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Article Effect of Heat Demand on Integration of Urban Large-Scale Renewable Schemes—Case of Helsinki City (60 °N)

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Abstract: Heat demand dominates the final energy use in northern cities. This study examines how changes in heat demand may affect solutions for zero-emission energy systems, energy system flexibility with variable renewable electricity production, and the use of existing energy systems for deep decarbonization. Helsinki city (60 °N) in the year 2050 is used as a case for the analysis. The future district heating demand is estimated considering activity-driven factors such as population increase, raising the ambient temperature, and building energy efficiency improvements. The effect of the heat demand on energy system transition is investigated through two scenarios. The BIO-GAS scenario employs emission-free gas technologies, bio-boilers and heat pumps. The WIND scenario is based on large-scale wind power with power-to-heat conversion, heat pumps, and bio-boilers. The BIO-GAS scenario combined with a low heat demand profile (-12% from 2018 level) yields 16% lower yearly costs compared to a business-as-usual higher heat demand. In the WIND-scenario, improving the lower heat demand in 2050 could save the annual system 6–13% in terms of cost, depending on the scale of wind power.

Keywords: decarbonizing pathways; district heating system; energy system flexibility; system dynamics modelling

1. Introduction

Decarbonization in the power sector has proceeded positively, which makes it also interesting to use electricity in other sectors as well (so-called sector-coupling). It is expected that the production of renewable electricity technologies will grow fast in the future and electricity can be easily converted to other final energy forms [1]. In particular, in the northern cities, the heating sector focusing on decarbonization will be important as a part of the overall climate change mitigation. The heating sector represents a major part of the final energy use in northern climates [2–4].

Northern cities form in this context an interesting case, as the heat demand may be well over half of the final energy use [5–8]. In cold climates, combined fossil fuels heat and power is often employed in an urban context for efficient energy production [6,9]. This is also the case in Helsinki, capital of Finland, which was chosen as a case study in this paper, where gas and coal-based combined heat and power (CHP) covers some 98% of the heat production [10,11].

As the 2015 Paris Climate Agreement urges rapid emissions cuts, the EU has set targets for CO_2 neutrality by 2050. Finland has an ambitious target to reach carbon neutrality already by 2035. Helsinki city is enfacing huge challenges with its energy system, which need mostly to be decarbonized in less than 15 years from now [12]. These challenges concern in particular the heating sector which is except for some heat pumps, composed of bio-boilers, fossil fuel-based, and local production. The

electricity system is coupled to the Nordic Electricity Exchange (Nordpool) with almost CO₂-free power available now [13–16], and could easier compensate for the fossil fuel loss. Therefore, choosing Helsinki as a case is very justified. The city needs to undergo a major energy transition in a short time and could also serve as an example to other cities in northern and cold climates. Using the Helsinki energy system as a case, this paper investigates alternative pathways for zero-emission energy production and integration of large scale variable renewable energies (VRE), with emphasis on the heating sector and heat demand. Heat demand and heating systems have received vast interest in the literature, e.g., for demand-side management [17,18], increasing the system flexibility in different system scale [19,20], or in terms of the effect of estimating the heat demand on energy system production planning [21–23]. The strategies for decarbonizing the energy system are ample, often depending on the local conditions and limitations [13,24–26]. In the Helsinki case, almost 100% dependence on CHP and district heating [10], forms a huge asset that may be worthwhile to be employed in some way [12]. At the same time, wind power is becoming the least cost power production option in the region. Wind power could be employed more extensively, as the wind conditions in northern Europe are good [27,28]. The electricity infrastructure and Nordic electricity market are also good in the Nordic region. However, relying on the Nordic electricity market may also encompass more uncertainties in the price of electricity or energy security [29,30].

