International Journal of Sustainable Energy Planning and Management Vol. 49 2026 103–116

International Journal of
Sustainable Energy Planning and Management

From Combustion to Conversion: Impact of Heating Demand Decrease on District Heating Systems

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ABSTRACT

Climate change is expected to reduce heating demand in Finnish buildings, impacting district heating (DH) systems. This study models small, medium, and large DH systems for the years 2030 and 2050 using Representative Concentration Pathway (RCP) climate scenarios. The analysis uses energyPRO to simulate system operations based on fuel price prioritization, comparing future scenarios to a 2023 baseline, and focuses to the changes on the heat generation side. The transition from high-emission systems to sustainable energy sources—such as waste heat, electric boilers, and nuclear—poses challenges for revenue and energy security. While national-level studies exist, local-level insights are limited. Results show that reduced heat demand can lead to significant revenue losses in current systems, although renewable heat production increases. Smart future systems that minimize fossil fuel combustion and rely on biomass-based renewables maintain more stable revenues due to lower emission costs and consistent fuel pricing. These findings support strategic planning for sustainable, cost-effective DH systems aligned with national and EU climate goals.

Keywords

District heating;
Sustainable energy systems;
Heat demand change;
Smart energy systems

http://doi.org/10.54337/ijsepm.11181

1. Introduction

Renewable Energy (RE) is in a key position in a sustainable energy system, the purpose of which is to mitigate and prevent problems created by emissions. Energy production companies themselves have an incentive to reduce their emissions due to upcoming regulative changes and emissions trading. One lesson learned from the European energy crisis is that the volatility of fossil fuels on the public market promotes the idea that a self-sufficient and renewable system is better than the old, fossil fuel dependent system with limited resources[1]. As a result of our turbulent times, companies enjoying natural monopoly positions may be interested in how climate change will alter energy demand, changing the cost structure of energy companies, and to what extent such changes can be addressed through renewable means.

Climate change is projected to significantly reduce heating demand in Nordic regions, with particularly strong effects in Finland [2–4]. Because of this change, the heat demand in the Nordic building stock will decrease somewhat in the future, which has been studied in Finland on multiple occasions with building energy simulations [5–10]. As in this study, all of the previous simulations have been based on Representative Concentration Pathway (RCP) datasets created by The Finnish Meteorological Institute (FMI). These scenarios envision possible future climates through different atmospheric carbon concentration pathways. RCP scenarios used in this work are RCP 4.5 and RCP 8.5, of which the former is the middle pathway for carbon emissions and largely explained by Thomson et al. [11], while the latter is a so-called “worst-case scenario” explained best by Riahi et al. [12]. Milder winters bring

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Received 27.11.2025 | Accepted 01.05.2026 | Published 19.06.2026

List of Abbreviations

CO_2	Carbon dioxide
CHP	Combined heat and power
DH	District heating
EB	Electric boiler
HX	Heat exchanger
HOB	Heat only boiler
HP	Heat pump
HDD	Heating degree day
LFO	Light fuel oil
NG	Natural gas
RE	Renewable energy
RCP	Representative Concentration Pathway
SMR	Small modular reactor
TRY	Test reference year
TES	Thermal energy storage
UO_2	Uranium dioxide

a clear change in our energy needs, and society and companies need to be able to prepare for this. As energy companies base their income on energy sales, it is important to look at the probable future climate to ensure their continuity.

Previous studies on the reduction of energy demand in energy systems have focused on the increased efficiency brought about by building technology, population or policy change, of which examples can be found from [13,14], or the optimisation of energy systems [15], which all inevitably have the potential effect of reducing energy end-use. These studies have not taken future climate considerations into account in the context of the heat demand change of Arctic areas. Notably, Hietaharju et al. were the first to connect heat demand change to a district heating (DH) demand change in Finland [16] by simulating a stochastic dynamic building model of one Finnish city. Elsewhere in Europe, Battini et al. [17] investigated using a multi-objective optimisation approach within RE integration and highlighted the importance of including climate change impacts into the design of sustainable systems.

This article is an investigative study on three DH systems which represent a sample of Finnish DH. The large DH system (hereinafter “L”) has a yearly energy demand of around 6.7 TWh. The medium-sized DH system (hereinafter “M”) provides around 450 GWh of energy annually. The small DH system (hereinafter “S”) provides annually around 17 GWh of heat energy. These systems were chosen for their variability in energy production methods, location and size. The systems were analysed, modelled and simulated with RCP scenarios and projected fuel prices for the years 2030 and 2050 with the modelling tool energyPRO, which is further explained in a later chapter.

As Mohseni and Brent argued, an important property of DH systems is the ability to enable a gradual transition from fossil fuels to renewable options [18]. They listed heat pumps (HP), waste heat, biomass and geothermal technologies as potential supply options for a decarbonised DH system [19]. These technologies are included in the concept of 4th generation district heating and smart energy systems, where DH plays a central role in sector coupling [19–21]. From the aforementioned list - HPs, waste heat and biomass - are particularly applicable under current Finnish conditions, whereas geothermal technologies are not planned in any of the studied systems as they currently stand.

Lund et al. [22] have stressed that the availability and sustainability concerns associated with biomass must be mentioned and managed. Finland, in particular, has a large reserve of biomass in the form of forests. They have become a topic of debate in recent years due to the decrease of their carbon sinks, as reported in [23], and previously raised as a concern regarding energy systems by Hyvönen et al. [24]. A large part of the Finnish energy sector uses wood biomass as an energy source. In the early 2020s, decreasing fossil fuels had meant increasing biomass combustion, namely forest residues [25]. About 45% of all energy wood in Finland comes from forest residues, and 45% from industrial wood waste [26]. In light of these facts, each system was analysed with regional biomass capacity estimation, to determine if the biomass usage of these systems currently - and in the future - is sustainable.

Because the country is having problems with forest carbon sinks being depleted [23], the energy sector requires an alternative to these energy production methods. More recently, DH systems have introduced electric boilers (EB) to maximise the profit from low-cost electricity hours. As Hiltunen et al. have shown [27], this is a feasible option to substitute fossil fuels, and a key characteristic of electrified smart DH systems relying on HPs, EBs and thermal energy storage

[20,21]. Such systems are volatile to the ever-changing price of electricity. The price is prone to fluctuation in the Nordic markets, due to a high share of wind energy in the power grid. Javanshir et al. [28] argued, that although there is heightened risk from volatile electricity prices, there are potential benefits of biomass-based and electrified systems, namely in the form of less emissions and less reliance on imported fuels.

