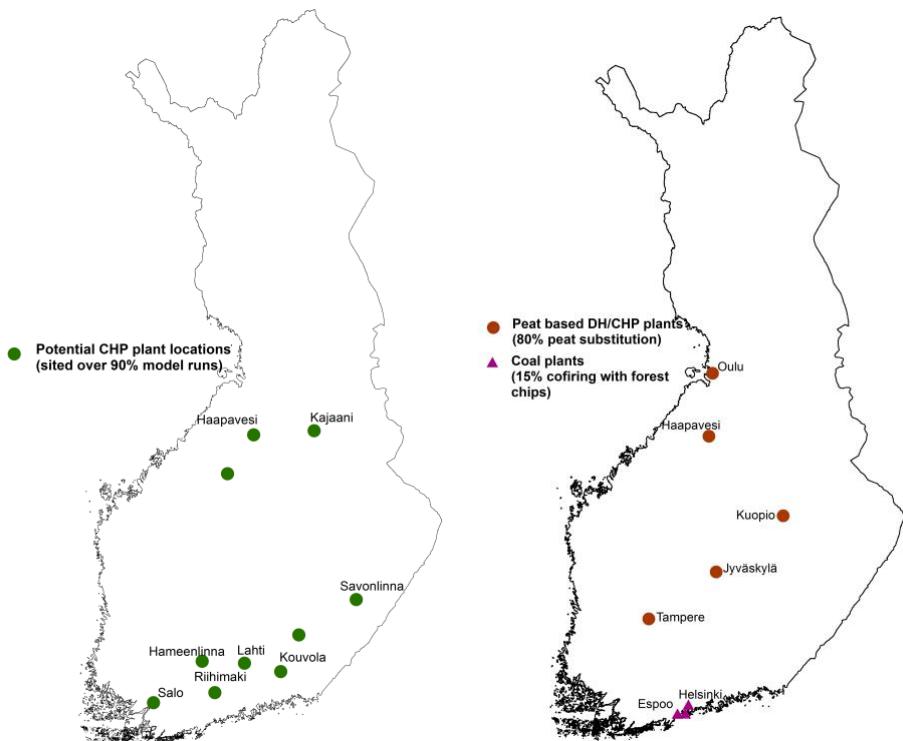
Figure 17. Cost optimal plant locations to meet the 2020 target of forest chips consumption. New CHP production plant locations (left). Selected existing coal and peat based DH/CHP production plant locations (right).

The forest chips supply potential to the ten CHP plants was directly dependent on the final

harvesting and pre-commercial thinning operations. Under present conditions (2017), the CHP plants consumed about 39.6 PJ of forest chips comprising 83% young thinning wood, 15% logging residues and 2% stumps. Furthermore, the market price of forest chips plays an essential factor in determining the share of CHPs fuel portfolio. Therefore, the influence of logging residue supply potential and price of young thinning wood on the fuel allocation to the future CHPs is presented in Figure 18.