There is a range of other technology options, such as heat pumps and thermal energy storage, which could provide an interesting option for improved power flexibility as well, e.g., in connection with power to heat (P2H) [31]. In Finland, applying biomass could be a partial solution for heating [32]. However, all in all, the above examples emphasize the complexity and systemic nature of the decarbonization, for which more comprehensive analyses are needed.

Previous studies have already touched on the issue of low or zero-emission energy systems, e.g., for Helsinki, and have provided scenarios for deep decarbonization [13–16]. However, these studies have focused less on the heating sector as part of the whole energy system, which is the subject of this paper. For example, the large wind power schemes with P2H could produce over half of the electricity needed in Helsinki and some of the heat demand (20%) [13–16]. Another study found that the contribution of bio-boilers to the heating sector may vary between 18% and 30% of total heat demand based on different decarbonizing scenarios [13].

Contrary to previous studies, we will also investigate here how the uncertainties in the heating demand by 2050 due to climate change and structural and technological changes may affect the decarbonization, sectoral coupling (P2H), and the rest of the energy system. An interesting question is also how these uncertainties would affect the energy system layout and whether could they change the order of least-cost solutions. The paper is organized as follows. Section 2 will present the methodology used in the paper. Section 3 includes the results and Section 4 concludes the outcomes.

2. Methods

The methodological approach is based on using a set of heat demand profiles for the year 2050, reflecting different change pathways. These hourly profiles are used is a sophisticated energy system model, which accurately describes the energy system of a city, in this case with data for Helsinki [23,33–36]. Among of applied models, the data-driven methods are accurate and powerful tools duo to using measured data [37,38]. In contrast, physical models are better in terms of generalization [39,40]. Data-driven models have widely been used for heat load forecasting using regression [35,41–45], and artificial neural networks [38]. Physical models could use the consumption behaviors [46,47] or customer social behavior [36], as well as daily or seasonal patterns [48]. Here, the dynamic model not only enables us to analyze the effects of the changing heat demand profiles on the energy system but also considers different energy technologies, constraints and boundary conditions.

The starting point of the analysis is the present energy system (2018) with the current fossil-based system, which is then transformed to a zero-emission system by 2050 employing renewable energy, clean heat technologies, e.g., CHPs and boilers with synthetic natural gas (SNG) and biogas, power-to-heat

strategies via heat pump, and coupling to the Nordic electricity market, which were considered feasible for this case. In the next section, the input data, modeling approach, and decarbonization strategies are presented in more detail.

2.1. Input Data for Helsinki

The starting point of the analyses is the present energy system in Helsinki (the year 2018) (see also Table 1). Heating dominates final energy consumption, or 6.7 TWh/yr (peak demand 2435 MW) while electricity demand was 4.4 TWh/yr [49]. HELEN Ltd, the main energy provider for Helsinki city, generated 7.2 TWh of district heat, of which 33% by gas, 53% by coal, 8% by heat pumps (HP), and the rest by biomass and oil [49]. The higher heat production by HELEN Ltd against the demand is heat loss through the district heating (DH) network (0.5 TWh) [50].

Year	Energy Sector	Gas CHP	Coal CHP 1	Coal CHP 2	Gas Boiler	Oil Boiler	Coal Boiler	Bio- Boiler	Heat Pump	Storage MWh
(2018)	Power	630	218	160						
	Heat	587	429	300	912	1010	190	92	127	5000

Table 1. Nominal output of plants in Helsinki (MW) for year 2018.

On the energy demand side in 2050, strong electrification of vehicles is assumed meaning that the car fleet of 300,000 vehicles in 2050 will be electric based (mix of electrical vehicles (EVs) and plug-in hybrid electric vehicle (PHEVs), 20 kWh/unit net battery capacity) [13]. The perceived population increase from 643,000 (2018) to 822,000 (2050) will raise the annual power demand and yearly hot water consumption by a factor 1.28 [51]. The electricity demand will raise to 7.2 TWh/yr. The district heating (DH) demand profiles in 2050 are based on a lumped building thermal performance modeling reflecting activity, climate, and building efficiency changes. More details about the year 2050 DH profiles are given in Section 2.3.