Another contender for fossil fuels has risen in Finland, which has been under much debate in the scientific community about its economic viability and place next to the RE systems. Satymov et al. have argued, that prioritising nuclear power could lead to higher cost for energy systems [29], while Teräsvirta et al. and Värri & Syri discussed how Small Modular Reactors (SMRs) would be profitable as heat-only options in DH [30,31]. All sources highlight that significant uncertainties remain regarding investment and other costs [29,30]. In any case, the technology is not mature enough to be accessed in 2020s and has some major regulatory obstacles in Finland [32,33]. Yet, for future smart DH systems, SMRs could be a viable option to replace some of the biomass-based baseload.

In addition to energy generation, smart DH systems must be capable of responding to fluctuations in an external power supply, particularly in the case of EBs. An effective strategy to mitigate such variations is the integration of thermal energy storage units. In Finland heat reserves have been erected and found to be quite useful during the heating season. According to Lieskoski et al., who made a review of Finland’s energy storages, the deployment of such storages has been made possible by removing barriers from legislation and with investment aid [34]. Other options, like intermediate-to-deep geothermal boreholes as storage for smart DH systems have been studied by Hirvijoki et al., and have been found to potentially function as efficient seasonal storage [35].

The focus of this paper is to analyse the effects of the projected heat demand on DH systems, and to find solutions for the future to curb revenue losses. This study is limited to assessing changes on the heat generation side. As the pressure from regulation to change systems toward more renewable and smart systems increases, and energy demand from customers decreases, to what extent should the DH systems change?

2. Methods and Materials

This paper analyses three DH systems, their operation and their assumed revenues with energyPRO. EnergyPRO is an energy system analysis tool, used to model, analyse and optimise energy systems, which has been documented in an article by Østergaard et al. in [36], and has been widely applied in smart energy system and DH planning studies according to [37]. The optimisation objectives were cost-effectiveness and CO_2 emission reductions. The system operation strategy determined in which order the objectives were possible to be executed. The single restrictive set for the model was that plants and boilers with the cheapest fuel operate first. This strategy helped to determine the ideal way to operate multiple power plants and boilers while being able to meet regional heat demands. System investment costs were not considered in the operation strategy, although such costs will most likely be a relevant issue for the real DH systems. The simulations represent idealised system operation.

The study follows logic shown in Figure 1. First, the data was gathered and analysed, after which the models were built in energyPRO. Models include a baseline scenario for each DH system type under each RCP scenario with 100% renewable or emission free futures. These revisions are explained and listed separately in Table 1. Future climate data for RCP 4.5 and RCP 8.5 were obtained from the FMI and are based on ensemble-mean projections from multiple global climate model simulations, downscaled for Finnish conditions and explained in [8,38].

The data descriptions can be found from chapters 2.5 and 2.6, along with information on each of the DH systems’ heat production unit configurations. In Figure 1, the “Smart systems” relates to the future systems.

The “revenue” metric used in this study corresponds to the income gathered from selling energy to consumers. In energyPRO, the sold energy was assumed to be the average cost of sold heat as EUR/MWh according to statistics from Finnish Energy for each system [39]. In chapter “Results of simulations” the revenue is reported after fuel and electricity costs to each system as EUR/MWh to determine the actual net revenue after energy costs.

2.1 The study cases

This study simulates three different DH systems located in Finnish municipalities, which have heating degree

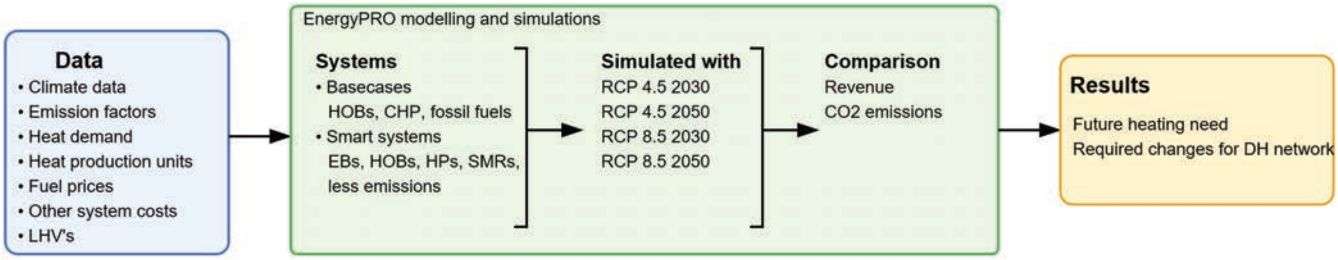

Figure 1: Logic of the modelling with energyPRO.

days (HDD) of 4409 °Cd (S), 4238 °Cd (M) and 3803 °Cd (L) in the baseline scenario, respectively. Only the largest DH system has a cooling service, which will not be considered in this study. The Finnish building stock uses about 66% of its energy demand on space heating alone [40]. The scenarios are expressed in Table 1. Each scenario was simulated with all the proposed RCPs.

2.2 The configuration of the S system

The S system generates heat by combustion of biomass, peat, and light fuel oil (LFO). All heat only boilers (HOBs) are relatively new. Heat is produced from three LFO boilers, one biomass boiler with a flue gas scrubber, a peat boiler, and a biomass boiler which uses wood pellets as fuel. Total DH capacity is 14.6 MW, with a heat demand of 17.1 GWh in 2023.

While SMRs would have been too large to provide heat for the small network, an EB was deemed enough to displace peat combustion. In order to provide reassurance for the operators, a thermal storage of 100 MWh was also introduced to the area, as a redundancy solution and to maximise EB usage.

2.3 The configuration of the M system

The M system consists of combustion of biomass, natural gas (NG), and LFO. Heat was produced from two combined heat and power plants (CHP) and 12 HOBs. The fuel used for heating in 2023 was 486 GWh, with an additional 64 GWh from heat recovery and 3.5 GWh of purchased energy from outside the system. The total usage of DH energy was 424 GWh (Figure 2, middle plot), and the network losses were around 70 GWh. The system has a 400 MWh sensible heat storage.