On average CHP plant (200MW$_{biomass}$) profit was calculated at 7.58 million euros per year. However, the plant profits varied among CHP plants between 1.49 million euros and 10.11 million euros per year. The average costs of the CHP supply chain comprised of 45% forest chips, 6% transport, and 49% plant production costs. The average plant income contribution comprised of 69% district heat sales, 18% electricity income, 12% bioelectricity subsidy and 1% EU emission allowance price.
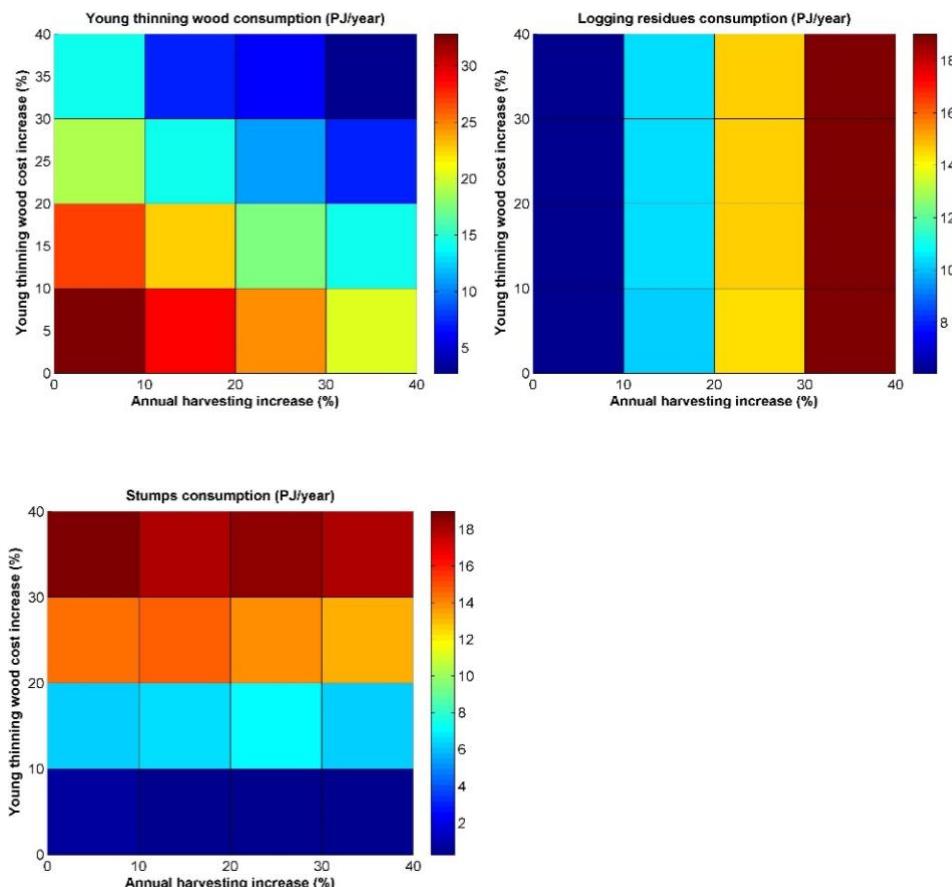
Figure 18. Effects of annual harvesting and young thinning wood price of CHP fuel portfolio.

2.5.4 Model parameter sensitivity analysis

In changing market conditions, the cost of bioenergy production is subjected to variations with respect to model parameter assumptions. Therefore, a sensitivity analysis of model parameter variations (±30%) on the final cost of FT-biodiesel and CHP plant profit is presented in Figure 19.

For FT-biodiesel production, the model parameters such as feedstock availability and transport have shown the lowest cost influence between 1-3% while investment cost and FT-biodiesel conversion efficiency have shown the highest cost influence between 21-27% on the FT-biodiesel cost. The energy wood cost have shown an influence of 8-10%, and the heat and electricity price shown an influence between 3-4% on the FT-biodiesel cost.

For CHP production, sensitivity of model parameters on the CHP plant profits are studied. The parameters such as forest chips costs, operating and maintenance, subsidy have shown an influence between 21-28%. The forest chip transportation cost had an influence between 9-11%. The plant investment have an influence between 51-53%. The electricity price shown an influence between 32-33% whereas heat price have shown the highest influence on the plant profit by almost 125-127%. A 30% decrease in heat price from the current market price would make the CHP investment not economically profitable.
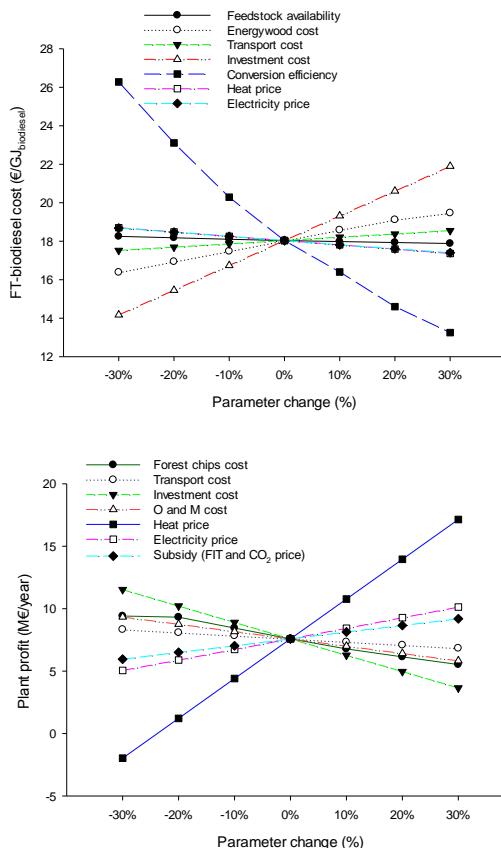
Figure 19. Parameter sensitivity analysis on FT-biodiesel cost (top) and CHP plant profits (bottom).