2.2. Energy System Modeling

The details of the optimization-based energy system model for the city-level analysis is explained in [52]. The model simulates the operation of all energy plants of a city, in this case, Helsinki. The optimization is based on 1-hour-timestep simulations over a year using a mixed-integer linear programming (MILP) approach written in Matlab-code. The objective function of the optimization minimizes the yearly running costs (OPEX) of defined systems as follows:

$$Min\sum_{t=1}^{time}\sum_{i=1}^{tech} (Fuels_{t,i} + Emission \ costs_{t,i} + O\&M_{t,i} - Revenues \ from \ sales_{t,i})$$
(1)

where *t* is time and *i* denotes the energy generation technologies employed. The input data of the model involve techno-economic information on power and heat production. Hourly times series are used for energy demand, renewable electricity (VRE), and market power price. Economic data includes emissions cost, fuel cost, and maintenance cost. The technical systems are subject to constraints, e.g., plant output limitations. In cold climates, due to quick ambient temperature drop (peak heat load), a ground source heat pump is supposed to extract a lot of heat from a limited heat ground loop. The current model employs a dynamic coefficient of performance (*COP*) for the heat pump to consider heat source limitations: *COP* = 3 if heat demand is <50% of the peak heat demand; *COP* = 2 for heat generation between 50% and 70% of the peak demand, and *COP* = 1 (i.e., an electric boiler) when heat demand > 70% of the peak demand (winter).

The model in Equation (1) seeks the lowest running costs (operating expenses (OPEX)) with VRE and storage technologies. In evaluating alternative systems, discounted capital expenditures (CAPEX) will also be added to obtain the total yearly cost:

Total yearly cost = OPEX +
$$(1 + r)^{-n}$$
 CAPEX (2)

where *r* is the interest rate (here 5%, also reflecting technology and economic uncertainities), *n* is the life-time in years, *t* stands for time, and *i* is the energy production technology. Moreover, the highest recorded interest rate is 5% in Finland (year 2000–2020). In this case, the new energy system is first fixed to get the CAPEX)and then the optimization is performed to receive the OPEX, which together yield the total yearly cost in Equations (2). Tables A1–A3 in Appendix A provide details on the input parameter values used.

2.3. Decarbonization Strategies

The two decarbonization strategies are chosen to make use both of existing infrastructure, such as the national grid infrastructure and electricity market [31], which could provide power flexibility [53] and on-cite infrastructure (plants, networks).

Two alternative production scenarios for the year 2050 are considered. The first one strives to use as much as possible of the existing infrastructure, i.e., the gas-CHP and boilers and bioenergy heat boilers running in 2050 with CO₂-free gas, e.g., SNG and biogas. Also, power-to-heat (P2H) with heat-pumps (HP) [54] and a link to the exogenous electricity market (Nordpool) is employed. The second scenario is based on wind power and P2H, HP, bio-boilers, and electricity market interaction. More details will be presented in Section 2.3.

The demand demand profiles considered are the following:

- Year 2018 heating demand (PRESENT): The annual heat demand is 6.8 TWh and the peak heat demand is 2360 MW.
- Year 2050 business-as-usual heating demand (BAU): The heat demand would follow a business-as-usual trend. The demand is affected by the rising ambient temperature and the increasing population. No major building energy efficiency measures are applied. The annual heat demand would then be 8.26 TWh (+21% from 2018 level) and the peak demand 2550 MW (+8% from 2018 level).
- Year 2050 heating demand with efficiency measures (EFF). In addition to the BAU, the demand is also affected by building energy efficiency measures according to EU policies (-1.5%/yr). The annual heat demand is 5.87 TWh (-12% from 2018 level) and the peak demand is 1932 MW (-21% from 2018 level).