The M system had ready-made plans for transitioning into a more renewable system; however, not fully. The plans included two EBs, and two HPs placed to utilise waste heat sources. With these choices, the system could be considered about 98% renewable (biomass and electricity as fuel) as the mainly gas-using CHP plant would have been phased out. However, some hours still require heat produced with fossil fuels.

To move the design of the system into a less emission emitting arrangement, an SMR was tested in the system. This change was deemed as the “Revision 1”. Later, in “Revision 2” the study discusses a fully RE system for the area, along with its limitations.

2.4 The configuration of the L system

The L system generates energy by combustion of biomass, LFO, and NG, with some EBs and HPs. Heat is produced mainly from two CHP plants, three HPs, and 11 HOBs. The overall energy expenditure in the grid was around 6.7 TWh (Figure 2, left plot), which included around 539 GWh of network losses. The whole DH system possesses around 14 GWh thermal energy storage (TES). The L system was simulated according to 2026 plans, because the investment decisions for several boilers had been made at the time of this study.

The L system has plans to minimise and diversify its energy operations so that the operations would be as renewable as possible. This means adding large EBs,

Table 1: Modelled scenarios for each system. All changes to systems are discussed in dept in Chapters 2.2-2.4.

Scenario	Large system	Medium system	Small system
Baseline	2026 (planned configuration)	2023 configuration	2023 configuration
Revision 1	Production changes + 800 MW SMR	Production changes + 50 MW SMR	Production changes + EB + biomass
Revision 2 (a, b)	Production changes + 600(a)/400(b) MW SMR	Production changes + EB + biomass	–

Table 2: Used fuels, their LHV’s, and CO_2 emission factors used in energyPRO.

Fuel	LHV (GJ/t)	CO_2 emission factor (t/TJ)	References and notes
Wood (forest residue, etc.)	10.2	0*	The Finnish Fuel Classification 2023 [43]. *The biogenic CO_2 of wood combustion is 112 t/TJ.
Wood pellet	17	0*	
Electricity		30 (g/kWh)	
Peat	12.3	103.2	
NG	38.2 (GJ/1000 m^3)	55.81	
LFO	43.2	73	
Uranium dioxide [UO_2]	3900 (GJ/kg)	0	World Nuclear Association [44].

HPs, and TES. Even after such changes, the system would use a significant amount of gas to run the CHP plants. To replace combustion of fossil fuels, four SMRs (800 MW) and biomass boilers were introduced into the system.

2.5 Fuels, CO_2 coefficients and power plants

In Finland, biomass usage, which includes wood combustion, is not considered a source of CO_2 emissions for the energy systems; rather, it is calculated as an emission in the Land use, Land-use change and Forestry -sector (LULUCF) [41]. The burned wood must meet the European Union sustainability quality requirements. Wood combustion has shown to be increasing in Finland [42]. This has the potential of increasing the price of energy wood more than is expected in this study. Lower heating values (LHV) of fuels and CO_2 emission factors were used to determine key figures from plants and boilers in each system (Table 2).

CHP, HOB, and HP configuration data are highly protected in Finland, and this study uses efficiencies and operation times from available historical data, in order to determine the most likely answers for the missing information. The base cases, which are later compared to the planned future systems, are listed in Table 3 and are based on datasets acquired from Finnish Energy [39].

All fully 100% RE or emission-free future capacities are listed in Table 3. Fuel prices were based on historical data and sources from previous studies, especially with regards to enriched UO_2 (Table 4).

3. Results of simulations

The modelled scenarios resulted in load demand curves are shown in Figure 2. The load demand curves were calculated according to Test Reference Year 2020 (TRY2020) weather dataset for all systems and later simulated with RCPs. The results for TRY2020 and RCP

Table 3: Systems modelled with energyPRO for the 2023 baseline and future scenarios. For CHP plants, heating power is denoted as “*h*” and electrical power as “*e*”.

	Efficiency	S	S (future)	M	M (future)	L	L (future)
Biomass boiler (MW)	90%	5.2	5.2	41	35	362	632
CHP (MW)	80%	–	–	105 h / 56 e [NG and biomass]	54 h / 16 e [Biomass]	582 h / 665 e [NG]	–
Electric boiler (MW)	100%	–	5	35	35	570	570
Gas boiler (MW)	90%	–	–	109	109	912	–
Peat boiler (MW)	90%	1	–	–	–	–	–
Oil boiler (MW)	80%	8.2	8.2	25	–	474	–
HX (MW)	300%	–	–	14	14	70	70
HP (MW)	300-350%	–	–	–	16.5	139	184
SMRs	100%	–	–	–	50	–	800
Thermal storage (MWh)	96%		100	400	400	14 750	14 750
CO_2 emissions (CO_2 t)		2 378	278	21 757	1 650	334 787	12 000

Table 4: Fuel prices and their projections for the future based on historical data and previous studies.

Fuel	**Prices 2023**	**2030**	**2050**	**Sources and notes**
Wood residues	28 EUR/MWh	+2%/yr	+2%/yr	The average price of energy wood, NG and LFO reported by Statistics Finland [45]. Inc. Taxes
Wood pellet	68 EUR/MWh	+2%/yr	+2%/yr	
NG	65 EUR/MWh	+2%/yr	+2%/yr	
LFO	150 EUR/MWh	+2%/yr	+2%/yr	
Electricity	Elspot 2023 + dist. + taxes	Elspot +10% + dist. + taxes	Elspot +20% + dist. + taxes	Elspot 2023 dataset on electricity prices. Includes regional distribution network capacity charges (S system: 4280 EUR/MW/month, M system: 1.55 EUR/MWh, L system: 1267 EUR/MW/month) and tax class 2 taxation. EBs operate on spot-pricing only.
UO_2	1.43 EUR/MWh	+2%/yr	+2%/yr	Based on previous studies of SMRs (burnup 45 GWd/tU) [30] and the USD/EUR exchange rate for 2023. Inc. Only fuel procurement costs

scenarios are shown in Figure 3 for each DH system. As assumed, the worst-case scenario (RCP8.5) in the year 2050 showed the biggest heat demand decrease compared to the TRY2020 baseline. Figure 3 shows that the largest absolute decreases in heat demand occur during the coldest winter days, which is expected given the strong temperature sensitivity of space-heating loads. The M system also exhibit pronounced day-to-day variation during summer, as domestic hot water demand creates fluctuations that were represented using hourly coefficients derived from measured data. To reduce the computation time in scenario simulations, this detailed summer profile was later simplified by replacing the hourly variation with an average summer load.