3. SURVEY

3.1 Survey linkage to the model

In Article I-III, the optimization model provided bioenergy solutions by optimizing two dimensions (2D) i.e., economic and environmental performance of the supply chain. However, in real world, social factors have been also found to have significant impacts on the successful production plant operation (Becker et al. 2013, Altman et al. 2015). Therefore, a three-dimensional (3D) optimization modelling approach becomes essential to optimize the bioenergy production with respect to economy, environment and social sustainability of the supply chain. The figure 20 presents the overview of 3D aspects of the supply chain at each step from biomass production to energy consumers. The social factors in the supply chain could be defined as farmer's willingness to supply biomass for energy generation, consumer's acceptance of biomass based energy for energy consumption and new employment opportunities created during the entire process of supply chain.

   As a first step to integrate the existing optimization model with social dimensions, a case study based on field survey in Poland (Article IV) was conducted to identify how significantly the social parameters could influence the biomass supply to production plant? In particular, farmer's willingness to supply biomass for energy generation taking into account on their knowledge and perception toward biomass for energy uses, cultural/ethical values, preferred contract mechanism, farm level infrastructure for collection, storage and transport, and uncertain market conditions due to changing policies were analysed.
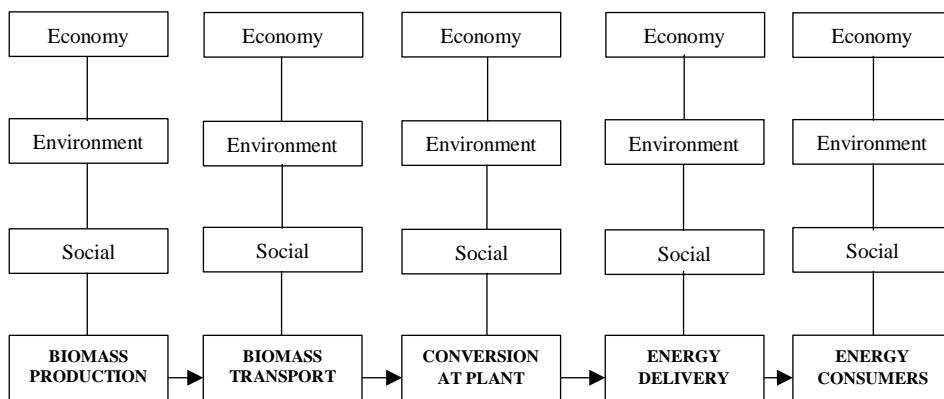
**Figure 20.** Three dimensions (3D) of the bioenergy supply chain

3.2 Survey inputs: study area and survey tool design (Article IV)

Two provinces from central (Kujawsko-Pomorskie) and southern Poland (Upper Silesia) were chosen for the field survey. The central Poland offers huge potential to develop renewable energy production while the southern Poland is abundant with vast coal deposits. Therefore, one virtual biomass CHP site at Torun from Kujawsko-Pomorskie province, and one retrofit cofiring (biomass and coal) CHP plant at Częstochowa from Upper Silesia was selected for this case study (Figure 21). Around both plant locations, farmers were then interviewed with the survey tool to analyse the biomass availability, existing uses and willingness to supply agro biomass for energy generation.

The survey tool was first designed in English and then was translated to local language in Polish. It consisted of three sections. The first section was devoted to socio-demographic information, farm size, source of energy at home, cultural values, cropping pattern and agricultural productivity, and existing uses of biomass at farm level. The aim was to estimate the surplus biomass that can be supplied to the CHPs after meeting their own needs. The second section was devoted to measure the farmer's knowledge and perception of the current biomass market challenges and opportunities through 8 Likert-scale statements. The final section was devoted to measure the farmer's willingness to supply biomass for energy generation through 8 Likert-scale statements.

