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Replacing fossil fuels with bioenergy in district heating – Comparison of technology options

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ABSTRACT

We combine previously separate models of Northern European power markets, local district heating and cooling (DHC[2]) systems, and biomass supply in a single modelling framework to study local and system level impacts of bioenergy technologies in phasing out fossil fuels from a DHC system of the Finnish capital. We model multiple future scenarios and assess the impacts on energy security, flexibility provision, economic performance, and emissions. In the case of Helsinki, heat only boiler is a robust solution from economic and climate perspective, but reduces local electricity self-sufficiency. Combined heat and power solution is more valuable investment for the system than for the city indicating a conflict of interest and biased results in system level models. Bringing a biorefinery near the city to utilize excess heat would reduce emissions and increase investment's profitability, but biomass availability might be a bigger limiting factor. Our results show that the availability of domestic biomass resources constrains bio-based technologies in Southern Finland and further highlights the importance of considering both local and system level impacts. Novel option to boost biorefinery's production with hydrogen from excess electricity is beneficial with increasing shares of wind power.

1. Introduction

Meeting the ambitious targets of the Paris Agreement requires significant greenhouse gas (GHG) emissions reductions in all energy production and consumption [1]. The heating and cooling sector plays a decisive role [2], as it currently accounts for half of the European Union's (EU) final energy consumption and 75% of heating and cooling was generated with fossil fuels, mostly natural gas in 2018 [3].

Two main options for decarbonizing heating and cooling are electrification and use of bioenergy. Electrification with heat pumps [4,5] is currently driven by sharp reductions in the generation costs of solar and wind power, together with policies that incentivize decarbonization [6,7]. Electrification of heat also increases opportunities for demand response and heat storages that can contribute towards balancing generation from variable renewable energy (VRE) sources like wind and photovoltaics.

Increased use of bioenergy, when produced from sustainable biomass feedstocks, is another main decarbonization option. Bioenergy currently represents a “drop-in option” that enables significant decarbonization without major changes at system level. New biomass-based technology options include integrated processes, for example the production of transport fuels and utilizing the excess heat in district heating (DH) [8]. The production of biorefineries can be further boosted by producing hydrogen from excess electricity in the case of high amounts of wind and solar power. However, expanding the use of bioenergy has its own constrains, most important ones being its availability [9,10], logistics of raw material [11,12], and likely competition of resources between energy and non-energy uses [13,14]. At the same time, there is pressure to increase CO_2 removals by the forests [15], which prevents significant increases in harvests [16].

In Finland, low-carbon solutions for the heating sector are currently in high demand, as a new law was recently passed that bans the use of coal in power and heat sector in 2029 [17]. This poses a challenge particularly for the Finnish capital Helsinki, where both natural gas and coal are used in large CHP units to provide heating and electricity. Current plans for phasing out coal

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[2] District Heating and Cooling (DHC).

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include investments in bioenergy together with increased use of heat pumps, heat storages and improved recycling of excess heat [18]. Consequently, Helsinki region is a suitable case study for heat sector decarbonization with real decisions to be made. Existing CHP generation in cities needs special considerations, when the amount of VRE is foreseen to increase.

Although meeting the ambitious mitigation goals requires quick action, it is important to understand the long-term implications of investment decisions to avoid harmful lock-in effects [19]. Various studies have assessed the impacts of transition to low carbon district heating [20–27]. Some studies have focused on the role of heat pumps and sector coupling in the heating sector both at Nordic [4,27,28] and city level [23,25,26]. Another trend foreseen by studies at the Nordic level is the replacement of CHP units with heat only boilers (HOBs), although HOBs are less attractive than heat pumps if either low electricity prices or high biomass prices are assumed [27]. Rämä and Wahlroos [25] concluded that the use of heat pumps in the Helsinki heating system may reduce heat load of the CHP units to a level that creates significant economic pressure on their operation [25]. Mikkola and Lund [29] concluded that energy system inflexibility can hinder the role of wind power in the Helsinki region, whereas heat pumps could enable wind power to replace fossil-based CHP. Helin et al. [27] studied the effects of heat pump investments on existing CHP units on a Nordic level and showed that large-scale heat pump investments decrease the price of district heating, while electricity price may increase. Hast et al. [20] studied low-carbon scenarios for Helsinki and concluded that both the consumption of wood pellets and electricity will increase. CCS technologies and small nuclear heat reactors [30,31] could also play role in reaching carbon neutrality by 2050 but are out of the scope of this study.

Many of the above-mentioned studies on the development of the DH system consider the problem from one viewpoint, generally from the larger system perspective without considering local constraints from the DHC grid or biomass availability. Similarly, some studies limit the analysis at city level, and acknowledge the benefits to coupling such analysis with the wider energy system [21,24].

To overcome the constraints and consequent knowledge gaps of separate sectoral models, we combine and model simultaneously Northern European power system, local DHC systems, and forest biomass supply in Finland. This allows studying options to replace fossil fuels in DH system both from local and systemic perspective. The approach is novel in the way that it combines multiple energy system layers in a single optimization task. In addition, the used model handles unit commitment and economic dispatch, stochastic forecasts, and reserves that are all relevant parts of the modern energy systems. We concentrate on studying the role of biomass-based heating solutions in replacing fossil fuels in the DHC system under different energy market scenarios in 2030 and beyond, and analyse impacts at the city and system level.

Following technology options are investigated in detail: heat only boiler (HOB), combined heat and power (CHP) unit, a biorefinery co-producing district heat and advanced biofuels for the transport sector as well as a biorefinery as the previous one but with hydrogen (H_2) enhancement [32,33]. Each technology is separately studied under different scenarios, where the amount of VRE, heat pumps, the price of CO_2 and the availability of biomass is varied. The performance of these investment options are examined using several indicators measuring a range of functionalities and impacts of the investments, divided in four categories, namely energy security, flexibility provision, economic performance, and climate impact.

Finally, we demonstrate how biomass-based heating solutions perform under varying conditions and what are the trade-offs between different indicators, and discuss the role of biomass-based heating in an urban energy system in 2030 and beyond.

2. Methods and assumptions

2.1. Modelling with backbone

Backbone is a highly adaptable energy systems modelling framework, which can be utilized to create models for studying the design and operation of energy systems. It allows to model both high-level large-scale systems and fully detailed smaller-scale systems. It has been previously used and validated in multiple peer reviewed studies, see chapter 2.3.

In this work, Backbone will be run as a unit commitment and economic dispatch model with a rolling time horizon. Slow units are presented with integer start-up and shut-down decisions. The power system includes reserve requirements and forecast errors. In this study, Backbone is not making investment decisions – instead, we focus on accurate operational representation of pre-made bioenergy options. Economic modelling in the used Backbone model instance takes assets as given and only optimizes their use according to marginal costs of production, while simultaneously ensuring hourly balance between energy supply and demand while respecting reserve requirements.

The modelled system is presented in Fig. 1. For presentation clarity, the model structure is divided into three ‘modules’. All modules are optimized simultaneously as a single model. Details of each module are presented in Table 1 and are briefly described below:

- Module A describes the ‘Northern European power and heat system’ (including Finland, Sweden, Norway, Denmark, Germany, Estonia, Latvia, Lithuania, and Poland). This part of the model represents the development of the surrounding system and enables modelling the impacts of increased VRE (mostly wind power), flexibility from reservoir hydro power, electricity trade, and large-scale system impacts from different decarbonization options.
- Module B describes the forest biomass supply in Finland, including domestic forest biomass, industry waste wood, and imported biomass. For modelling purposes, Finland is divided into 19 regions providing biomass either directly or through terminals to the power and heat plants. Considered biomass feedstocks include industry waste wood (e.g. bark and sawdust), forest logging residues, small diameter stem wood, and imported pellets.
- Module C describes the power and heat sector's biomass demand in Finland. For modelling purposes, Finland is divided into 10 heating regions, one of which is the Helsinki's DHC system. This part of the model enables to study the availability of biomass for Helsinki, considering demand in other heating regions, and the impact of the biomass-based heating solutions in future energy system in light of the information obtained from Modules A and B.

A schematic presentation of the modelled energy system is shown in Fig. 2. Local DHC grids are connected to Northern European electricity grid, which contains electricity only units and electricity storages in the form of hydro power reservoirs. New VRE units are built into Northern European grid, and new heating and cooling units are built to local DHC grids. Thermal heat and power units include both existing units in the model area, and studied investment options in Helsinki, the focus of the analysis. Liquid fuels produced in the biorefineries are sold to the transport market.