3.1 Presenting the results of the S DH system

The comparison of the S system is shown in Figure 4 in RCP 4.5 in 2050. Changes made to the system consisted of the removal of a peat boiler and the addition of an EB in its place, with a TES of 100 MWh. The net revenue after energy expenditures remained below the baseline level (from EUR 956 000 to EUR 760 000) due to very high distribution costs for electricity in the region. CO_2 emissions were reduced, from around 2 300 t CO_2 to less than 300 t CO_2.

Replacing the peat boiler with an electric one caused most of the emissions from the system to diminish, and the CO_2 emissions left were purely from the electricity used (Figure 5).

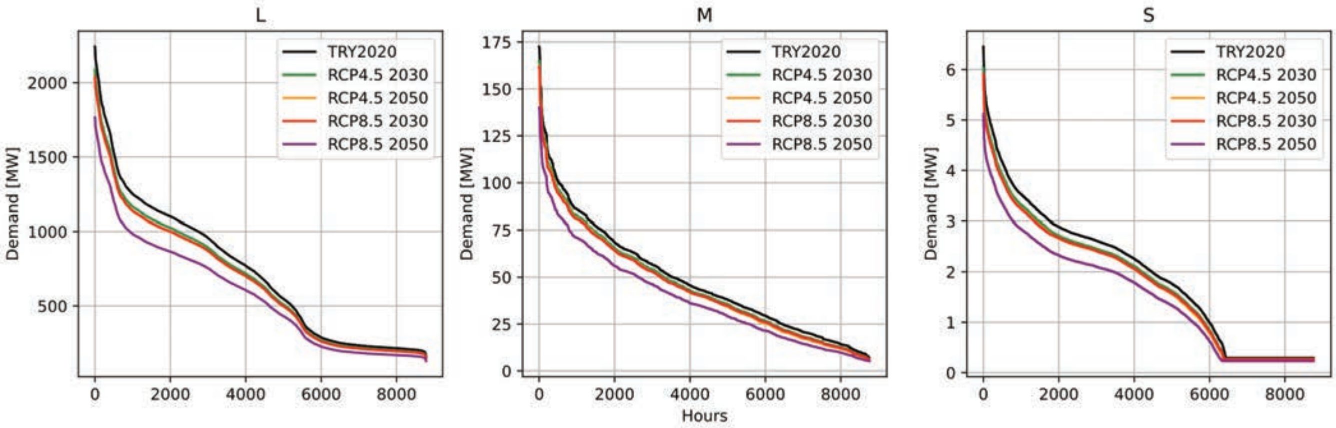

Figure 2: Load demand curves for each system (Large, Medium, & Small) according to baseline (TRY2020) and RCP climate data.

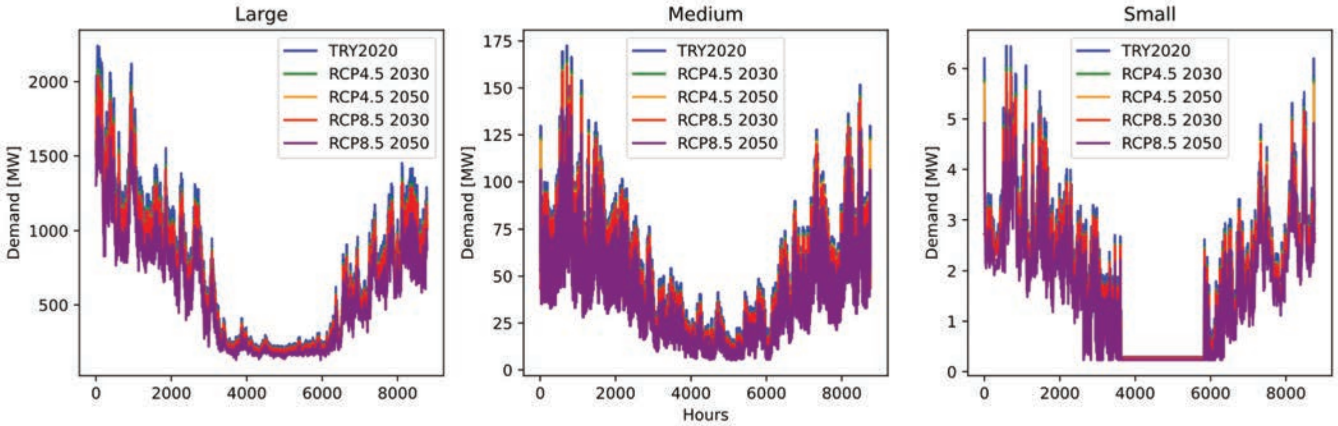

Figure 3: Heat demands in each system (Large, Medium, Small) in TRY2020 and RCP scenarios.

3.2 Presenting the results of the M DH System

The M system was compared from the Baseline of 2023 in RCP 4.5 2050 to Revision 1 in RCP 4.5 2050. Changes made in the system included phasing out the gas combustion CHP and adding an SMR plant in hopes to balance out the lack of a large CHP plant. Revision 1 (Figure 6) illustrates a successful implementation of the 50 MW SMR in the system. Although technically the SMR fit into the system, it did cut off both HPs, which were deemed necessary for the system.

The system CO_2 emissions declined from 8 700 t CO_2 to 1 650 t CO_2, excluding biogenic emissions when comparing the Baseline and future plan in RCP 4.5 in the year 2050. Due to the relatively low cost of enriched UO_2 (Table 3), the system's revenue loss was not substantial even in the future scenario (from EUR 33 400 000 to EUR 42 400 00).