3.3 Methodology

The field survey was conducted separately in Torun and Upper Silesia. Farms located within 100 km radius of the CHP plants were considered for data collection. A simple random sampling method was employed to identify farmers for the questionnaire survey. Initially, data collection was scheduled to take place in July but it was postponed to August – September due to the timing of harvesting season. In Upper Silesia, the contact details of some farmers were collected from online auction sites, magazines and advertisement sites who usually puts advertisement to sell their agricultural products.
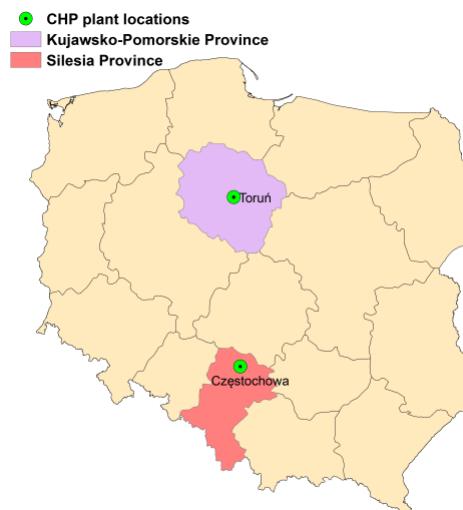
Figure 21. Map of provinces in Poland with two study provinces highlighted.

The email communication between them proved to be unsuccessful. Therefore, data from them were collected in person by taking appointment time to have a face to face questionnaire response. In addition to this, Agricultural Advisory Centre from Częstochowa, Łódź, Opole and Kraków were contacted to assist in data collection from the farmers. Farmers visiting the centre were requested to self-fill the questionnaires and by this method about 50 survey responses were obtained. In Torun, farmer's database that was previously developed by the local partner for earlier research was utilized to conduct the data collection. The survey team mostly visited the farmers in person to collect the surveys. In addition, a small amount of responses were received through posts. In total, 210 completed surveys were collected from both study locations (110 survey responses around Torun and 100 survey responses around Częstochowa). Descriptive statistics were used to analysis frequency of the basic data about farmers. To unveil statistical significance among study variables, a non-parametric tests such as Chi-square through the cross tabulation method was employed. IBM SPSS statistical software version 21 was used in the data analysis.

3.4 Survey results

The demography of the survey respondents from both locations shown that about 63% of the farmers were aged between 40-65 years and 32% were aged below 30 years old. The farmers were predominantly male about 62% in Torun and 74% in Upper Silesia. In Torun, the land holding is classified into 56% owned, 21% leased and 12% mixed ownership whereas in Upper Silesia, the majority of the farmers about 94% owned their agricultural lands. The average size of agricultural land area in Torun and Upper Silesia was 25.5 ha and 7.4 ha respectively. The size varied greatly in both locations from one hectare as the smallest land holding unit to the largest 181 ha in Torun and 60 ha in Upper Silesia. About 50% of the farmers considered farming as the only source of income for their livelihood. Importantly, 75% of the farmers considered farming as their cultural heritage. Most farms were equipped with farm machineries such as tractors (92%), harvesters (44%), baler (49%), and trucks (15%).

In both locations, wheat was the major crop planted followed by barley, corn, rye and triticale with one cropping season. The agro-biomass comprise mostly 'straw' residuals collected after the crop harvesting. In Torun, the existing uses of agro biomass were classified into 15% cooking or heating, 42% animal fodder, 14% animal bedding, 19% field ploughed or not collected and 10% sold. In Upper Silesia, the existing uses of agro biomass were classified into 29% animal fodder, 35% animal bedding, 35% field ploughed or not collected and 1% sold.

The descriptive statistics of the farmer's answers to eight statements related to their willingness to sell surplus biomass for energy production is presented in Table 3. The frequencies and results of the cross tabulation method showing the significance of factors that influence the farmer's willingness to collect and store biomass as part of the biomass supply chain is presented in Table 4 and Table 5. The independent variables selected in the cross tabulation method included: gender, age, land ownership (own), availability of farm machinery (MACH), energy source at home (renewables vs fossil fuel, ENS) and the perceived value of farming (source of income vs cultural heritage, PERC).

Table 3. Farmer's willingness, contract preference and biomass market awareness to supply biomass for energy generation in Torun and Upper Silesia.