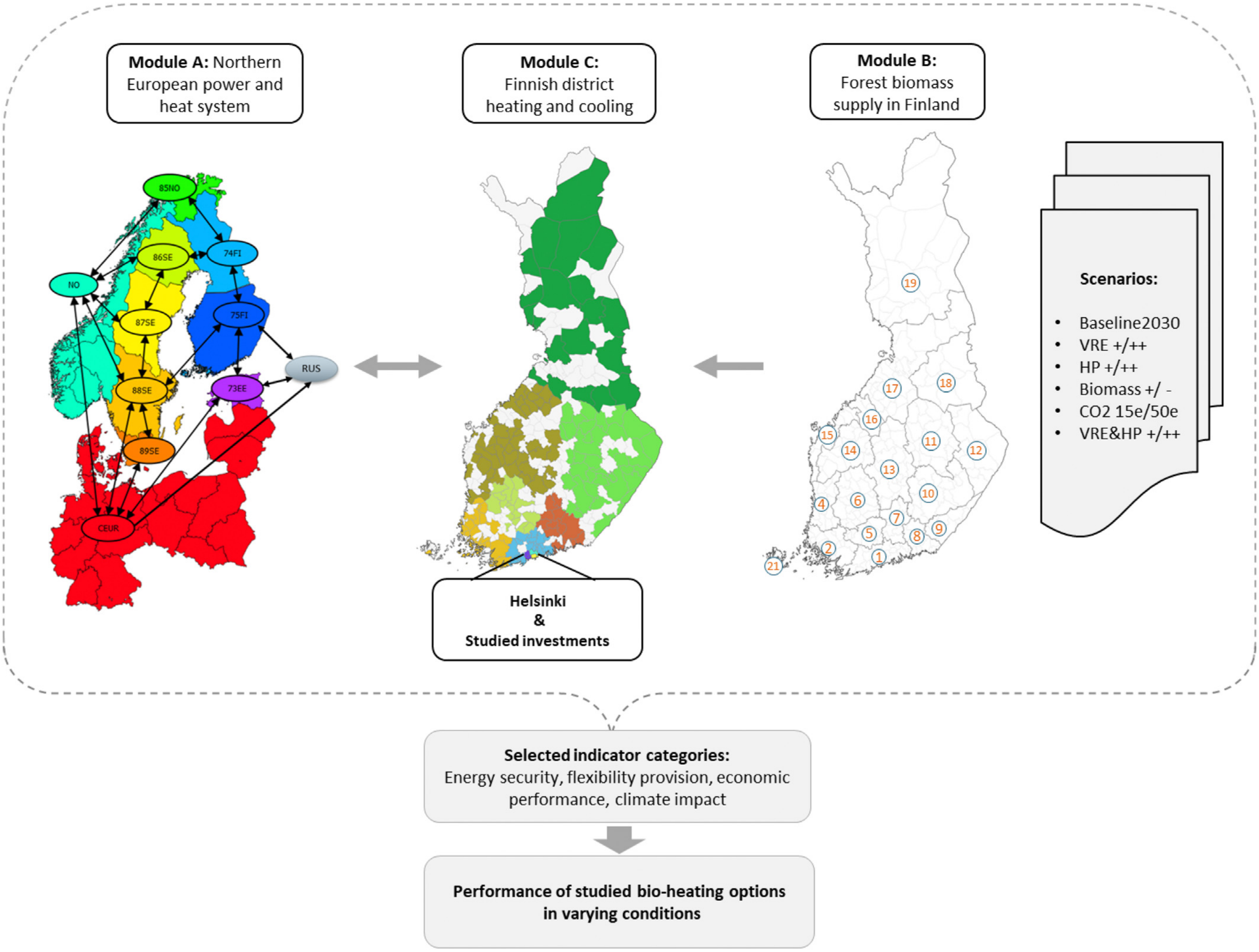

Fig. 1. Illustration of the Backbone model framework instance developed for the purposes of this study. The modelled system includes Northern European energy system (Module A), more detailed power and district heating model for Finland (Module C), and forest biomass supply for Finland (Module B). Each module fully interacts with each other and are optimized simultaneously.

2.2. *Baseline 2030 scenario*

Our baseline 2030 scenario assumes a plausible development in the Northern European power and heat system to meet at least 40% GHG reductions in the EU. The target is achieved with investments in variable renewables, building new interconnectors, and increasing the price of carbon emissions. Table 1 summarises main assumptions for each module in our baseline scenario.

The data of module A has been previously used and documented by Rasku et al. (2019) [34] and Rasku et al. (2020) [35]. The modelling approach in module B has been previously used by Anttila et al. (2018) [10], but it was adapted here by summing the supply to 18 regions. The data and approach in module C has been built on the work of Lindroos et al. (2019) [36].

The uniqueness of this study arises from combining all these separate modelling efforts under a single model that enables much wider analysis and comparison of local and system level impacts. Combined modelling allows much more flexible sensitivity analysis as previously separate modules now directly interact with other modules and can set operational limits, e.g. through the regionally available amount of biomass.

The district heating demand will change in each region based on the development of DH customers, heating degree days (HDD), and energy efficiency measures. The future demands of modelled heating regions are estimated based on population (Pop) statistics and projection of the Finnish Statistics Centre [56], statistics and projection of heating degree days by the Finnish meteorological institute [57,58], and linear projection of historical DH demand per capita after normalizing the historical data with historical heating degree days.

Heating degree days and DH demand per capita are projected to decrease from 5% to 10% between 2017 and 2030 and from 8% to 13% from 2017 to 2040 (Table 2). In some regions, these trends are partly or fully compensated by increasing population, but some regions might see almost 30% decrease in DH demand from 2017 to 2040.

Fig. 3 presents the main results from baseline (BSL) 2030 model run, and compares them to 2017 statistics [41,43,59]. The electricity generation in the Northern European power system is decarbonized mainly with increasing amounts of wind and solar power. Biomass and hydropower generation also increases to some extent. The total demand increases due to electrification, and 35% decline in the generation of nuclear electricity has been assumed in source data. Logging residues, small diameter stem wood, imported

Table 1
Parameters used in modelling.

Parameter	Module A “Northern European power and heat system”	Module B “Forest biomass supply in Finland”	Module C “Finnish district heating and cooling”
Model year	2030		
Model run type	Dispatch run, investments as scenarios		
Modelled regions	Nordic countries, Baltic countries, Germany, Poland	Finland divided to 19 regions (NUTS 3 regions)	Finland divided to 10 areas that are formed by grouping the largest cities and their surrounding areas. Helsinki, Espoo, and Vantaa have separately operated grids with weak DH connections.
Modelled grids	Electricity and district heating (DH)	Biomass supply and terminals	District heating (10 regions) and district cooling (Helsinki and Espoo only)
Transfer links	Electricity interconnectors from ENTSO-E Ten Year Network Development Plan 2018 [37]	Transfer of logging residues allowed within 200 km distances from the supply region.	20 MW DH links between Helsinki-Vantaa and Espoo-Vantaa
Generation capacities and annual demands	National data from PRIMES modelling (Reference 2016 [38], and GHG 40% scenarios [39]) and regional data from EU E-highways 2050 project [40].	Regional annual amounts for logging residues and small diameter stem wood from national resource centre [41]. Annual amount of wood residues from industry from the Finnish district heating statistics. No upper limit for pellet imports.	Regional capacities and demands from power plant register [42] and Finnish district heating statistics [43]. Coal based capacity phased out according to Finnish government's decision to phase out coal use in public power and heat by 2029 [44]. DH demands calculated based on change in population, heating degree days, and energy efficiency, see Table 2.
Detailed unit parameters	Technology Data for Generation of Electricity and District Heating from DEA [45].	Storage losses of biomass: 3%/month for logging residues and industrial wood residues, 2%/month for small diameter stem wood and wood energy stored in terminals [46,47]. Maximum share of 10% of logging residues to terminals, the rest is small diameter stem wood [48].	Assumptions on unit parameters based on existing units [42,43], planned/expected retirements, and announced investments. CHP units in Helsinki, Espoo, and Vantaa are modelled unit-by-unit, other units are aggregated by unit type and fuel.
Reserve demand	Electricity: Nordic System Operation Agreement and Continental Europe Operation Handbook	–	DH: +30% capacity over average winter peak demand according to current capacity margins in Finnish DH grids.
Storages	Reservoir hydro is the largest electricity storage in the region. Modelled according to current units and reservoirs [49,50].	Biomass can be stored on road side (no limits on amount), and biomass terminals. Biomass terminal storage capacities are limited for each region based on [48].	DH: 14 GWh (140 MW) for Helsinki, 1h peak demand for others (0.9–1.7 GWh, 90–170 MW) Biomass: 12h on-site storages modelled for thermal units consuming biomass
Time series	Hourly electricity demand from ENTSO-E and Nordpool [49,50]. Variable renewable dataset from MERRA-2 data [51–53]. Modelled weather forecast ranges from ECMWF [35].	Assumed flat hourly supply of each biomass type.	District heating time series constructed from open data from Helsinki Energy [54].
Fuel types	Natural gas, oil, coal, biomass, hydro, wind, PV, nuclear	Finland: Logging residues, small diameter stemwood, and wood residues from forest industry. Imported wood pellets available at coastal regions.	Natural gas, oil, waste, coal, biogas, energy wood from module B, peat.
Costs and prices	CO$_2$: 30 €/tCO$_2$, hard coal: 15.5 €/MWh, lignite: 8 €/MWh, gas: 25 €/MWh, oil: 53 €/MWh, waste 0 €/MWh, FI biomass 10–35 €/MWh, peat: 15 €/MWh, biomass excl. Finland 24 €/MWh, electricity: modelled, heat: modelled.	**Finland**: Small diameter wood: 21 €/MWh + transfer cost if transferred to other regions, Logging residues: 19 €/MWh + transfer cost if transferred to other regions, wood residues: 10 €/MWh, transfer not allowed, pellets: 35 €/MWh, peat: 15 €/MWh **Transfer costs**: 0.03–0.04 €/MWh/km, max 200 km.	See module A and B
Taxes (fuels, electricity)	No taxes modelled outside Finland	No taxes for biomass	DH generation taxes are defined by fuel and unit type: Gas CHP 12 €/MWh$_{DH}$, gas heat only 17 €/MWh$_{DH}$, oil heat only 22 €/MWh$_{DH}$, electricity taxes + distribution costs large heat pumps 30 €/MWh$_{EL}$ [55].

pellets, heat pumps, and increased use of natural gas replace all of coal and 36% of peat in the district heating fuel mix.

Fig. 4 shows the available and unused forest energy wood in different parts of Finland in the baseline 2030 scenario. In total, 23.8 TWh of sustainable biomass is available for use in Finland for power and heat sector. 70% of it is available in the Central and Northern parts of the country which have the largest forest resources. These areas have invested to biomass-based power and heat capacity and do replace coal and peat with biomass, but approximately 7 TWh of the potential remains unused. Southern Finland has highest population density but only 17% of the resources, and therefore it needs to rely on import biomass either from other regions in Finland or from abroad. Power and heat units in Helsinki consume 0.10 TWh of domestic biomass resources and import 0.6 TWh of pellets in the baseline 2030 scenario.

Between 2014 and 2018, the DH demand in Helsinki varied from 6.5 TWh to 7.2 TWh depending on the severity of the winter heating season. The city's own utility company supplies 99% of the DH demand while the rest is transferred from the neighbouring cities of Espoo and Vantaa.