In Figure 7 the Baseline and the Revision 1 are compared with heat consumption and production. The system has some inconsistencies with consumption and production, which can be explained by a 400 MWh TES in the system, which is charged by all nearby units, including the CHP and SMR (Figure 6 and Figure 7).

The year 2023 was then compared to Revision 2 where the system had an EB and a biomass boiler installed in addition to the Baseline. CHPs and gas boilers were successfully phased out, with only minor revenue losses (from EUR 33 400 000 to EUR 32 400 000). The system had no major CO_2 emission reductions compared to the Revision 1, due to the large share of electricity in the system (Revision 2: 5 900 t CO_2).

The reduction in CO_2 emissions in the Revision 2 -scenario can be traced back to the removal of the CHP plant and phasing out NG combustion (Figure 8).

3.3 Presenting the results of L DH System

The L system was also compared from the Baseline of 2026 in RCP 4.5 2050 to the Revised plan in RCP 4.5 2050 (Figure 9). With an addition of 800 MW of SMRs, the system was able to cover most of the baseload, while electric and biomass boilers were able to meet the peak load.

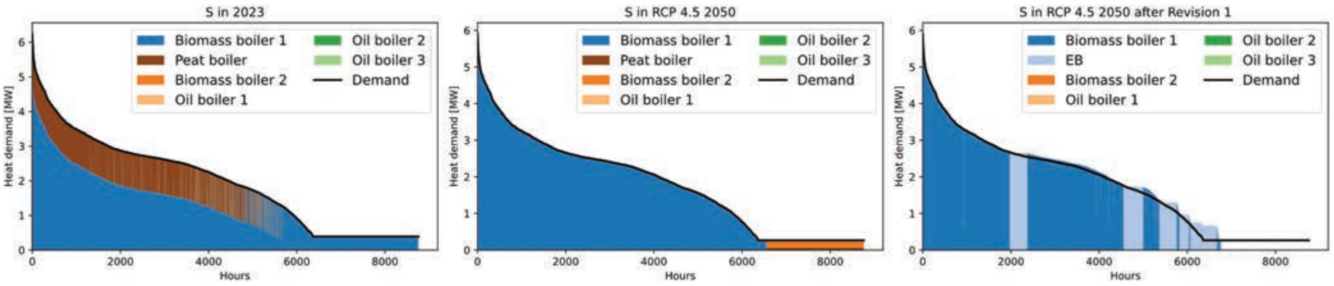

Figure 4: Small system simulation with original system (left), original system in the future scenario (middle), and the revised RE plan (right).

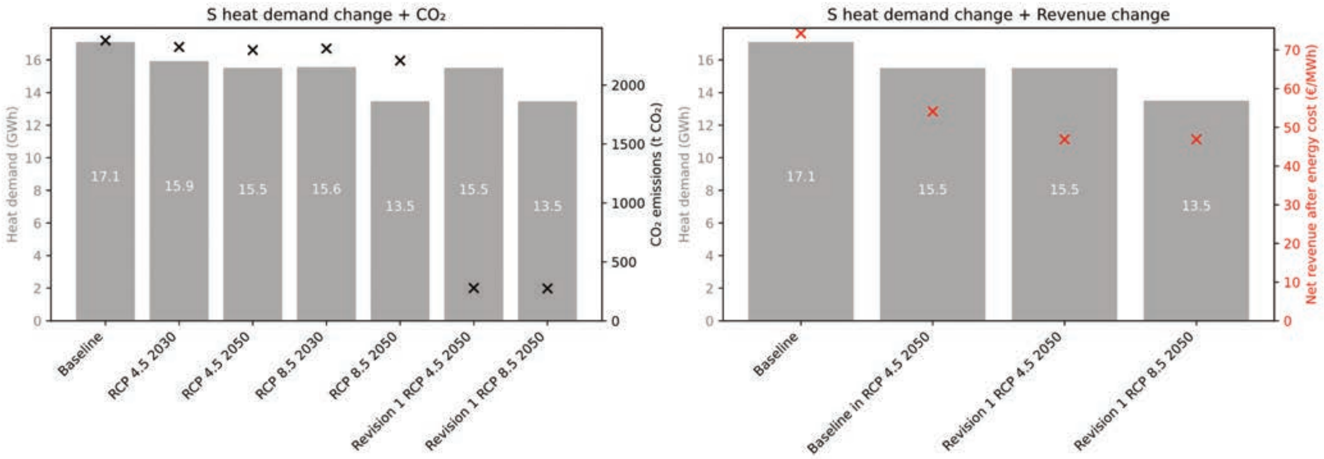

Figure 5: Projected heat demand in the Small system with overlay of CO_2 emissions (left) and net revenue change (right).

The 800 MW of SMRs consisted of 4 units of 200 MW, which were capable of handling the baseload in the system. As 800 MW is quite an ambitious amount of power for the area, scenarios of 600 MW and 400 MW were run in simplified demand models as well, and those performed well (Figure 10). The subsequent changes in these scenarios resulted in higher biomass and electricity usages, with CO_2 emissions rising slightly and revenue decreasing somewhat.

The L system saw the most changes to CO_2 emissions when SMRs were introduced into the system and NG was phased out (with 800 MW of SMRs) (Figure 11). From the base case to RCP 4.5 in 2030 and onwards, the system also saw some major emission reductions, due to NG boilers being online for a shorter duration in time, than earlier. This had the effect of reducing CO_2 emissions more than with the simple heat demand reduction.