Items	Statement	Torun			Upper Silesia		
		Yes (%)	No (%)	INS[1] (%)	Yes (%)	No (%)	INS[1] (%)
Willingness	surplus agro-biomass for selling	30	53	17	33	53	14
I have/can	transport agro-biomass to the power plant with my own vehicle?	22	65	13	21	68	11
	collect and store the agro-biomass in my farm until it is picked up by the purchaser	16	68	16	37	52	11
Contract choice	sell my agro-biomass via binding contract?	35	40	25	24	40	36
I would like to	sell my agro-biomass via fixed price?	38	34	28	30	48	22
	sell my agro-biomass via market price?	19	51	30	29	39	32
Awareness	Selling agro biomass would increase my income?	38	26	36	24	21	47
	There is currently high demand for agro biomass for energy in your region?	30	14	56	16	39	37

[1]INS= I am Not Sure

Table 4. The farmers' willingness to collect and store biomass: Cross-tabulation method

Location	Gender			Age			Land ownership			Chi-square (Asymp. Sig. (2-sided)		
	Male (%)			Young (%)			Own (%)					
	Yes	No	DK[2]	Yes	No	DK	Yes	No	DK	Male	Young	OWN
Torun	19	65	16	14	73	14	17	69	14	0.003	0.038	0.003
US[1]	43	45	8	41	45	10	38	52	8			

[1]Upper Silesia, [2]DK = I don't know, Young = less than 40 years, Own = own land

Table 5. The farmers' willingness to collect and store biomass: Cross-tabulation method

Location	Machinery			Energy source			Perception			Chi-square (Asymp. Sig. (2-sided)		
	Tractor			Fossil Fuels			Cultural Heritage					
	Yes	No	DK[2]	Yes	No	DK	Yes	No	DK[2]	MACH	ENS	PERC
Torun	16	67	16	15	64	21	18	66	17	0.002	0.001	0.001
US[1]	39	53	8	39	53	9	42	53	5			

[1]Upper Silesia, [2]DK = I don't know, MACH = machinery, ENS = energy source, PERC = perception

4. DISCUSSIONS

The long-term goal of the Finland government is to embrace a decarbonized future with a 2030 target to increase the share of renewable to 50% in final energy consumption and to increase the share of biofuels in transport to 30% as approved in the National energy and climate strategy 2030 (TEM 2016). One of the measures include that Finland will phase out the use of coal in 2029 by increasing carbon taxes and introducing new laws on subsidy packages for energy firms that exits the coal use (Euractiv 2018). In addition, cities and rural municipalities in Finland are increasingly investing their efforts to become carbon neutral by reducing CO_2 emissions with the use of domestic wood and other renewable energies in the production of heat, electricity and liquid biofuels. For example, the capital city of Finland, Helsinki aims to become carbon neutral by 2035 with a share of wood-based energy production in their energy portfolio (HK 2018). However, the future success of building a bio-based society depends on several factors such as availability of raw materials, cost effective supply chain, existing industrial infrastructure, innovation, new investments, societal acceptance, product markets, funding, environmental sustainability and required policy support mechanisms.

Therefore, to build carbon neutral cities, an efficient and geographically explicit energy planning strategy is imperative to replace the imported energy such as coal or oil with domestic renewable energy resources. Finland with its long tradition of using wood fuels for energy (heat and power) coupled with the second-generation BTL technological expertise offers an opportunity to paradigm shift from existing fossil-based economy to future bio based economy. The national bioeconomy strategy (MMM 2014) strives to increase the existing national bioeconomy output from 64 billion Euros (2013) to 100 billion euros by 2025, and to create 100,000 new jobs.

Large-scale new investments are greatly needed to achieve national targets and goals of Finland. However, a commercial large-scale bioenergy production requires an economy of scale to be achieved as larger production runs lower unit cost of biofuel or energy produced. On the other hand, the transportation distance for biomass may increase with proportional to plant size increasing the cost of transport and the total unit costs. Furthermore, the scale of bioenergy investment also depends directly on the energy demand capacity of the regions. Integrated biorefineries with local pulp mill or large CHPs plants help to overcome the economy of scale and energy demand capacity constraints as it produces several main products such as heat, electricity, transportation biofuels and bio-based chemicals. Nevertheless, integration at all existing forest industrial clusters may not be feasible due to safety issues, technical risks, feedstock availability, competition, and existing energy supply (e.g., district heating from other sources such as DH/CHPs).