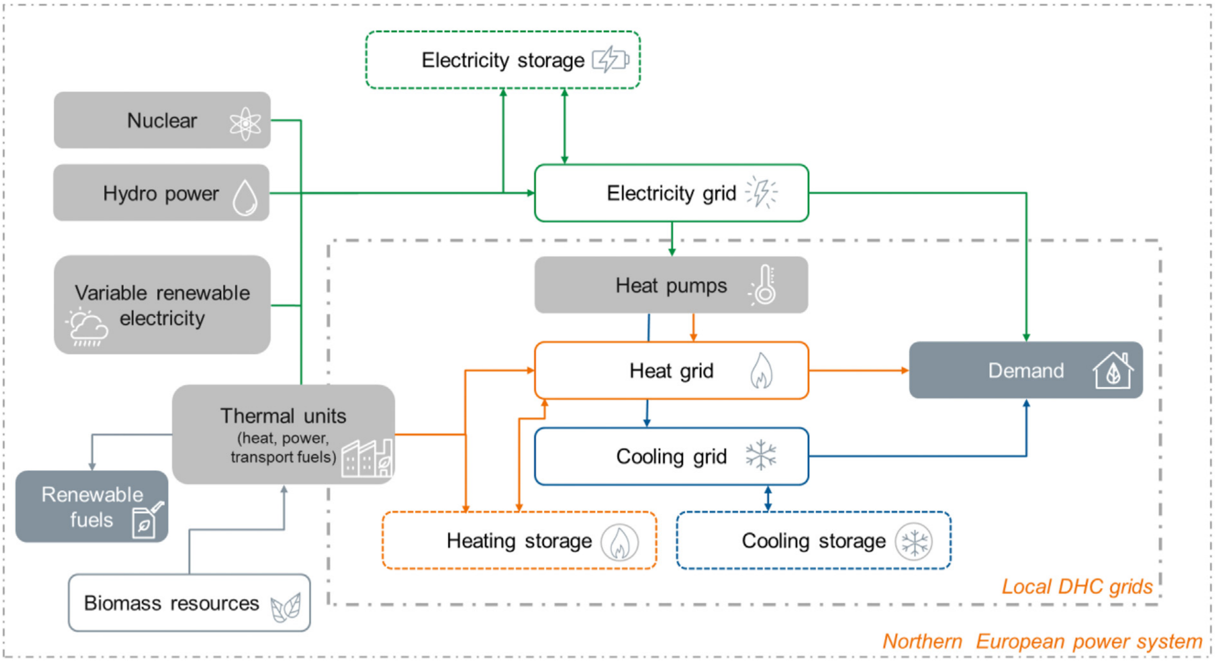

Fig. 2. Schematic illustration of the modelled energy system.

Table 2
Summary of projections of major components in DH demand and resulting DH demands in different heating regions.

	Change 2017–2030				Change 2017–2040			
	HDD	Pop	DH/cap	DH demand	HDD	Pop	DH/cap	DH demand
Helsinki	−8%	13%	−9%	−4%	−13%	18%	−13%	−6%
Espoo	−8%	16%	−6%	+4%	−13%	23%	−8%	+4%
Vantaa	−6%	17%	−8%	+2%	−11%	25%	−11%	+2%
Surrounding capital region	−6%	1%	−5%	−10%	−11%	2%	−8%	−16%
Turku region	−6%	0%	−5%	−10%	−10%	−1%	−8%	−18%
Tampere region	−6%	5%	−5%	−6%	−10%	6%	−8%	−12%
Lahti region	−5%	−7%	−5%	−17%	−10%	−12%	−8%	−27%
Western and Central Finland	−6%	−4%	−5%	−14%	−10%	−8%	−8%	−23%
Eastern Finland	−5%	−7%	−5%	−16%	−9%	−12%	−8%	−26%
Northern Finland	−5%	1%	−5%	−8%	−9%	0%	−8%	−16%

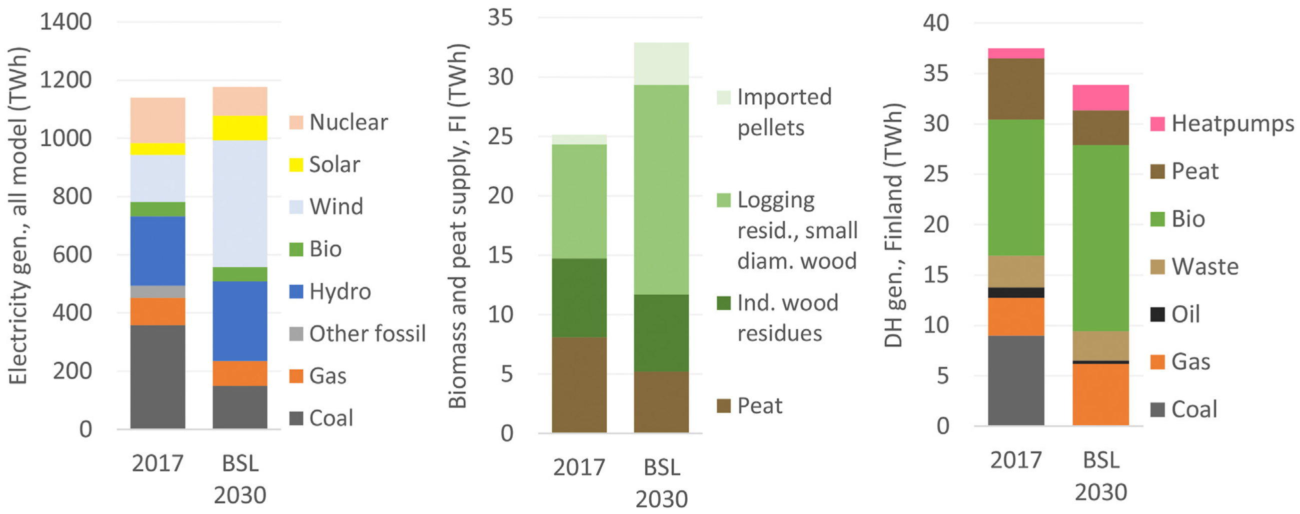

Fig. 3. Electricity generation in the model area (left panel), biomass and peat supply to power and district heating in Finland (middle panel), and district heating generation in Finland (right panel).

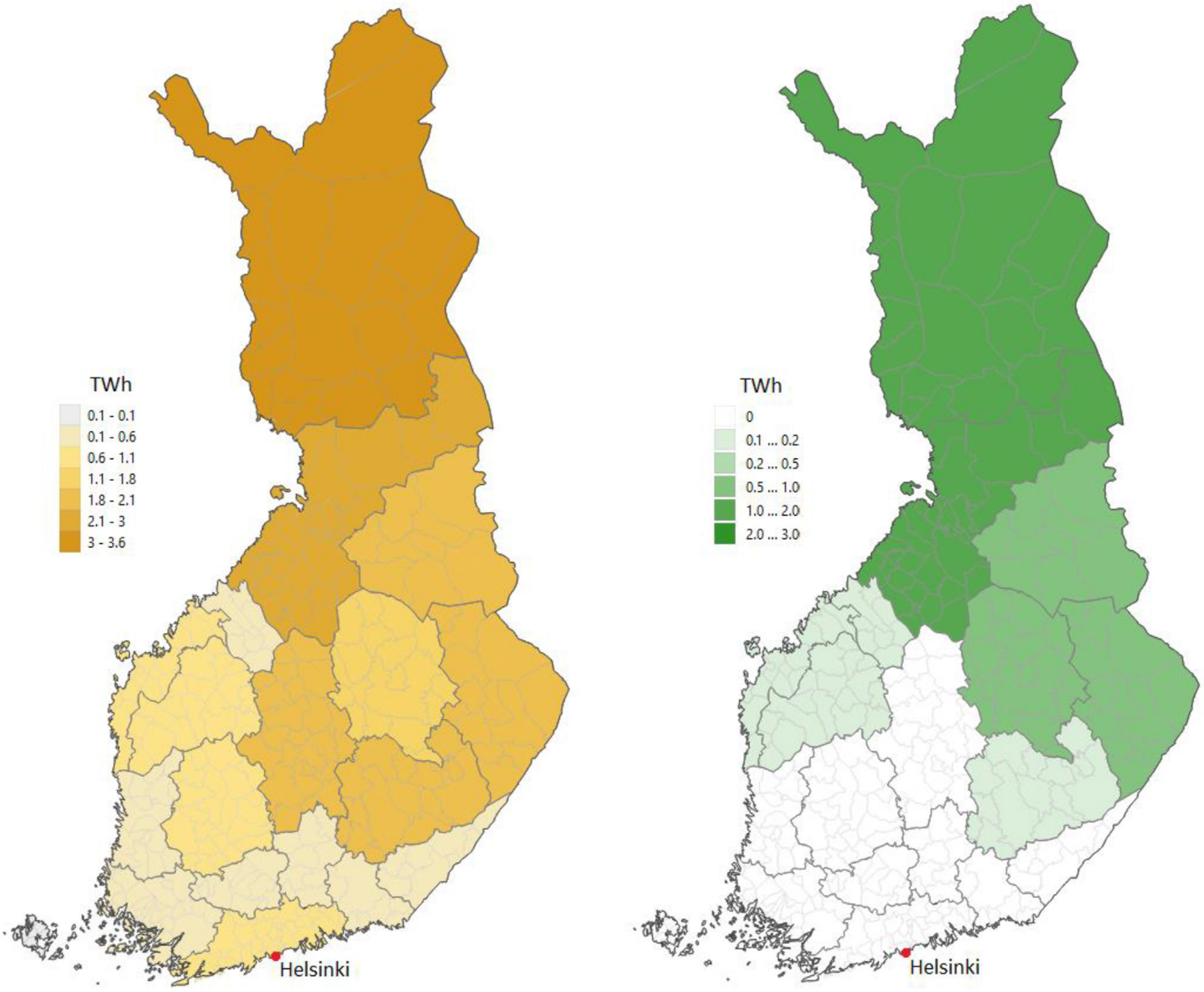

Fig. 4. Available (left panel) and unused (right panel) forest energy wood in the baseline 2030 scenario.

Helsinki's current power and heat system is based on two coal CHP plants (total 1200 MW_{th}), two NGCC plants (total 1350 MW_{th}), gas-based heat only boilers (HOBs) (total 640 MW_{th}), biomass-based HOB (100 MW_{th}), large-scale heat pumps (145 MW_{DH}), and oil boilers for peak demand (1750 MW_{th}). As a response to a new law that bans the energy use of coal after 2029, the city owned utility of Helsinki needs to replace its current coal CHP plants. Helsinki has already decided to invest in large-scale heat pumps (+60 MW_{DH}) and large heat storages (+11 GWh_{DH}, +120 MW_{DH}). These current and planned plants make up the baseline energy system for Helsinki in our model runs. In addition, Helsinki is planning second biomass HOB (+250 MW_{th}).

Large heat pumps have the lowest marginal cost and operate as base load units throughout the year. The existing bio-HOB unit has the second lowest marginal cost and operates almost continuously except during the lowest loads in the summer (Fig. 5). These are followed by NGCC units, gas HOBs and oil HOBs. Heat storages are used to balance short-term variability in the demand. Storages and trade links (20 MW) to neighbouring cities offer some additional flexibility and allow more stable operation of the units.

The annual electricity demand of Helsinki can be divided between end-users (4.3 TWh) and heat production (0.1 TWh), which is mainly used in large-scale heat pumps. On an annual level, 90% of the electricity has been produced within the city limits. For the purposes of our study, we assume that the end-user electricity demand remains at current level, while demand for electricity in heat production increases to 0.5 TWh by 2030 in the baseline scenario.