4. Analysis of each DH system

The simulated changes in annual energy demand and peak power under the RCP scenarios align closely with previous findings for Finnish building stock (e.g., Hietaharju et al. [16], Pulkkinen et al. [8]warming climate requires adaptation measures from buildings, making it necessary to study the future thermal energy demand of buildings. This paper studies the impact of climate change on the thermal energy demand of buildings in a heating dominated climate of Finland, under “representative concentration pathway” (RCP). In all systems, the milder winter conditions in RCPs 4.5 and 8.5 reduced both total energy demand and peak load, with peak reductions being proportionally larger due to the strong temperature sensitivity of heating demand. These lower peaks decreased the number of hours during which high-marginal-cost peak boilers operated

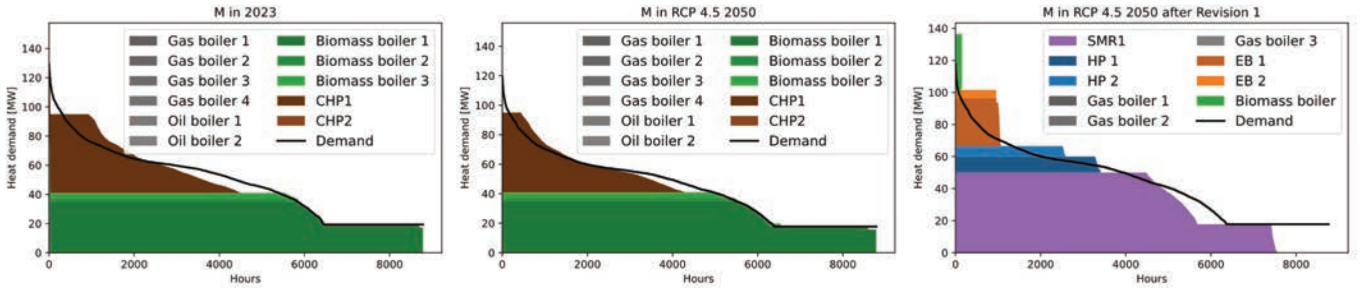

Figure 6: Medium system in 2023 (left) and in 2050 under RCP 4.5 (middle). Finally, revision 1 with a goal to reduce fossil fuel usage (right) in RCP4.5 2050. Systems pictured here as “Operation time order”.

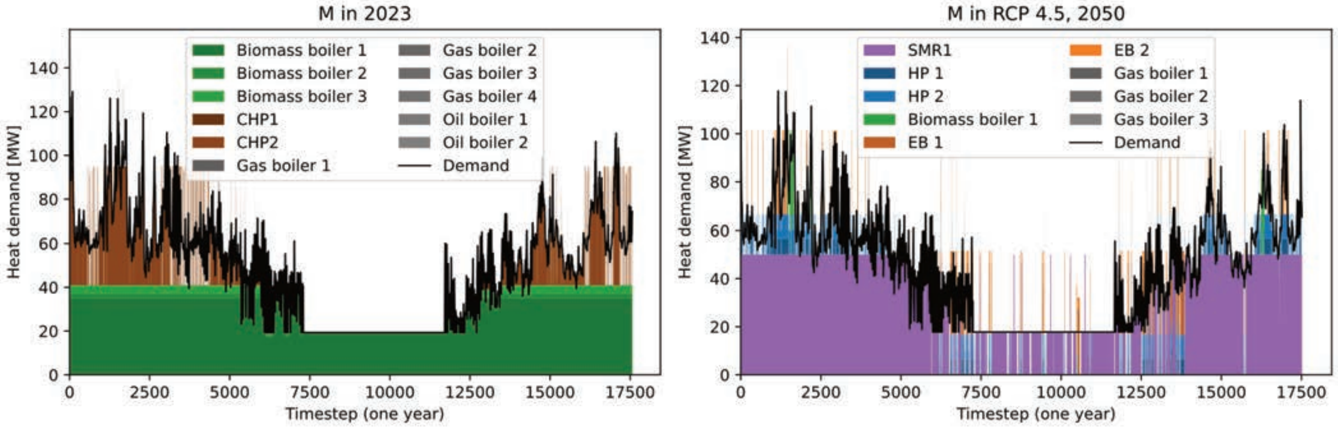

Figure 7: Heat consumption and production in the Medium system in 2023 (left) and Revision 1 (right).

and increased the ability of TES to cover residual peak periods. While the reductions were not sufficient to alter the preferred composition of production technologies, they suggest that future systems may be dimensioned with smaller peak-load capacities, particularly in the M and L systems. Although detailed investment optimisation is beyond the scope of this study, the results indicate a potential for cost savings through downsizing peak-load assets as climate warming reduces extreme-load conditions.

System size and location strongly influenced the feasibility of electrification. High regional electricity distribution costs limited the use of electric boilers in the small system, whereas the medium and large systems benefited from lower tariffs, enabling more flexible operation of electric boilers and heat pumps. Biomass use decreased in absolute terms under the RCP scenarios due to lower heat demand, but its relative role remained as is unless the production portfolio was modified (as it was in Revisions 1 and 2).

The L system had a successful simulation with phasing out CHPs and adding SMRs. The Revision 2 with a) 600 MW and b) 400 MW of SMRs was deemed necessary due to the limited spatial availability of urban areas. Fitting 800 MW of SMRs in a densely populated urban area can be unrealistic, but as the objective of this study was to find what fits into the energy system alone, spatial design concerns were left outside the scope of this study. The quantity of SMRs here affected CO_2 emissions and revenue somewhat, and the system could operate effectively with the lowest simulated number of SMR (400 MW). The lowest quantity of SMRs allowed

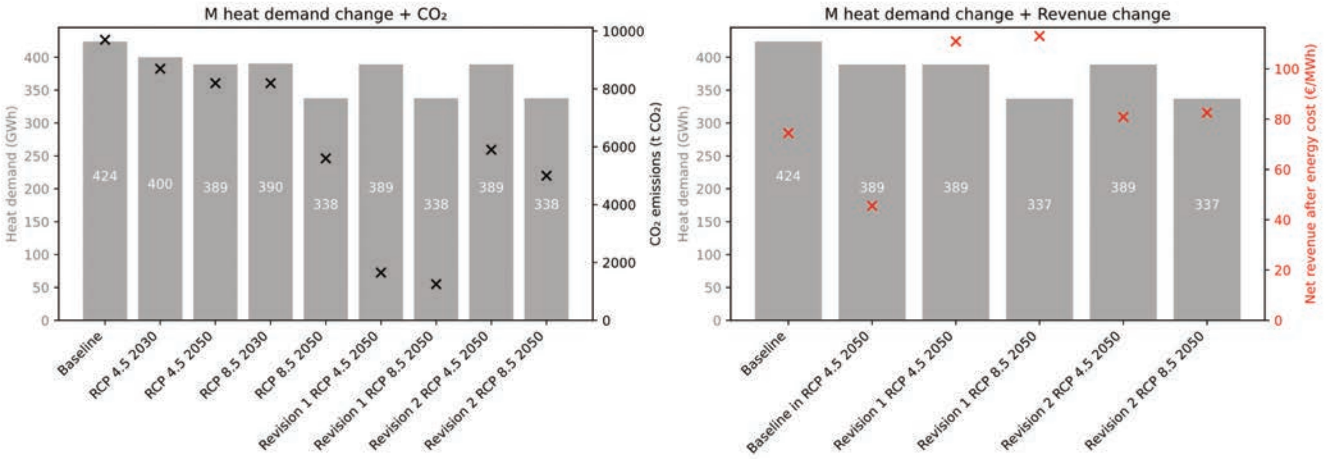

Figure 8: Projected heat demand in the Medium system with overlay of CO_2 emissions (left) and net revenue change (right).