In this study, potential expansion of standalone both liquid biofuels and CHP investments in Finland were investigated by employing a spatially explicit techno-economic optimization model to optimally locate the new productions plants by minimizing the costs of the supply chain with respect to biomass resource, existing industrial competition, and energy demand. Model results proven that the primary factors such as the availability of biomass and prices, biomass and biofuel import prices, nearness to the market, transport infrastructure and existing industrial competition affects the future production plant location optimization as also confirmed by Hilmola et al 2010, Leduc et al 2009, and Jong et al 2017. The model results on the spatial distribution of new FT-biodiesel or CHP production plant locations indicate that most of these plant locations are concentrated in the Southern and South-western part of Finland (Article II-III). The liquid biofuel plant sites are located closer to the feedstock supply regions whereas CHPs are mostly positioned around high heat demand regions within a 20-25 km heat transportation distance (Article I-III). The model solutions on liquid biofuel

plant locations also include the possibility to sell the plant residual heat to the nearby municipalities (Article I-II). This include also the heat load variations between peak winter and summer season. Furthermore, the plant sites are well served by both roadways and railways for feedstock and biofuel transport. Interestingly, 61% of these production plant locations have also access to ports and inland waterway transport as well.

In addition to plant location optimization, the model results also provide information on appropriate technology that is suited to fulfil the local needs of a given area. In Article I for Eastern Finland, diffusion of technological choice based on CO_2 costs coupled with season heat demand variations revealed that biomass to methanol production technology was preferred over CHP generation at higher CO_2 costs (>145 €/t_{co2}). This is because methanol fuel saves more emissions per unit of energy generated although CHP technology has high overall conversion efficiency. Nevertheless, CHP production is more cost competitive and economically viable at lower CO_2 costs. This implies that from the emission point of view, biomass can be efficiently used in liquid biofuel production to substitute fossil fuels than in CHP plants to generate heat and power when the carbon costs are set higher. Azar et al. 2003, Wahlund et al. 2004, Schmidt et al. 2010 and Börjesson et al. 2010 observed the similar findings that the deployment of biomass conversion technologies shifted from heat and power production to liquid biofuels when carbon tax was introduced in their model analysis. Noteworthy is that Finland was the first country in the world to introduce carbon tax in 1990 to provide climate solutions (UNFCCC 1991). Since 2013, carbon tax is calculated as the combination of carbon and energy tax. Currently, the CO_2 tax is applied to most fossil fuels users in road transport, domestic off-road transport, industry, agriculture and fishing, residential and commercial except electricity production.

The obligatory biofuel blending with transport fuel for distributors has increased the innovations on second-generation BTL technologies boosting the new biofuel plant investments and several pipeline projects are en-route to be realized (IIF 2018). Large-scale biofuel plants require huge amount of feedstock from various sources like logging residues, sawmill residuals, and other industrial streams. In Article II, the model provided solutions on what type, and share of feedstock can be allocated to future FT-biodiesel production plants with respect to its costs of the supply chain. Under present market conditions, the FT-biodiesel production plants consumed about 91% energy wood and 9% sawmill residuals. The sawmill residuals are the cheapest feedstock but their availability is limited and proportional to sawn timber production which depends on the annual harvesting and/or the situation of lumber market. The energy wood is produced mainly from the pre-commercial thinning of young wood and logging residues obtained from final harvesting. The model simulations also shows the vulnerability of feedstock price variations which revealed that 30% increase in energy wood cost would change the feedstock share of FT-biodiesel plants to 40% energy wood, 51% pulpwood and 9% sawmill residuals. Similarly, 30% decrease in pulpwood costs would completely replace the energy wood share with pulpwood in the biodiesel production. Though in reality the pulpwood are not meant for neither liquid biofuel nor in CHP production, model results emphasized that the uncertainties in market price can alter the end use of that feedstock.

As per present legislations, subsidies are granted 100% for small diameter wood (or otherwise non-commercial wood material) used in CHPs for only electricity production but not heat. In addition, Feed in Tariff (FIT) based on price of CO_2 emission permits coupled with peat tax was introduced to increase the share of forest chips in CHPs. The introduction of subsidies as a driving policy decision is in force to achieve 97.2 PJ of forest chips consumption by 2020. As it stands today, only 59% of 2020 target of forest chips consumption has been achieved. In Article III, the model results showed that the share of forest chips consumption in existing coal plants and peat-powered plants can be increased by cofiring