2.3. Model validation

Backbone is an open source model available to all researchers and companies under GNU Lesser General Public License. The details of the modelling framework are presented by Helistö [60], and the open-source model can be downloaded from.[3] The modelling framework is implemented using General Algebraic Modelling System (GAMS). The performance of the Backbone model has been validated against the PLEXOS model. In the validation, both models provided very similar results for modelled systems [34].

Backbone model investments and related methodologies have been studied by Helistö et al. (2020) [61] and Helistö et al. (2021)

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[3] https://gitlab.vtt.fi/backbone/backbone.

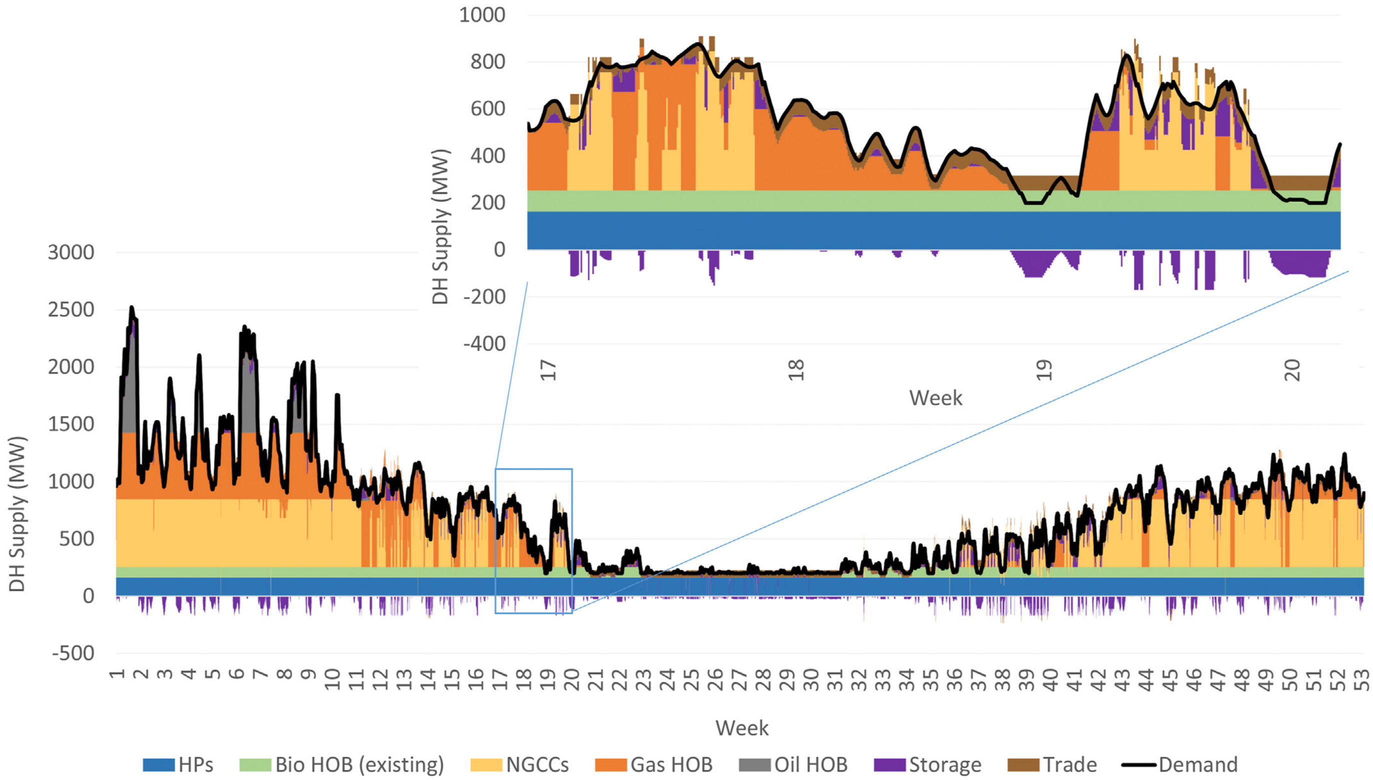


Fig. 5. Full year hourly dispatch of the Helsinki DH production in the baseline 2030 scenario.

[62].

Each of the modules used in this study and their features have been used, documented, and validated in several peer reviewed studies. Rasku et al. (2019) [34] published the dataset for the Northern European power system (module A) and aligned the baseline assumptions with reference European studies (Table 1). Backbone includes uncertainty of weather forecasts, e.g. wind power time series, and the best approaches to model these were compared by Miettinen et al. (2018) [63]. Modelling approaches of stochastics were further improved by Rasku et al. (2020) [35]. In this study they benchmarked the operations of hydropower, windpower, and other generation under larger share of variable generation and uncertain forecasts.

The regional forest biomass supply (module B) is benchmarked against extensive Finnish Forest statistics that show both regional production and consumption from Historical years [41]. The approach for modelling the future regional supply and demand is based on Anttila et al. (2018) [10].

The data and approach for district heating modelling (module C) has been built on the work of Lindroos et al. (2019) [36] that covered the district heating and cooling of Helsinki. In this study, the coverage has been expanded to whole Finland. They documented and validated the model that gave accurate production mixes when using historical years and data on taxes and prices.

One important indicator validating this combined modelling approach is the hourly electricity prices in the modelled scenarios. The model produces correct shape of the electricity price duration curve for Finland when comparing to historical data (Fig. 6). The highest prices arise from scarcity during peak loads when model has to start up least efficient units. Large share of reservoir hydropower in Nordic countries prevents larger amount of very low hourly prices despite increasing share of wind power.

2.4. *Modelled scenarios*

We model baseline and 10 different scenarios (Table 3) to represent uncertainty in the wider energy system. We model five different biomass investment options (Table 4 and Table 5) in each of these scenarios to investigate how different investment options would fare in the different futures. The combination of scenarios and technology options gives a total of 55 modelled cases. Four performance indicator categories are used to evaluate the feasibility of biomass investment options in each case (See Section 2.5).

First, we model the baseline scenario for 2030 as described in Section 2.2. Then, we create alternative scenarios by modifying following parameters and assumptions: CO_2 price, VRE capacity, heat pump capacity, and biomass availability. Based on the literature review in the introduction, we chose the following scenarios:

- lower (CO_2-10) and higher (CO_2-50) CO_2 price compared to reference price (27 €/tCO_2),
- more (Biomass+) and less (Biomass-) biomass available in Finland,
- significant (VRE+) and very significant (VRE++) increase of VRE availability,
- significant (HP+) and very significant (HP++) increase in the use of heat pumps, and
- a scenario combining significant (VRE+ & HP+) and very significant (VRE++ & HP++) increase in both VRE and heat pump capacities.

2.5. *Studied biomass technology options*

Following five technologies are considered and separately

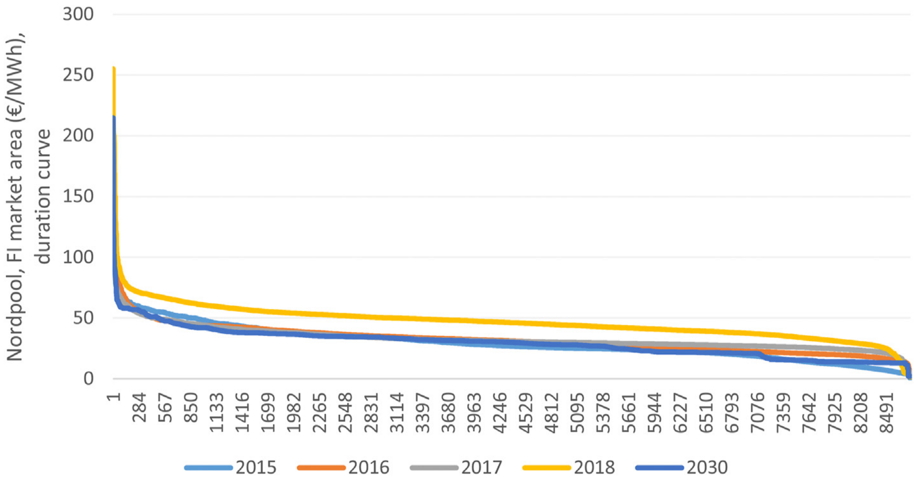


Fig. 6. Duration curve of hourly electricity prices in Finland in 2015–2018 (stat) and 2030 baseline.

Table 3
Scenarios studied.

Scenario	Region		Scenario names, values		
			Baseline 2030	**CO_2-10**	**CO_2-50**
CO_2 price	Model area	€/tCO_2	30	10	50
			Baseline 2030	**Biomass-**	**Biomass+**
Biomass availability	Finland	TWh/a	23	18	29
			Baseline 2030	**HP+**	**HP++**
Heat pump increase	Helsinki	MW_{DH}	163	326	652
	Finland	MW_{DH}	289	986	1952
			Baseline 2030	**VRE+**	**VRE++**
VRE increase	Finland	Wind, GW	3.9	4.5	5.2
	Nordic	Wind, GW	26	29	34
	Model area	Wind, GW	121	139	161
	Finland	PV, GW	1.0	1.2	1.4
	Nordic	PV, GW	3.1	3.6	4.1
	Model area	PV, GW	83	96	110
			Baseline 2030	**VRE+&HP+**	**VRE++&HP++**
VRE and heat pump increase			*Combination of VRE and HP scenarios*		

Table 4
Studied biomass technology options for biomass-based heating technologies in Helsinki and their technical specifications. In the case of Refinery+H_2, operation mode A refers to operating the refinery without H_2 boosting (i.e. like in Refinery), whereas operation mode B refers to using H_2 boosting option.

Biomass option		Consumption		Production			Efficiency		
Technology	Info	Bio	Elec	Elec	DH	Synfuel	Elec	DH	Synfuel
		MW	MW	MW	MW	MW	–	–	–
No investment	Otherwise current plans, but no new biomass to Helsinki								
CHP	Helsinki invests in bio-CHP	250		82.5	202.5		0.33	0.81	
HOB	Helsinki invests in heat only biomass boiler (current plan)	250			285			1.14	
Refinery	Helsinki invests in biorefinery	150			49.5	78		0.33	0.52
Refinery+H_2	Helsinki invests in biorefinery with H_2 boosting option								
Mode A	Mode A in operation, no H_2 boosting	150			49.5	78		0.33	0.52
Mode B	Mode B in operation, H_2 boosting used	150	150		70.5	147		0.235	0.49

modelled in each scenario:

- heat only boiler (HOB),
- combined heat and power (CHP) plant,
- biorefinery (Refinery) co-producing advanced biofuels and DH, and
- biorefinery as above, but with electrolytic hydrogen input to enhance carbon efficiency (Refinery+H_2), and
- no new biomass-based heating (No investment).