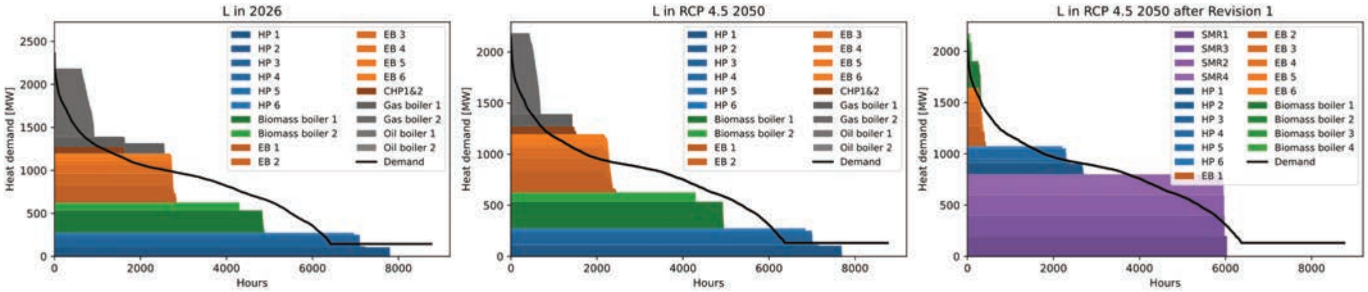

Figure 9: Large system with Baseline (left), in the future (middle) and the revised plan to reduce fossil fuels (right) in RCP 4.5 2050. The duration curve pictured here as “Operation time order” and with a simplified demand model.

the EBs to be more flexible with regard to their operation. Overall, EBs operated effectively here, due to relatively low distribution costs.

In the M and L sized systems the revenue increased in Revisions despite the decreasing heat demand (Figure 8 & Figure 11). This was due to the TESs being charged with cheaper electricity via HPs, and the TES charge lasting longer than in the scenarios of less heat demand. Similar effects were noticed in the S system, even though the effect was less noticeable. This connects to the principles of smart energy systems, where flexible electric technologies operate according to electricity market conditions. In practice, this flexibility is highly dependent on regional electricity distribution tariffs. The S system’s high tariffs limit electrification, while the M and L systems can use EBs and HPs more effectively, shaping how each system can participate in smart DH.

4.1 Regional biomass capacity estimation

A regional biomass capacity estimation was performed for the systems, with a primary focus placed on regional forest residues from integrated harvesting. Residue estimation was conducted from data collected by the Natural Resource Institute Finland’s (Luke) Biomass Atlas [46]. An estimation was made to find out if the regional biomass capacities would be able to meet the requirements of the DH systems’ plans (Table 5). Values from the Biomass Atlas were given as m^3/a, which were converted to “tons annually” with a rough estimation of 0.8 t/m^3 for fresh wood density according to Luke’s energy wood measurement guide [47].

Finland’s annual production amounts to approximately 5.3 Mt of energy wood from integrated harvesting [46]. The three systems in the year 2023 used about 0.7 Mt of that, which is about 13% of the entire total. The L system requires interregionally exported wood. Technically, however, Finland’s own reserves are enough to cover all of the systems with their current (2023) demand, and in the future scenarios with these rough estimations.

5. Conclusion

The aim of this study was to assess how projected heat demand will affect DH systems, and to explore strategies for mitigating revenue losses and support the transition towards smart DH systems. Our results for change of heat load show similar results found in Hietaharju

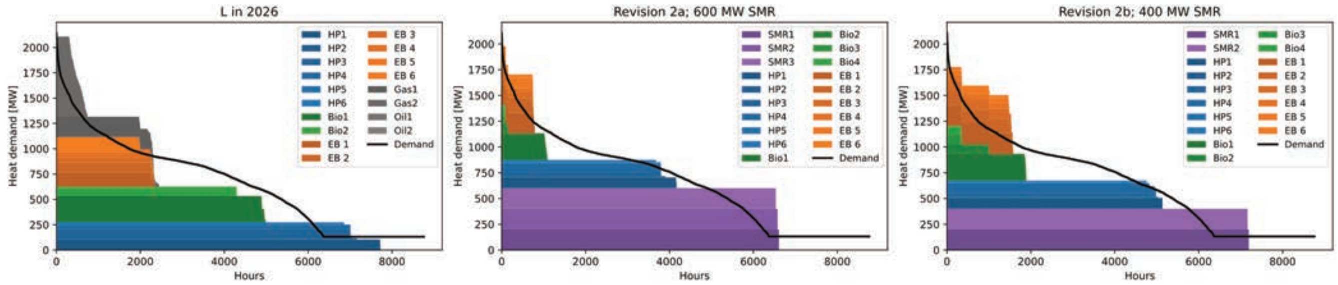

Figure 10: Large system with Baseline (left) compared to SMR 600 MW scenario (middle) and SMR 400 MW scenario (right). The duration curve is pictured here as “Operation time order” and with a simplified demand model.