The boundary conditions and applied parameters for above cases are given in Tables A1–A3 in Appendix A. The energy production strategies analyzed include fixing the energy system to 2018 level (REF) to provide a reference case, and two deep decarbonization scenarios leading to zero-emissions: Reference scenario (REF):

In this scenario, the Helsinki energy system is kept in its year 2018 set-up (Table 1) and analyzed with the different heat demand profiles and parameters sets, generating three cases REF-PRESENT (2018 heat demand), REF-BAU (2050 BAU heat demand), and REF-EFF (2050 EFF heat demand). All gas technologies in scenarios for 2050 are clean gas technologies, e.g., SNG and biogas.

Existing infrastructure scenario (BIO-GAS):

In the BIO-GAS scenario, existing energy infrastructure is employed as much as possible with the following elements:

- Utilizing the existing gas CHP with climate-neutral biogas or bio-SNG.
- Employing more intensively the Nordpool electricity market.
- Adding heat pumps for heating and biomass boilers (typically for peak demand).

The range of nominal size of the energy plants considered is shown in Table 2. The capacity of the HP and bio-boiler is based on the peak heat load. HP was sized up to 25% and 50% of the peak heat load and bio-boiler, which has lower yearly investment cost, was sized 25%, 50%, 75%, and 100% of the peak heat load.

System Variable	Energy Sector	Gas CHP	Gas Boiler	Bio- Boiler	Heat Pump
Alternatives for profile EFF (MW)	Power Heat	0; 630 0; 587	0; 912	 92; 480; 970; 1450; 1932	 127; 483; 966
Alternatives for profile BAU (MW)	Power Heat	0; 630 0; 587	0; 912	92; 640; 1274; 1910; 2550	92; 640; 1275

Table 2. Nominal output of energy plants in Helsinki for scenario BIO-GAS (MW).

In Case EFF, there are 60 possible combinations of the energy system configuration. However, only those combinations which can provide a demand and supply balance will be discussed in the results section. The technology combinations can be grouped into four categories based on the role of the gas technologies:

- No gas: electricity is fully handled exogenously through the electricity market, heating is handled by the heat pumps and bio-boilers.
- Gas boilers: as in the "No gas" case, but existing gas boilers are used for heating.
- Gas CHP: as in the "No gas" case, but the existing gas CHP is used.
- Gas boilers and gas CHP: as in "No gas" case, but existing gas boilers and gas CHP are used.

Wind power and P2H scenario (WIND):

In this case, wind power is extensively used, as well as P2H with heat pumps, limited use of bio-boilers, mainly for peak heat demand and back-up purposes, and linkage to the Nordic Norpool power exchange is included.

The nominal outputs of the energy plants considered are shown in Table 3. The wind power capacity considered is 750 MW (39% of annual power demand), 1500 MW (58%) and 2500 MW (96%). The bio-boiler and HPs are sized to 25%, 50%, 75%, and 100% of the peak heat demand. This case leads to 75 different system configurations. The acceptable combinations are grouped into three categories based on the wind power capacity: "Wind 750 MW", "Wind 1500 MW", "Wind 2500 MW".

System Variable	Energy Sector	Bio- Boiler	Heat Pump	Wind
Alternatives for profile EFF (MW)	Power Heat	 92; 480; 970; 1450; 1932	 127; 480; 970; 1450; 1932	750; 1500; 2500
Alternatives for profile BAU (MW)	Power Heat	 92; 640; 1275; 1910; 2550	 127; 640; 1274; 1910; 2550	750; 1500; 2500

Table 3. Nominal output of energy plants in Helsinki for scenario WIND (MW).

3. Results and Discussion

First, the reference scenario for 2050 was run, also to check the compatibility of the optimization tool with reported values [10], which is shown in Appendix A. The power production (from gas and coal) in simulation case is slightly higher (0.35 TWh). For the HELEN electricity production, the sources are gas (43%) and coal (31%), which are produced within the city, and nuclear (22%) and (4%) renewables, which are produced outside the city The power generation outside Helsinki

corresponded to a surplus of 2.3 TWh over the consumption in 2018, which was not accounted for here [34].