Both bio-CHP and bio-HOB were selected on the basis that they currently represent the most common bio-based options to produce DH. Ambitious targets to reduce emissions from transport have created incentives to produce advanced biofuels from lignocellulosic biomass [8]. A substantial amount of heat is produced as a by-product to biofuels and if such plants are built it could be attractive to integrate the co-produced heat with a DH system [64]. One further concept is to supplement such biorefineries with electrolytic hydrogen to increase the carbon efficiency (biofuel output) using low-carbon electricity [32,65]. This type of

Table 5
Operational parameters and economic assumptions for biomass technology options. All costs are escalated to 2018€ and scaled to the examined capacity using cost scaling exponent of 0.6.

Technology	Operations				Costs			
	Min load	Ramp rate	Availability	Min. online & shutdown	Inv. cost	Variable O&M	Fixed O&M	Start-up cost
		%/h	Hours of year	Hours	M€/MW	€/MWh	% of inv. cost	€/MW
No investment								
CHP	40%	100%	100%	8	1.1[a]	0.6	2%	7
HOB	40%	100%	100%		0.9[b]	2.4	2%	7
Refinery	40%	100%	100%		2.75[c]	2	2%	7
Refinery+H_2			100%		3.35[d]		2%	
Mode A	40%	100%				2		7
Mode B	40%	100%				2		7

[a] Investment costs estimated based on a biomass-CHP plant commissioned in 2020 in Finland having capacity of 215 MW, electric output of 70 MW, DH output of 175 MW and an investment cost of 200 M€. See (in Finnish): https://bit.ly/2TAwfYF.

[b] Technology Data for Generation of Electricity and District Heating from DEA [46].

[c] Investment cost estimates based on [8], but assuming 30% cost reduction due to learning.

[d] Same investment than for the Refinery, but added with electrolyzer investment cost at 600 €/kW$_e$.

'enhancement' could operate dynamically based on the electricity price and create an industrial scale demand response solution for the power market.

Capacities and efficiencies for each biomass option are shown in Table 4 and operational parameters and economic assumptions in Table 5. Both HOB and CHP plants are modelled as modern bioenergy production units based on general parameter data from databases. Cost information is estimated based on publicly available data from existing commercial or demonstration units. Helsinki's current plan is to invest in 250 MW biomass HOB, and this capacity is also chosen for our HOB and CHP units. For the biorefinery, a feedstock capacity of 150 MW was chosen.

Modern biomass heating plants typically feature efficient heat recovery from flue gases via flue gas condensation and heat pumps, resulting in 114% for the HOB and CHP. Minimum load for both plants as well as biorefineries is assumed to be 40% and ramp rate 100%/hour. In addition, minimum operation and down time of 8 h is used for the CHP plant. The potential annual availability of all technologies is 100%. In addition, we have modelled efficiency losses in partial load (2% points) and fixed the heat-to-power ratio for CHP unit. All investment options utilize domestic biomass (mainly logging and forest industry residues) and imported pellets. The cost data is split into investment cost, variable and fixed O&M costs, and unit start-up cost.

2.6. *Performance indicators used*

Energy sector investments can provide multiple services to the city and the energy system as whole. The feasibility of the investment can be assessed with several performance indicators measuring a range of functionalities and impacts of the investments. The used indicators are grouped to four categories:

1) Energy security: share of local/domestic electricity produced, share of domestic fuels, and size of energy storages.
2) Flexibility provision: full load hours (FLH), number of start-ups, and average ramp rate.
3) Economic performance: payback time and internal rate of return (IRR).
4) Climate impact: GHG emissions at Helsinki and the system level.

For energy security indicators, we calculate the share of local and domestic electricity generation from the output of units. Similarly, we calculate the share of domestic fuels in power and heat sector from the fuel input to the units. The size of energy storages is a comparison of the current fossil fuel storages to biomass storages.

Flexibility provision indicators are used to assess how much studied investments provide flexibility in the modelled cases. Flexibility is needed in operating the energy system with varying production and demand. The heat capacity of the DH grid and buildings eliminate the need for minute level or shorter balancing of heat, but units need to balance the hourly and weekly changes in demand and possible faults in the system. We measure the flexibility provision by counting the number of start-ups in the model runs, the average ramp rate (% of the capacity per hour) and full load hours. These allow to analyse how the model operates the unit and estimate how much flexibility the unit provides. This could be significantly less than theoretical flexibility based on the input data, for example if the unit has the cheapest marginal cost and is operated as much as possible.

Economic performance is one of the main criteria when companies make investment decisions. The payback time is calculated by dividing the investment cost (Table 5) by the change in annual operating costs compared to baseline scenario. For calculating IRR, net cash flows required to determine net present values are calculated as difference of annual operation costs and the investment costs. Investment costs are annualized over 20 years. The calculations are done from the perspective of Helsinki including only local energy flows and associated costs, and from the system perspective including all energy flows and associated costs.

Climate impact indicators include the emissions from burning of fuels and the upstream emissions of the fuels (Table 6). Emissions from fuel combustion are according to IPCC emission factors [66]. Upstream emissions factors for coal, oil, natural gas, and waste are from Refs. [67,68], for peat from Ref. [69], and for imported pellet from RED2 [70] (production with grid electricity and drying with biomass). Upstream emissions of supplied forest biomass includes emissions from cutting and handling, chipping, and transportation from road side to plant sites [71]. Emissions from roadside storages to plant sites are calculated based on transport distance from supply areas to demand areas based on factors reported by Ref. [71]. Emissions due to building the infrastructure are not included in the calculations. In addition, emissions due to possible changes in forest carbon stocks or sinks due to increased use of forest biomass are not included. Similarly to other indicators, we calculate the GHG balance for both Helsinki and the system.

Transport distance of biomass is limited by both emissions and economics. A transport distances up to several thousand kilometres are still allowed using default emissions factors from EU's RED2 directive [70]. Previous studies have arrived also to slightly stricter distances from 500 to 1000 km [72]. In our modelling, we assume a

Table 6
GHG emission factors ($kgCO_2/MWh$) of fuels used in modelling.

Parameter	Module A “Northern European power and heat system”	Module B “Forest biomass supply in Finland”	Module C “Finnish district heating and cooling”
Emissions from fuel combustion	Coal: 350 $kgCO_2/MWh$ Oil: 280 $kgCO_2/MWh$ Natural gas: 200 $kgCO_2/MWh$ Biomass: 0 $kgCO_2/MWh$ Waste: 156 $kgCO_2/MWh$	-	Peat: 380 $kgCO_2/MWh$
Emissions from fuel upstream	Coal: 58 $kgCO_2/MWh$ Oil: 55 $kgCO_2/MWh$ Natural gas: 46 $kgCO_2/MWh$ Waste: 3 $kgCO_2/MWh$	Logging residues: 4 $kgCO_2/MWh$ +0.013 $kgCO_2/MWh/km$ Small wood: 6 $kgCO_2/MWh$ +0.013 $kgCO_2/MWh/km$ Pellets: 54 $kgCO_2/MWh$	Peat: 33 $kgCO_2/MWh$

maximum transport distance of 200 km within Finland due to economic reasons. In practice, the transport distances of domestic biomass are often shorter as consumption is spread around the country [71]. Imported pellets are often from Baltic countries and we assume that those qualify with EU RED2 criteria and can be used to replace fossil fuels also in coming decades.

3. Results

3.1. Energy security

Fig. 7 shows the produced electricity, district heating and transport fuels in Helsinki and the required electricity imports. Studied investment options changed the share of local electricity production in Helsinki from 54% (Baseline 2030, no investments) up to 59% (Baseline 2030, CHP) or down to 44% (Baseline 2030, HOB). Studied investment options have similar, but significantly smaller effect on the system level.

The changes in the scenario had larger impact resulting to shares of local production from 11% to 60%. Addition of VRE generation (VRE+, VRE++) decreased electricity production in Helsinki, as lower electricity prices decrease the FLHs of NGCC units. Increase in the amount of heat pumps (HP+ and HP++) also reduces electricity production in Helsinki due to less demand for heat from the city's NGCCs. Furthermore, HPs as well as the use of H_2 boosting in the case of biorefinery increase the total electricity demand in Helsinki. Generally, the HOB and biorefinery with H_2 boosting lead to lowest electricity self-sufficiency in every scenario.

The H_2 boosting enhances the yield of the refinery and therefore the model produces 45–80% more transport fuels compared to a biorefinery without boosting mode. The highest increase in H_2 boosting was in VRE++, VRE+ and CO-10 scenarios, which present lower electricity prices compared to baseline 2030. On the contrary, the lowest benefit from electrolyzer investment is obtained in scenarios leading to high electricity prices (HP++, HP+, CO_2-50).

The share of domestic fuels remains only at 1% in Helsinki in baseline 2030 scenario, as all fossil fuels are imported (Fig. 8). Biomass investments did not significantly increase the share of domestic fuels, as all biomass in Southern Finland is already used, even without the additional investments in Helsinki (Fig. 4), and the additional biomass comes from imports. The total fuel consumption in Helsinki increases in the biorefinery cases as the refineries consume additional biomass and electricity to produce bioliquids. Biorefineries slightly increase the use of domestic biomass in Helsinki as they can utilize biomass evenly throughout the year, while the CHP and HOB use biomass mostly during the winter in response to heat demand.