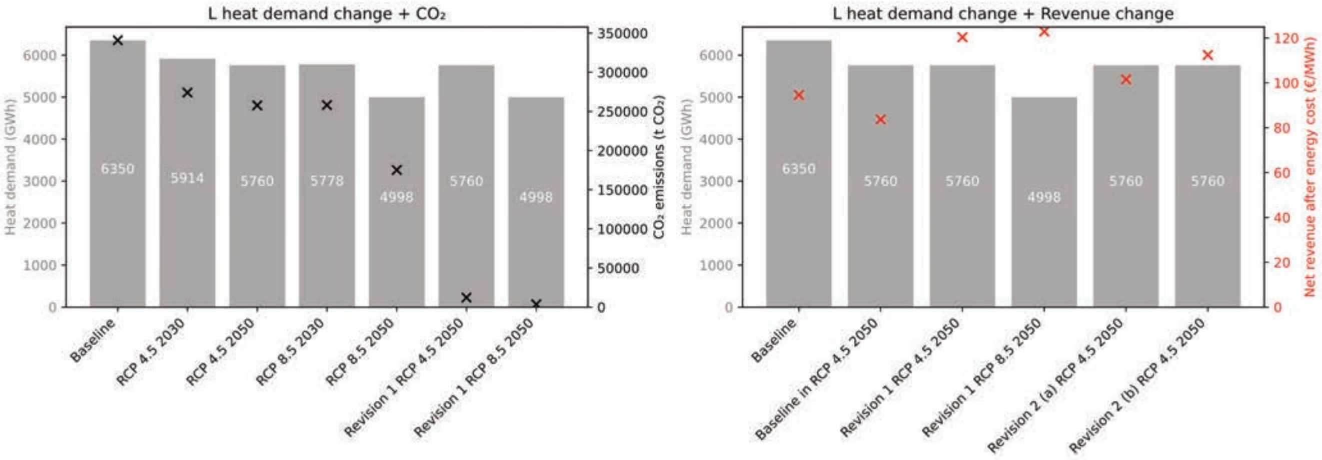

Figure 11: Projected heat demand in the Large system with overlay of CO_2 emissions (left) and net revenue change (right).

et al. [16], without their renovation strategy for buildings. The change of heating demand will affect the revenues of DH systems. Each system (owner) decides, on how they wish to respond to these changes. In this study the chosen method was the changing of the energy production methods, in order to determine to what extent sustainable systems could save revenue. However, the results for profitability of investments to RE technologies differ based on the DH system under scrutiny.

In Hiltunen et al. [27] they found that EBs could be used to reduce the production costs of DH systems, particularly by taking advantage of the low electricity price hours. Generally, this was found to be true in this study as well for L and M systems. However, the S system had issues due to high electricity distribution costs, which made the added EB lose a significant amount of revenue for the system compared to the traditional peat and biomass boilers.

As previous studies found, SMRs may be profitable in densely populated urban areas [30,31]. According to the results of this study, however, as SMRs currently present in their Finnish scale of 50 MW minimum, they are too large for the M- or S -sized systems to be energy efficient. In the case of the M system, an SMR could have fitted in, however, it would have cut off waste-source HPs from the area. As the HPs are already being invested into, and an SMR would be coming into play perhaps only in the 2030s, pursuing an SMR, and abandoning investment in the HPs, would not be recommended. More importantly, the HPs recover waste heat, which increases the area's energy efficiency, and they have other local effects, such as positive economic impacts. Nuclear energy is not included in Lund et al. [19]'s definition of 4th generation DH systems, as it is not RE. In larger DH systems SMRs can support variable RE technologies effectively by balancing the base-load of heat demand alongside biomass boilers, HPs and EBs (Figure 11).

Notably, it can be assumed that regions with smaller DH systems than the L-sized systems will most likely have a harder time integrating SMRs into the supply chain. Additionally, it will likely be challenging to satisfy the stringent safety requirements that often come with SMRs, especially when larger systems have more capital, knowledge, and experience regarding these systems. Unless, that is, the SMRs are made both technologically and legislatively as modular as possible. The uranium price projections are uncertain and the investment costs

Table 5: Regional biomass capacity estimation based on forest wood residue harvesting from each systems' Finnish province. R1 indicates Revision 1 and R2 indicates Revision 2.

System	Available wood [t/yr] [46]	Demand [t/yr]	Demand 2050 [t/yr]
S	124 000	3 400	1 500
M	92 000	180 900	5 300 [R1] / 46 600 [R2]
L	157 000	531 200	114 000 [800 MW SMR]
Total	373 000	715 500	120 800 [R1] / 195 100 [R2]

for systems are expected to be steep, as Satymov et al. explained in [29]. Lack of available data made including the review of SMRs difficult for this study. However, overall, we can assume that the future systems will prioritise minimising expensive fossil fuel combustion as such systems are already doing so in Finland.

Smart systems rely on interlocked grids of heat and electricity, as Lund et al. have listed in [19]. Often the smaller DH systems are located in areas with underdeveloped electricity distribution capacity with long distribution distances, which can make investment costs for those systems high, as stated by Hyvönen et al. in [24]. Waste heat is also not readily available to these systems due to lack of nearby large industrial plants.

With current available information, the L- and M-sized systems are able to participate in the 4th generation DH concept. Smaller systems are hindered by their location specific characteristics. Smaller systems are able to participate in smart systems, granted large investments to the DH system can be made.

Biomass combustion is already popular in Finland and will likely continue to be in areas where the electricity distribution costs are very high, like the S system. In Finland, the price of wood has shown to be increasing, and the price is still very dependent on many external conditions, like the severity of cold winters. Warmer winters can cause thawed ground, which can cause difficulties in wood harvesting, causing the prices to go up. Additional and more accurate investigation into the complex biomass capacity estimation should be studied more extensively, in order that it could be carried out with more certainty.

The heating demand decrease effect on DH systems is significant on its own, and with effects of other major building energy efficiency improving methods, it will cause major revenue loss for DH systems in Finland. For more comprehensive estimation on effects of the climate change to DH systems, calculating the potential of cooling demand change on each region should be carried out as well. Moving towards smart and sustainable DH systems is not only a recommendation for the Nordic and Arctic DH systems, but also a means of survival, when heating remains a basic necessity for societies. Lower cost heating allows for energy equality regardless of region or system size. It is important to include other strategies than simply raising consumer energy price as a strategy to mitigate companies' revenue decrease.

Acknowledgement: The study was partly carried out in Adapting the built environment of Kanta-Häme to climate change -project in Sustainable Energy Systems -research group. The project was co-funded by the European Union. The study was presented at the 11th International Conference on Smart Energy Systems.

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