3.1. Existing Infrastructure Scenario (BIO-GAS)

The cases with the minimum yearly cost and their production breakdown are shown in Figures 1–4. The results in Figure 1 include four clusters with different markers: "No gas", "Gas boiler", "With gas CHP", and "With gas boiler and CHP". The "No gas" option includes bio-boilers and HP, while in "Gas boiler", existing gas boilers (912 MW) are employed. The existing gas technologies (boilers and CHP) are modified and supposed to run on clean fules, e.g., SNG and biogas. "With gas CHP" solutions include bio-boilers, HP, and existing gas CHP (630 MW_{el} and 587 MW_{th}). Both existing gas boilers and gas CHPs are implemented alongside bio-boilers and HP in "With gas boiler and CHP".



Figure 1. Emission-free alternatives for Helsinki (scenario BIO-GAS) with heat demand profile EFF (BB = bio-boiler and HP = heat pump, numbers refer to MW).



Figure 2. Power and heat production system of Helsinki (profile EFF) for the scenario (BIO-GAS) (BB = bio-boiler and HP = heat pump, numbers refer to MW).



Figure 3. Emission-free alternatives for Helsinki (scenario BIO-GAS) with heat demand profile BAU (BB = bio-boiler and HP = heat pump).



Figure 4. Power and heat production system of Helsinki (profile BAU) for the scenario BIO-GAS (BB = bio-boiler and HP = heat pump, numbers refer to MW).

From Figure 1, one can compare the state of the different zeros emission solutions against each other and reference system in terms of annual investment and running costs. To read Figure 1, first, select the solution cluster, e.g., "Gas boiler" and track a specific system with applied abbreviations and numbers. The abbreviations and numbers describe the capacity of applied technologies, e.g., "BB480HP127" means the system has a bio-boiler with capacity 480MW and an HP as large as 127 MW. The distribution of the clusters (from left to the right) indicates the system synthesis complexity e.g., two clusters ("With gas CHP", and "With gas boiler and CHP"), on the right side, have more diversity in applied technologies. Figure 1 also shows how the different zeros emission solutions are correlated with the exogenous electricity market. Solutions with higher yearly annual cost imports higher power from the exogenous electricity market. From Figure 1, one can compare the state of the different zeros emission solutions against each other and the reference system in terms of annual investment and running costs.

The first notable observation for solutions without gas CHP ("No gas" and "Gas boiler") is that the exogenous coupling to the Nordic electricity market is almost constant. These alternatives have a lower annual investment cost but due to dependency on the exogenous electricity market, their running cost is high. In the "No gas" series and "Gas boiler" categories, the alternatives with minimum CAPEX ("BB1450HP127" for profile EFF and "BB2550HP127" for profile BAU) rely on bio-boiler mainly (over 80%) in heat production, because of lower yearly investment costs. Heat production for solutions with the highest CAPEX ("BB1932HP970" for profile EFF and "BB2550HP1274" for profile BAU) includes a high contribution from HP since the HP capacity is large enough to cover the main part of the heat demand and is cheaper. Including the gas CHP ("Gas CHP" and "Gas boiler and gas CHP")

significant reductions occur in imported power, -42% to -21% based on the size of the HP. However, with empowering the P2H via HP scaling up, the contribution of CHPs reduces by around 43% due to cheaper heat production through HPs.

The overall power production breakdown for both DH demand profiles is comparable, but the principal differences are in the bio-boiler and HP sizing. Here, e.g., we search for minimum bio-boiler capacity in cases with "Gas boiler". With profile EFF, the minimum bio-boiler size is 480 MW (25% of peak heat demand) while with profile BAU the bio-boiler needs to be scaled to 50% of the peak heat load (1274 MW). The reason for a higher capacity in solutions with profile BAU is the higher heat demand (32% and 40% higher peak heat and total heat demand). The storage capacity for the system is constant (16,600 MWh) for which reason the systems with a lower heat demand need lower heating plant capacities.