Also here, changes due to scenario have larger impact on the results than the selected biomass technology. Additional heat pumps decrease the fuel input approximately three times more

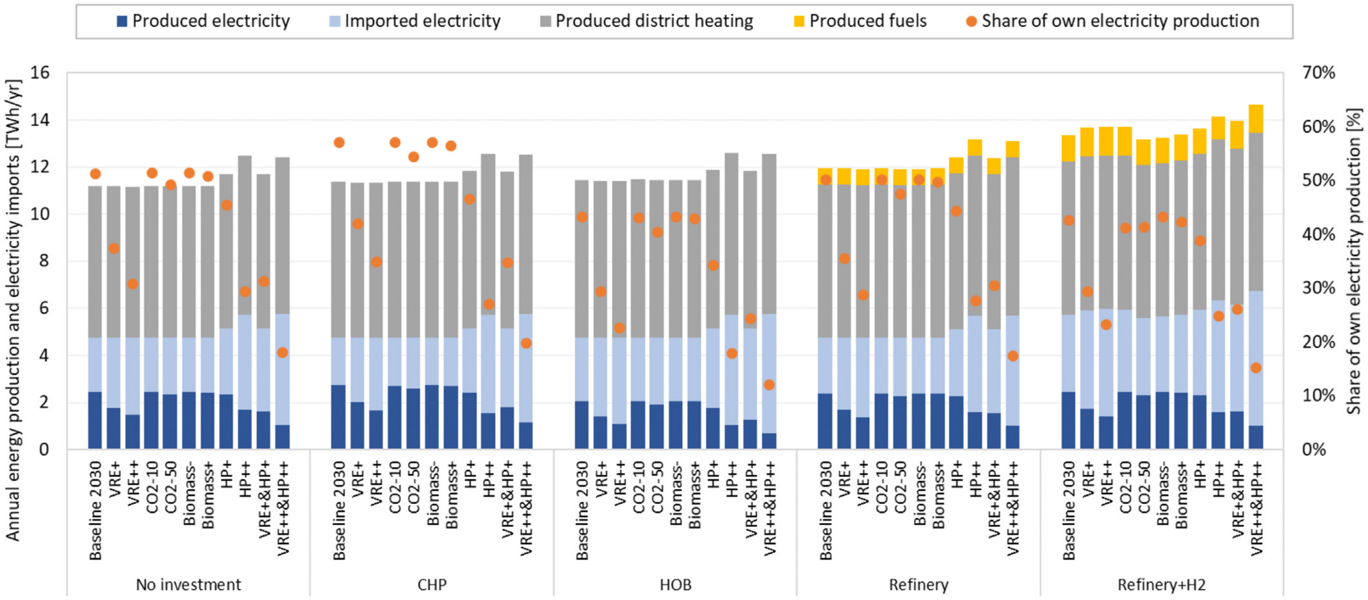


Fig. 7. Energy production in Helsinki, amount of imported electricity (left axis), and the share of electricity produced in Helsinki (right axis).

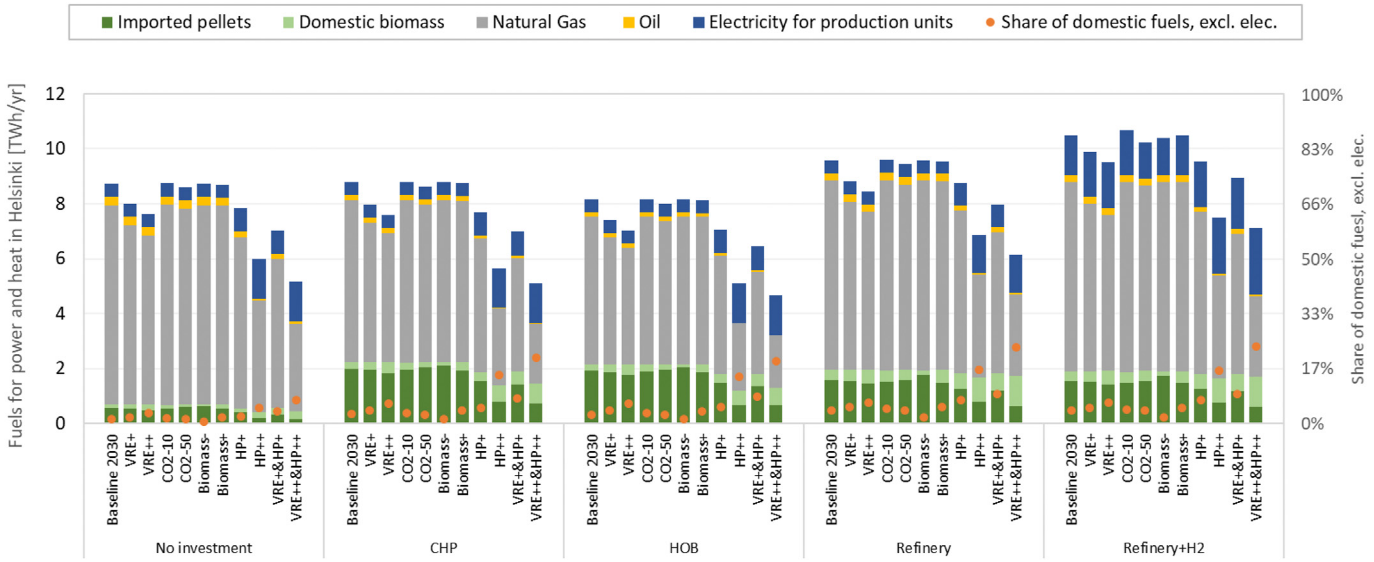


Fig. 8. Fuels and electricity for power and heat sector in Helsinki (left axis) and the share of domestic fuels (right axis).

than they increase the electricity needed for production units. For all investment cases, the share of domestic biomass is highest in HP++ and VRE++&HP++ scenarios, as additional heat pump capacity replaces biomass consumption also in other parts of Finland, leading to improved biomass availability in Southern Finland. VRE++ scenario increases the domestic biomass use in Helsinki in all investment options because VRE generation lowers electricity prices and reduces CHP production in Finland, which leaves more biomass for Southern Finland. Assuming larger biomass resource (Biomass+ scenario) has small impact on the availability of domestic biomass in Helsinki.

Coal can be stored cheaply in large quantities, which is not the case for natural gas in Southern Finland, as there are no large local storages. Thus, phasing out the coal decreases the amount of stored fuels, but investing in biomass technologies improves the situation as Southern Finland has some existing storages for the biomass and current coal storages could be converted for the pellet storages.

3.2. *Flexibility provision*

The CHP and HOB have lower marginal cost than fossil units in Helsinki and therefore have running hours above 50% in most modelled cases (Fig. 9). The most negative effect on the running hours of CHP and HOB is observed in the HP++ and VRE++&HP++ scenarios, due to the large amount of heat produced by heat pumps. Similarly VRE+ and VRE++ scenarios decrease the FLHs of a CHP unit due to low electricity prices. Low CO_2 price also decreases the FLHs of a CHP unit, since NGCC units overtake it in the merit order.

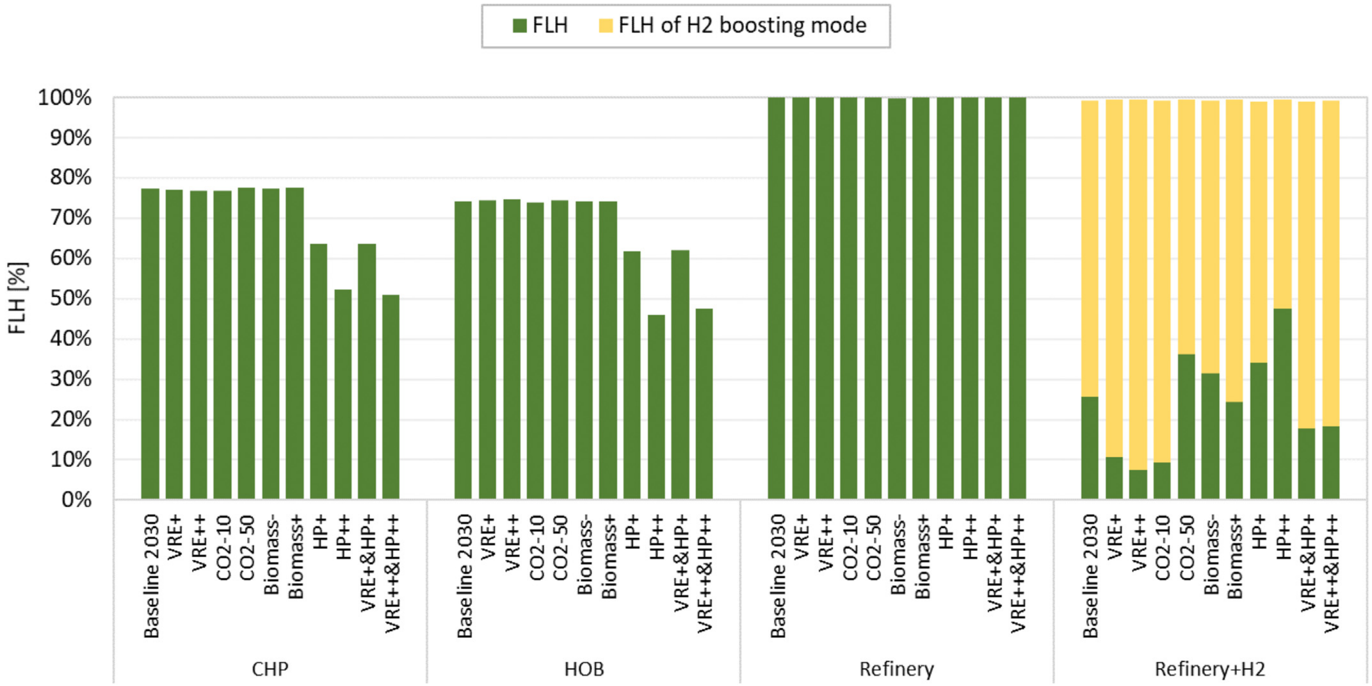


Fig. 9. Full load hours (FLH) of investments under different scenarios.

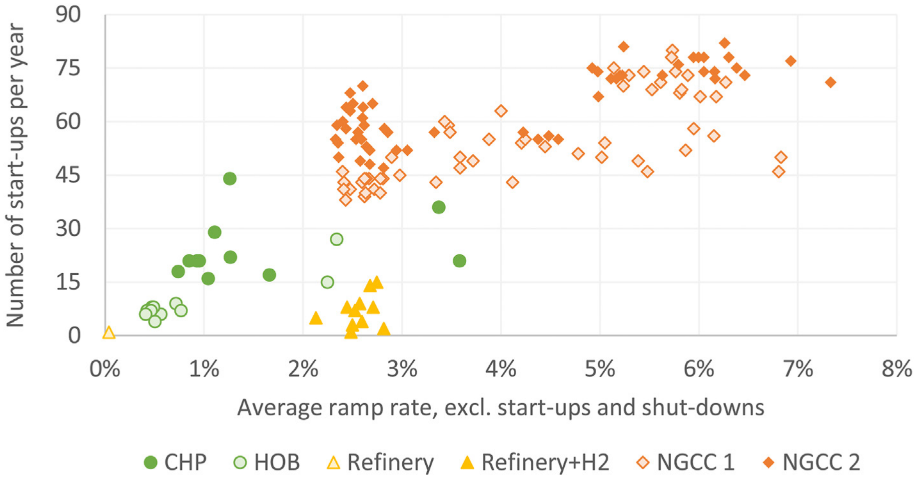


Fig. 10. Number of start-ups and average ramp rates (excl. ramping during start-ups and shut-downs) of units in the modelled scenarios.