coal with forest chips and substituting peat with forest chips. However, the new CHP investments are needed if 2020 targets have to be achieved. Noteworthy is that the existing CHPs are not able to increase the share of forest chips consumption due to prevailing low electricity prices and relatively low peat tax. Actually, the use of forest chips in CHPs have been on the decline by 20% since 2012 despite the support for electricity generation but its use has been steadily increasing in heat only plants for example from 2012 by 47%. The cost effective supply chain of forest chips procurement for CHPs is a prerequisite for profitable CHP operations. The model results showed that the effect of annual harvesting and young thinning wood price on the resource allocation of future CHPs showed greater influence on the type of feedstock chosen for heat and power production. The plant consumption of logging residues increased by three folds when the annual harvesting was increased by 30% from the present level. On the other hand, 30% increase in young thinning wood price would force CHP plants to include stumps in the fuel mix (36% young thinning wood, 16% logging residues and 48% stumps). However, in reality such high share of stump use in energy production would cause severe environmental and detrimental effects on forest soil structure, soil fertility and loss of soil carbon (Moffat et al. 2011). The Finnish forest strategy aims to increase the present annual harvesting level from 58.5 million m3 to 80 million m3 by 2025, which would eventually also increase the supply of logging residues, stump and industrial by-products like sawmill residuals for energy consumption.

Besides market factors, farmer's ability and willingness to supply biomass for energy generation also plays a vital role in the successful expansion of bioenergy industries. Survey results from Poland case study revealed also that unwise policy decisions and unfavorable market conditions could adversely affect the farmer's willingness to collect, store and transport biomass to energy installations. Results have shown that over two-thirds of farmers were unwilling to supply biomass owing to unstable biomass market conditions marked by low demand and price. In addition, only few farmers (19% in Torun and 29% in Upper Silesia) were interested to have a biomass supply contract with companies as per market price. Most farmers preferred to have a binding contract with a fixed price for long term. The study also revealed that willingness to supply decision varied with respect to gender, age, land ownership, farm machinery infrastructure, energy source at home and perception about biomass for energy production. Similar type of survey study conducted by Rämö et al 2009 among private forest owners revealed that almost 50% forest owners were uncertain of their willingness to supply biomass due to low price, limited knowledge and underdeveloped biomass market at that time. In Finland, private forest owners own almost 61% of the forests in the country, and their willingness to sell forest biomass to energy industries becomes crucial for the energy industries. Inclusion of willingness to supply in the biomass supply chain would help to analyze the biomass supply potential realistically in a given area. Therefore, the methodological approach followed in Poland's case study (Article IV) could be further modified to study the Finnish forest owner's attitudes towards supplying wood biomass to energy production.

Moreover, consumer's acceptance and willingness to use bio-based solutions would also define the future growth of bioenergy industries. In Finland, the popularity of low emission cars have continued to raise and diesel driven cars have now the full possibility to use renewable diesel without any obstacles. Statistics Finland 2017 report on GHG emissions shows that country's net emissions in to atmosphere declined by 9% when compared to 2016. Since 1990, net emissions have decreased by 49% (EU average is 26%). The use of wood fuels in primary energy consumption and in traffic have helped to cut down the emissions in energy and transport sectors. The model findings in Article II shown that installation of five FT-biodiesel production plants could contribute 4% of total emission reductions from the 1990s level.

5. CONCLUSIONS

The wood fuels from the Finland's forests will continue to play a vital role in replacing fossil fuels to achieve country's climate and energy goals. This optimization modelling approach provide solutions for the whole value chain from forest to energy end-user to efficiently utilize the limited forest resources in a cost efficient and environmentally sustainable manner in future bioenergy production plants. The model solutions include cost-optimal production plant locations, plant size, choice of technology, feedstock resource allocation with import options, minimized cost of supply chain, income from by-product sales and emission savings. In this study, the optimization model has been applied at both regional and national level to design an energy planning strategy. At regional level (Eastern Finland), the model optimized two bio-methanol production plant locations to achieve zero fossil gasoline consumption in the transport. The results also provided insights into the introduction of carbon tax as a policy measure that could yield cost-effective emission reduction measures. At national level, model results presented the optimal strategy to achieve 2020 targets of biofuel share in traffic and forest chips consumption in combined heat and power production. To achieve 25.2 PJ of biofuel production in traffic, the model optimized five FT-biodiesel plant (390 MW$_{feedstock}$ each) locations producing biodiesel at an average cost of 18 €/GJ$_{biodiesel}$ including by-products income. To achieve 97.2 PJ of forest chips consumption, ten new cost optimal CHP (200 MW$_{feedstock}$) plant locations were identified. Certainly, the evaluation of model results indicates that the spatial distribution of feedstock resources, industrial competition and energy demand coupled with geographical cost variations shown significant influence in plant location optimization. The liquid biofuel production plants were located proximity to the forest resources while the CHPs were mostly positioned around cities.