The total yearly cost of REF-PRESENT-case is 574 M€, REF-BAU is 682 M€ (due to higher heat demand), and REF-EFF is 627 M€. The total yearly cost of the solutions with profile EFF vary from 481 M€ ("BB1450HP127" in "No gas") to 676 M€ ("BB1932HP970" in "With gas boiler and CHP"). The yearly cost for the solutions with profile BAU varies between 574 M€ ("BB2550HP127" in "No gas" series) and 800 M€ ("BB2550 HP1274" in "Gas boiler and gas CHP"). For profile EFF, increasing the yearly investment cost by 360M€ from BB1450HP127" ("No gas") to "BB1932HP970" ("Gas boiler and gas CHP"), the running cost only drops 160 M€ (44% of increased total yearly investments). The same is found with the zero-emission alternatives with profile BAU, where the yearly investment increases by 400 M€ and results in 173 M€ savings in running costs (43% of total yearly investment increase). The solutions with profile BAU save the total yearly cost up to 16% against the cost of REF-PRESENT with a total annual cost of 574 M€. For alternatives with profile EFF, the maximum saved total yearly cost in comparison with "REF-PRESENT" is 18%. Results show that, applying the discussed strategies to remove the carbon from the production sector, solutions still have lower total yearly cost against such "no action and emitting systems" as "REF-EFF" (628 M€) and "REF-BAU"(682 M€). The mentioned solutions with profile EFF cut the total yearly cost in comparison with "REF-EFF" up to 23% and solutions with profile BAU reduces the total yearly cost against "REF-BAU" up to 16%.

3.2. Wind Power and P2H Scenario (WIND)

System configurations with minimum total yearly costs and their production balance are shown in Figures 5–8. With the lower wind power capacity (750 MW) there is no export of power and the imported power covers 77% to 100% of the annual power demand. With a larger wind capacity of 1500 MW, the contribution from the exogenous electricity market is from 58% to 93%, from 7% to 15% of the wind power is exported as a larger HP (e.g., 100% of the peak heat demand) keeps the VRE self-consumption high. With a wind power level of 2500 MW, 23% to 33% of the applied VRE power is exported due to an hourly mismatch between the VRE and power demand.



Figure 5. Emission-free alternatives for Helsinki (scenario WIND) with heat demand profile EFF (BB = Bio-boiler and HP = heat pump).



Figure 6. Power and heat production system of Helsinki (profile EFF) for the scenario WIND (BB = bio-boiler and HP = heat pump, numbers refer to MW).



Figure 7. Emission-free alternatives for Helsinki (scenario WIND) with heat demand profile BAU for scenario WIND (BB = bio-boiler and HP = heat pump, numbers refer to MW).



Figure 8. Power and heat production system of Helsinki (profile BAU) for the scenario WIND (BB = bio-boiler and HP = heat pump, numbers refer to MW).

The effect of the heat demand profile in this scenario affects the sizing of the HP and bio-boiler. With 750 MW of wind power, the required bio-boiler capacity for profile EFF is 75% of the peak heat demand (1450 MW) while for profile BAU with a 32% higher peak heat load, the required bio-boiler capacity needs to be 100% of the peak heat load (2550 MW). Through total investing around 700 M€ to increase the HP capacity and wind power from 750 MW to 2500 MW, only 170 M€ for profile EFF and 186 M€ for profile BAU running cost can be saved. Large-scale wind power (>1500 MW) results in more export and cannot reduce the running cost significantly. The solutions for profile BAU have in general 6–15% higher total yearly cost compared to systems with profile EFF due to a higher heat demand. The results for system "BB1450HP127" with 750 MW wind power (40% of the annual power demand) along with improved heat demand (profile EFF) have a lower total yearly cost (586 M€) than the reference system "REF-EFF" which still uses fossil-based energy plants (628 M€). Even with higher heat demand (profile BAU), "BB2550HP127" with 750 MW wind power has total yearly costs close to the reference system ("REF-BAU").