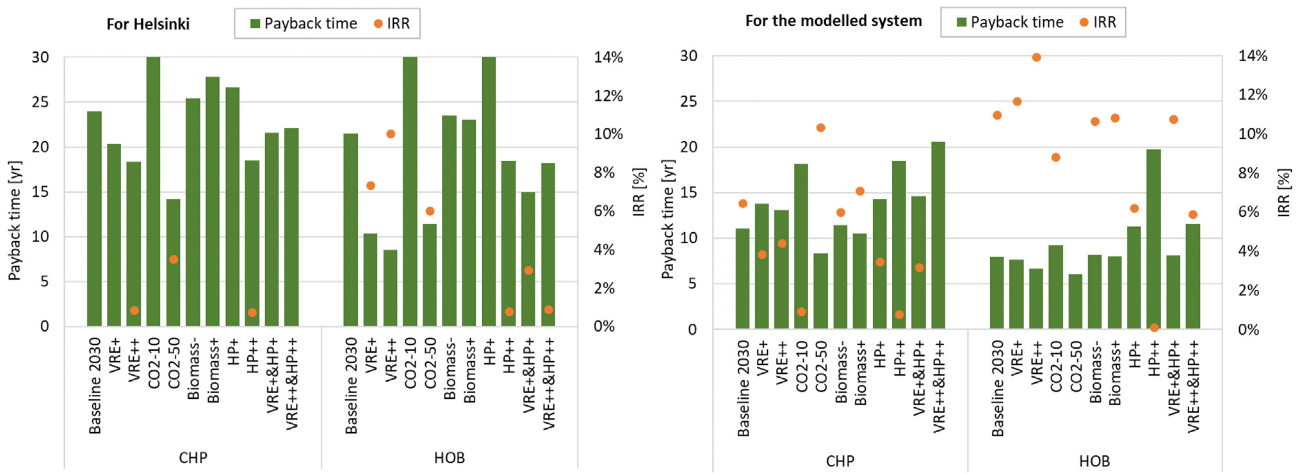


Fig. 11. Payback time (left axis) and internal rate of return (IRR) (right axis) for CHP and HOB investments from Helsinki's perspective (left panel) and from the perspective of the whole system (right panel).

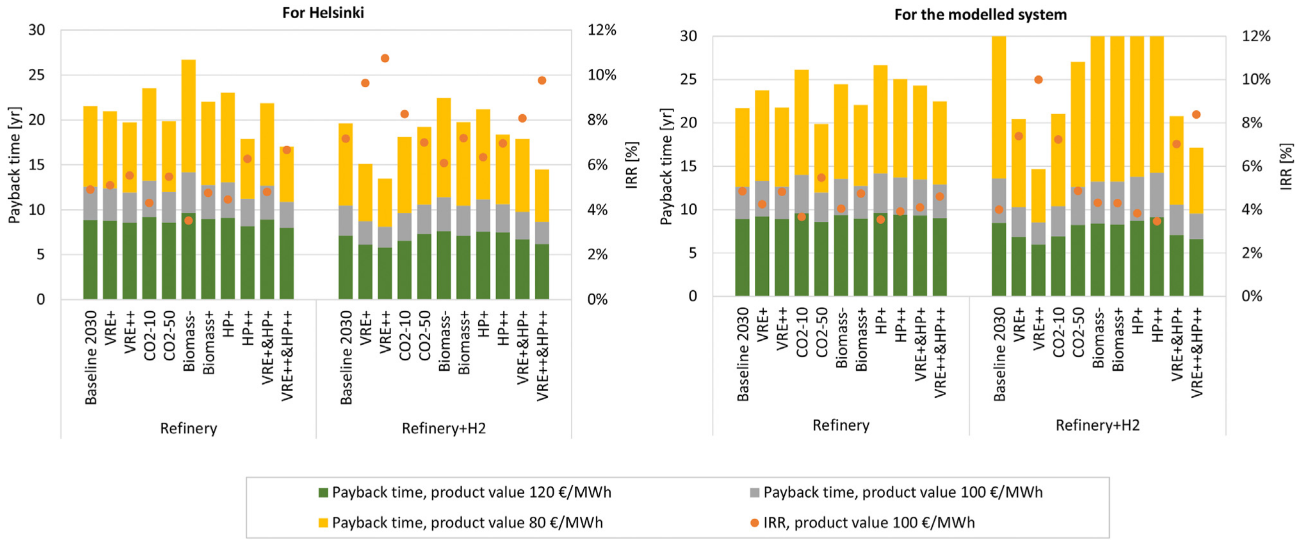


Fig. 12. Payback time (left axis) and internal rate of return (IRR) (right axis) for biorefinery and H_2 boosted biorefinery investments from Helsinki's perspective (left panel) and from the perspective of the system (right panel).

Changes in the availability of domestic biomass does not have significant impact on the running hours since imported biomass already sets the marginal cost of biomass fuel.

The biorefineries operate most of the time (98–100%) as their revenue is received from transport fuels. However, heat pumps are needed also for the production of district cooling and cannot therefore be fully replaced with heat from biorefineries. The H_2 boosting mode is activated in the biorefinery (Refinery+H_2) for 46–91% of the time, depending on the availability of low-cost electricity in different scenarios. Increase in VRE and low CO_2 price reduces the electricity price, thereby encouraging the use of electrolysis, while higher electricity prices (HP+, HP++, CO_2-50) discourage the use of electrolysis.

Studied biomass based units were operated large shares of the year resulting to a smaller number of start-ups and lower average ramp rates than NGCC units in Helsinki have (Fig. 10). Especially the refinery without H_2 boosting was operated at baseload throughout the year and provided very minimal flexibility to the system. Hydrogen boosted refinery provided additional flexibility through shifting between the operation modes, but it provided more heat than the city needed during the summer and the heat production was switched off approximately 10 times during the summer.

Studied CHP and HOB investments had the same minimum load and maximum ramp rate in the input data (Table 5), but HOB unit had higher operation hours resulting to lower average ramp rates than the CHP unit. Large NGCC units in Helsinki had largest amount of starts and largest average ramp rates of these units. These results demonstrate how unit could be more flexible by design, but still provide less flexibility to the system. Studied investments had lower marginal cost of operation than existing NGCC units in the Helsinki system and thus pushed the NGCC units to lower operation hours and providing the system balancing in combination with fossil heat only boilers. Large differences in number of start-ups and average ramp rates of NGCC units are explained by both scenarios and investments.

3.3. Economic performance

Both bio-HOB and bio-CHP were more profitable from the system perspective than from Helsinki's perspective (Fig. 11). Both investments reduce the system level costs and costs of district heating production in Helsinki, but decreased electricity generation from existing CHP units, which reduces Helsinki's income from the produced electricity. According to the results, a bio-CHP investment was not profitable investment (IRR below 2%) from Helsinki's perspective under any of the modelled scenarios. However, bio-CHP in Helsinki would be profitable investment from the system perspective in baseline (IRR 5+%) and if assuming high CO_2 prices (CO_2-50) (IRR 10+%). HOB is a profitable investment for Helsinki if the operation of existing NGCC units is more expensive than in the baseline scenario (VRE+, VRE++, CO_2-50).

Increasing share of VRE reduced the value of CHP for Helsinki, but increased the value of CHP for the system (Fig. 11). CHP can provide balancing services and produce reserve capacity in high VRE systems, but crucially the investor would not see all the benefits in the modelled scenario that indicates to a decreasing willingness to invest in CHP technologies despite the possible benefits.

The investments in biorefineries are driven by transport sector policies, resulting in demand for bioliquids, and possible penalties of not achieving the targeted bioliquids amounts. The economic indicators of biorefineries are therefore calculated with different product values (Fig. 12). The economic feasibility of the biorefineries strongly correlates with the value of the produced transport liquids and studied refineries required product values above 100 €/MWh to be profitable. Studied scenarios had relatively small impacts except the high VRE shares that lowered the average electricity prices and significantly improved the profitability of the refinery with H_2 boosting.

Biorefineries were more profitable investment for Helsinki than what their system level benefits were. Selling excess heat to DH grids also improves the profitability of biorefineries, but the location in Southern Finland would increase the value of feedstock having opposite impact reducing the profitability. From the system perspective, biorefineries increase the cost of power sector, but reduce the overall energy system costs through added value of the sold transport fuels. In this modelling, a part of the added costs were not in the Helsinki region and the profitability was better from local perspective.