The model also presented valuable information on how market uncertainties would affect the future biodiesel or CHP production. Mainly feedstock cost variations were found to have significant influence on the type of feedstock used at the plant. The energy wood from forests, and sawmill residuals from sawmills are the favourite choice of feedstock because of less expensiveness and more availability. Sensitivity analysis revealed that investment costs, conversion efficiency, heat price are the most plant influential parameters followed by feedstock cost, electricity price, subsidies, and transport cost. The variation of these parameters in the absence of government subsidies would cause challenges to promote the use of forest chips in the future biofuel or CHP industries.

Survey analysis helped to understand that willingness of feedstock suppliers (farmers or forest owners) would also play a vital role for the future success of biofuel or CHP industries. Uncertain market conditions favoured by unstable policies forced two-thirds of Polish farmer's unwillingness to supply biomass for energy generation. Therefore, formulation of socially inclusive policies are imperative for the future success of bioenergy industries with long-term market stability.

To conclude, this conceptual and mathematical modelling effort contributes greatly to an understanding of the feasibility, constraints, and potential for the future investment opportunities of bioenergy production in Finland. The results of this modelling study could be of significant importance to local governments, companies and communities to take new investment decisions on the liquid biofuel and CHP production in Finland. In addition, integrating social aspects of bioenergy production into model analysis would further enhance the investment decision and to expand the positive impact of biomass use in energy generation.

6. FUTURE WORK

The present modelling framework offers opportunities to integrate also the societal factors such as willingness, acceptance, perceptions and employment influencing the potential expansion of bioenergy industries. The resource input data of the model would be updated with both agro-biomass and Municipal Solid Wastes (MSW) supply potentials. Similarly, the technological portfolio of the model would be further extended to include other biomass conversion pathways such as Synthetic Natural Gas (bio-SNG) production, pyrolysis bio-oil production, and ethanol production. Furthermore, potential integration of biorefineries in the existing forest industrial clusters with closed loop energy ecosystem will be included in the model. Bioenergy with Carbon Capture and Storage (BECCS) offers great potentials to make bioenergy solutions 'carbon negative' and therefore, its potential applications would be further studied in the model analysis. In addition, Life Cycle Assessment (LCA) of the supply chain model would help to make more informed decisions on the technological investments with more emission reduction impacts. The existing supply chain of the model does not include waterway transport system to transport biomass or biofuel and therefore, it would be added in the future transport network analysis. With further model extensions, strategies to achieve 2030 targets of Finland with required policy options could be presented to decision makers for an effective geographical energy planning with low-carbon solutions.

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APPENDIX 1: Database of BeWhere Finland model

No	Model variables	Data description	Data Source*
1	Forest resources	Multi Source National Forest Inventory (10 and 11)	http://www.metla.fi/ohjelma/vmi/vmi-moni-en.htm
2	Wood imports	Finnish annual forestry statistics	Finnish Statistical Yearbook of Forestry
		Finnish Transport Agency	www.portal.liikennevirasto.fi
3	Forest industries	Pulp and paper industries	www.forestindustries.fi
		Sawmill industries	www.sawmilldatabase.com
		Pellet industries	Heinimö et al 2009
4	Energy industries	Small scale DH plants	http://www.lampoyrittajat.fi/Kartta
		Large DH/CHP plants	www.tts.fi, www.kuntaliitto.fi, www.kyrotekniikka.fi/referenssit www.tetrays.fi, www.tulostekniiikka.com, www.energia.fi
		Liquid biofuel plants	www.fortum.com, www.st1.eu, www.kaidi.fi, www.greenfuelnordic.fi, www.borealbioref.fi, www.ymparisto.fi
5	Transport network	Digi road network	www.digiroad.fi
		Rail network	www.maanmittauslaitos.fi
		Railway terminals	www.vr.fi
6	Energy demand	District heat – Building stock	www.stat.fi, www.energia.fi www.traf.fi
		Transport fuel – Vehicle stock	
7	Firewood demand	small scale housing	www.stat.luke.fi, www.stat.fi

*In addition to the above listed data source, published literatures, field visits and personal communications with respective organisations were also included in the final calculations. Each plant information was crosschecked about their actual location, active operation and other plant data.