Table 4 summarizes the analysis (scenarios "BIO-GAS" and "WIND") in terms of applied technologies and system synthesis, annual total cost (annual running cost+aanual CAPEX). The results have a color ranking to show the best alternatives with the lower annual total cost (greenish) and the worst options with the higher annual total cost (reddish). Table 4 provides good indicators for the decision-makers to select zero-emission infrastructures based on available technologies and planned annual budget. For example, in scenarios with the EFF heat profile, within the range of 580–600 M€ in yearly total cost, two options are available: a system with clean gas technologies and medium-size HP (BB1450HP127, Case No.11) or a system integrated with 750 MW wind power and existing HP (BB1450HP127, Case No.13).

Case No.	Gas Technology /Wind Power	System Composition Profile EFF *	Annual Total Cost for EFF (M€)	System Composition Profile BAU *	Annual Total Cost for BAU (M€)	Difference of Solutions (EFF-BAU %)
1	No gas	BB1450HP127	481	BB2550HP127	574	19
2	No gas	BB1450HP480	503	BB1910HP640	601	20
3	No gas	BB1932HP970	577	BB2550HP1274	699	21
4	With gas boiler	BB480HP127	494	BB1274HP127	575	16
5	With gas boiler	BB480HP480	509	BB1274HP640	609	19
6	With gas boiler	BB1932HP970	591	BB2550HP1274	713	21
7	With gas CHP	BB970HP127	551	BB1274HP640	640	16
8	With gas CHP	BB970HP480	581	BB1910HP127	676	16
9	With gas CHP	BB1932HP970	664	BB2550HP1274	786	18
10	With gas boiler and CHP	BB92HP127	562	BB640HP127	643	14
11	With gas boiler and CHP	BB92HP480	586	BB640HP640	684	17
12	With gas boiler and CHP	BB1932HP970	677	BB2550HP1274	799	18
13	750MW	BB1450HP127	586	BB2550HP127	679	16
14	750MW	BB1450HP970	682	BB2550HP1274	804	18
15	750MW	BB1450HP1930	831	BB2550HP2550	998	20
16	1500MW	BB1450HP127	706	BB2550HP127	799	13
17	1500MW	BB1930HP970	796	BB2550HP1274	918	15
18	1500MW	BB1930HP1930	944	BB2550HP2550	1111	18
19	2500MW	BB1930HP127	882	BB2550HP127	975	11
20	2500MW	BB1930HP970	968	BB2550HP1274	1088	12
21	2500MW	BB1930HP1930	1115	BB2550HP2550	1182	6

Table 4. Summary of zero-emission solutions for scenario BIO-GAS and scenario WIND.

* BB = bio-boiler, HP = heat pump, the numbers refer to the capacity in MW.

The difference in the annual total cost due to the assumed heat demand profiles appears higher in solutions with larger energy plants. The reason for this is the difference between the BAU and EFF profiles in heat peak load (32% higher in BAU profile), which means the need for installing larger infrastructures in solutions with BAU profile. In general, the effect of the heat demand profile depends on applied technologies. With introducing the gas technologies the difference goes lower between alternatives for both applied heat demand profiles. Increasing the heat demand (32% and 40% higher peak heat and total heat demand) can increase the total annual cost by around 16–21% for options without gas CHP. For solutions with gas CHP, the effect of higher heat demand could lead to 14–18% higher total yearly cost. For solutions with wind power, the effect of the higher heat demand can result in a 6–20% higher annual total cost.