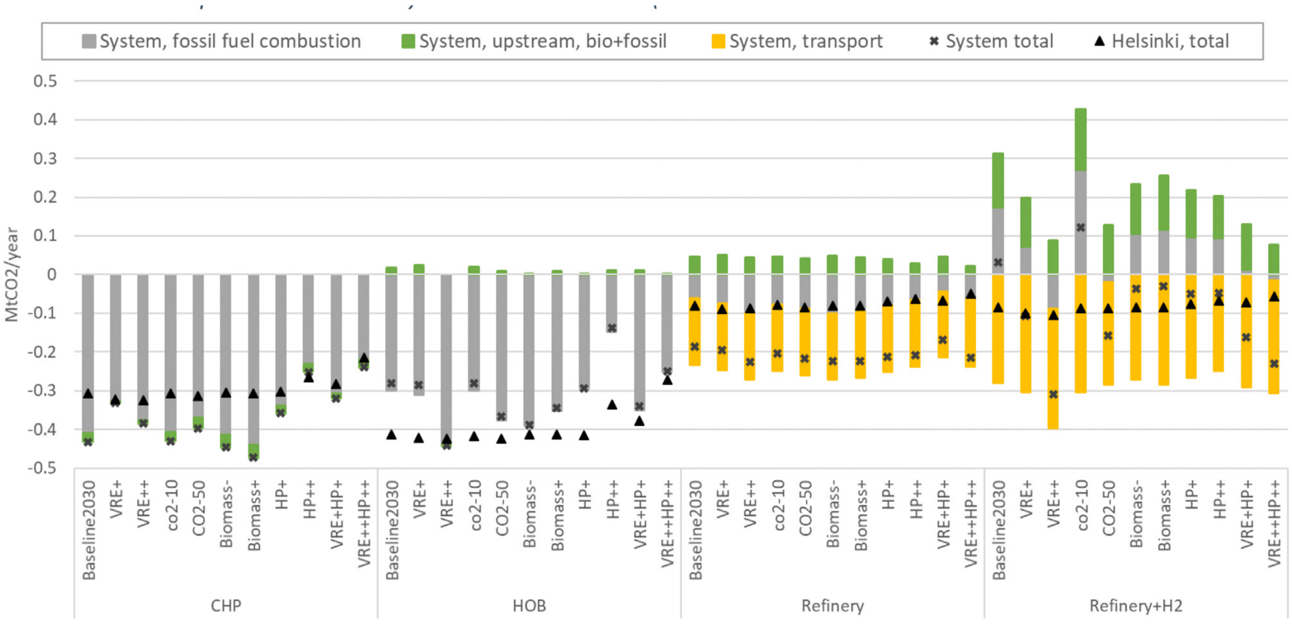
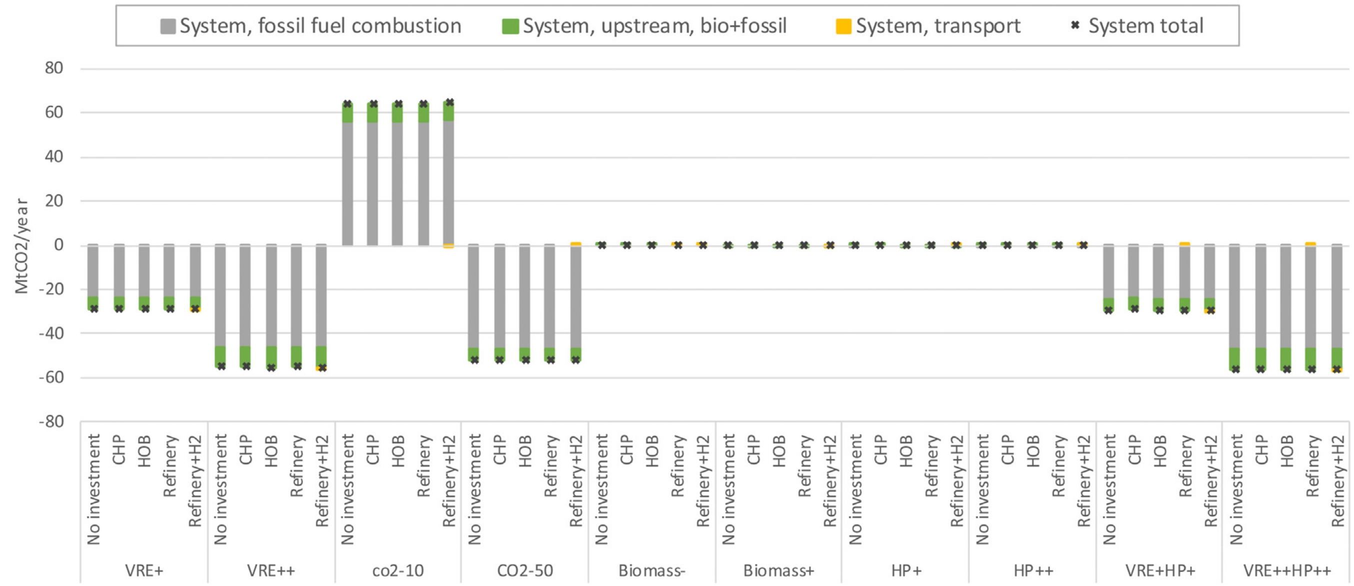


Fig. 13. Change in GHG emissions from fossil fuel combustion, in upstream emission, emissions from transport sector and total emissions compared to no investment.

a) System



b) Helsinki

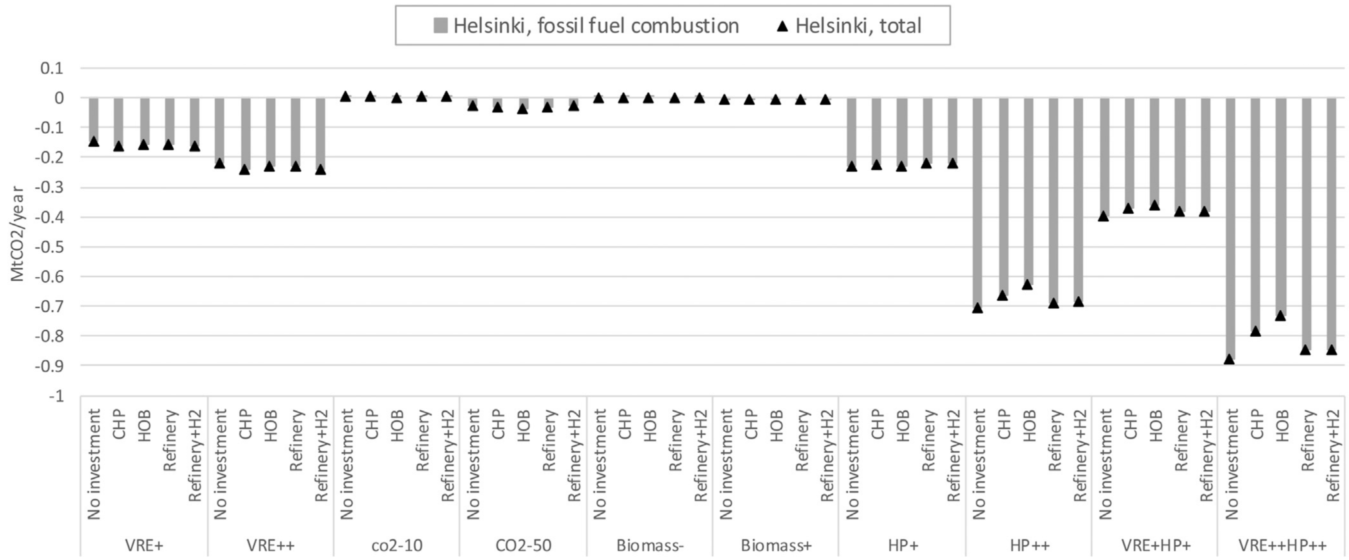


Fig. 14. Change in GHG emissions compared to baseline 2030 scenario at a) System level and b) Helsinki level.

3.4. *Climate impacts*

All studied biomass options reduce the system total emissions (Fig. 13). The only exceptions are the refinery with H_2 enhancement for biofuels in the baseline and in low CO_2 price scenario, where electricity from a coal power plants is used for H_2 production. A CHP plant reduces emissions more at system level than in Helsinki, as bio-CHP replaces other electricity production outside Helsinki. In contrast, a HOB reduces more emissions in Helsinki than in system, as the lost electricity needs to be produced elsewhere. HOB investment results to highest emission reduction at Helsinki level in all scenarios.

A biorefinery with H_2 enhancement increases energy production related emissions at the system level, but reduces emissions both in the transport sector and in Helsinki. This highlights the fact that a key driver for the biorefinery investment is the production of transport fuels. However, when the biorefinery is integrated with the city's DH network it can help to lower the emissions at city level. The total emission reductions from the biorefinery with hydrogen enhancement is significantly better in VRE++ scenario than in scenarios with lower wind shares.

An investment decision made in Helsinki is not significant at system level, as the emission saving impact is small in relation to the emissions of the whole system. In contrary, the examined scenarios have clear impacts on the system level emissions (Fig. 14). At system level, VRE+ and VRE++ (also combined with HP+ and HP++) scenarios reduce the most emissions, as does 50€ CO_2 price. In contrast, 10€ CO_2 price increases the system level emissions. In Helsinki, HP++ and VRE++&HP++ scenarios reduce most emissions, despite which bioenergy investment is chosen. Changes in the CO_2 price or biomass availability in Finland have minor impacts on emissions at Helsinki level for all investment options. For

Helsinki, the total emission includes only fossil fuel combustion, as other (upstream) emissions take place at system level.

In future studies, the GHG impact assessment could be complemented by taking into account also the possible impacts of biomass use on forest and soil carbon stocks and sinks. This would require including one more module to the modelling framework, with the dynamics of forest carbon stock changes due to varying harvest scenarios [16,73].

4. Discussion and conclusions

All studied biomass-based technology options (CHP, HOB, refinery, and refinery + H_2) replaced fossil fuels in the studied energy system both at local and system level and thus reduced CO_2 emissions in the system. Each technology had a positive climate impact when calculating the replaced fossil fuel and upstream emissions from the fuel chain unless coal electricity was used to generate H_2 for refinery.

If climate impacts are measured per used fuel, HOB was the most effective technology to reduce emissions on local level (0.27 $MtCO_2/TWh_{fuel}$ on average in modelled cases) while CHP was the most effective on system level (0.24 $MtCO_2/TWh_{fuel}$). HOB performed slightly worse on system level (0.21 $MtCO_2/TWh_{fuel}$) as lost electricity generation was replaced in other units in the system. Refineries were less effective when measured per used fuel, but refineries reduced emissions in the transport sector where emissions could be hard to mitigate otherwise.

In the modelled case study, heat had higher value than electricity due to new investments in wind power. This is a significant change in the operation environment of the energy utilities and made HOB units more profitable investments than CHP units. In addition, HOB had smaller investment cost, which further reduces the risk for the investors.

Increased value of heat creates a business case to bring refineries closer to cities where excess heat could be utilized in the district heating grids. However, biorefinery investments are driven by transport sector policies and the main source of refineries' income was from the production of transport fuels. From this perspective, district heating connection creates additional value, but is not a decisive factor.

Increase in the number of heat pumps has significant potential to decrease emissions in Helsinki, but creates challenging conditions for the bioenergy investments. Heat pumps can produce heat relatively competitively, but will lead to further reductions in the local self-sufficiency of electricity generation.

These results indicate that local decision-makers could have a tendency to replace CHP units with heat only units or heat pumps leading to reduced local electricity generation and possibly to increased local demand of electricity. Decreasing share of CHP units has been the observed trend in Finland [43] and modelled cases suggest the continuation of this trend. However, CHP units had higher value for the whole system than for the Helsinki. In the case of increasing wind power, the CHP's value for the system slightly increased, but the value for Helsinki decreased. This clearly indicates increasing value of balancing power in a system with high share of variable generation, but the investor is not necessarily rewarded. This is an interesting topic for further studies.

Sustainable biomass is a scarce resource whose use should be optimized at local, regional and national level. However, current units and investments will contribute to a lock-in effect where other potential uses are prevented due to lack of feedstock availability. The examined investment options had different impact at the local DHC grid and at the system level. In reality, DHC operators make investment decisions based on their own local interests, which might lead to outcomes that are less optimal from the whole system perspective.

Credit author statement

Tomi J. Lindroos: Conceptualization, methodology, investigation, formal analysis, Writing - Original Draft, visualization, Writing - Review & Editing. **Elina Mäki**: Writing - Original Draft, visualization, writing - Review & Editing. **Kati Koponen**: Writing - Original Draft, visualization. **Ilkka Hannula**: Conceptualization, supervision, project administration. **Juha Kiviluoma**: Methodology, software. **Jyrki Raitila**: Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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