4. Conclusions

In this study, we have analyzed CO₂-free options for cities, with emphasis on how different heat demand levels and profiles could affect CO₂-free production schemes. Helsinki city (Finland) was used as a case, with two heat demand profiles, enabling the consideration of building energy efficiency improvements, activity, and ambient temperature changes (BAU and EFF). Two scenarios (BIO-GAS and WIND) focus on a zero-emission system operating with existing gas technologies and bio-boilers and another with large-scale wind power integration. Both scenarios include options for improved energy system flexibility such as power-to-heat and thermal energy storage and linkage to the electricity market.

Assumptions for the heat demand profile affects the best solutions in sizing the heating energy plants and total yearly cost consequently. While the heat demand may increase due to ambient temperature and growing population (BAU profile) with applying the building energy efficiency measures (EFF profile), there is a better potential for reaching more economically feasible solutions (with a significant saving in the total yearly cost). For the BIO-GAS scenario, if building energy efficiency was included in heat demand (–12% of 2018 level), the alternatives with the least yearly investment cost (share of the bio-boiler in heat production is over 80%) can save the total yearly cost up to 23% in comparison with REF-EFF and 29% against of REF-BAU. Lower heat demand also enables the emission-free solution to save the total annual cost up to 16% against the alternatives practicing without building energy efficiency improvement (BIO-GAS scenario with BAU profile). In scenario BIO-GAS, increasing the heat demand from EFF to BAU changes the P2H share by 2% to 30% based on the size of the HP (6–50% 0f peak heat load).

In the WIND scenario, the lower wind power capacity (750 MW and 40% of total power demand) resulted in full wind power self-consumption due to the lowest hourly mismatch between the wind power and power demand. Large-scale wind power synthesis, however, requires more interaction with the Nordic power market, due to a temporal mismatch of power supply and demand. Improving the heat demand (EFF profile) can make wind included solutions more economically feasible. Cutting the peak heat load and annual heat demand by 24% and 33%, respectively (EFF profile in comparison with the BAU profile), can save the total annual cost 6% (wind power scale 2500 MW) to 13% (wind power scale 750 MW). In the Scenario WIND, the share of P2H (in all VRE scales) for the BAU solutions varies from 3% (the size of the HP is 6% of the peak heat load) to 40% (the size of the HP is 100% of the peak heat load) higher than the share of P2H for the EFF alternatives due to the higher heat demand (21%).

To reach a zero-emission energy system, actions in both the demand side and production side are important. Reducing the heating demand through building energy efficiency measures in a heat dominated urban energy system is important to the zero-emission energy system transition.

Possible prediction errors in the power and heat demand were not considered, but these could cause some mismatching errors between supply and demand and influence the running costs. A more comprehensive parametric study would be applied to better understand the effects from different parameter values and variables for future work.

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Appendix A. Details on Helsinki Energy System and Input Parameter Values

Figure A1. Power and heat production system of Helsinki in the 2018.

Fuel	Cost (€/GJ) 2018	Cost (€/GJ) 2050
Oil	9.7	9.8
Coal	3.8	4.2
Natural gas	8.3	9.7
Wood pellets	5.6	7.7

Table A1. Fuel costs (excl. taxes) for year 2018 and 2050 [55].

Emission cost for 2018 is 15 €/tCO₂ and for 2050 is 130 €/tCO₂.

Table A2. Operation and r	maintenance costs for	year 2018 and	l 2050 [<mark>32</mark>].
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Technology	Cost (€/MWh) 2018	Cost (€/MWh) 2050
Oil boiler	1.1	1.32
Coal boiler	1.1	1.32
Gas boiler	1.1	1.32
Bio-boiler	1.1	1.32
Coal CHP	4.5	5.40
Gas CHP	4.5	5.40

Table A3. Specific emissions [32].

Fuel	Emissions (tCO ₂ /TJ)
Oil	79
Coal	93
Gas	55

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