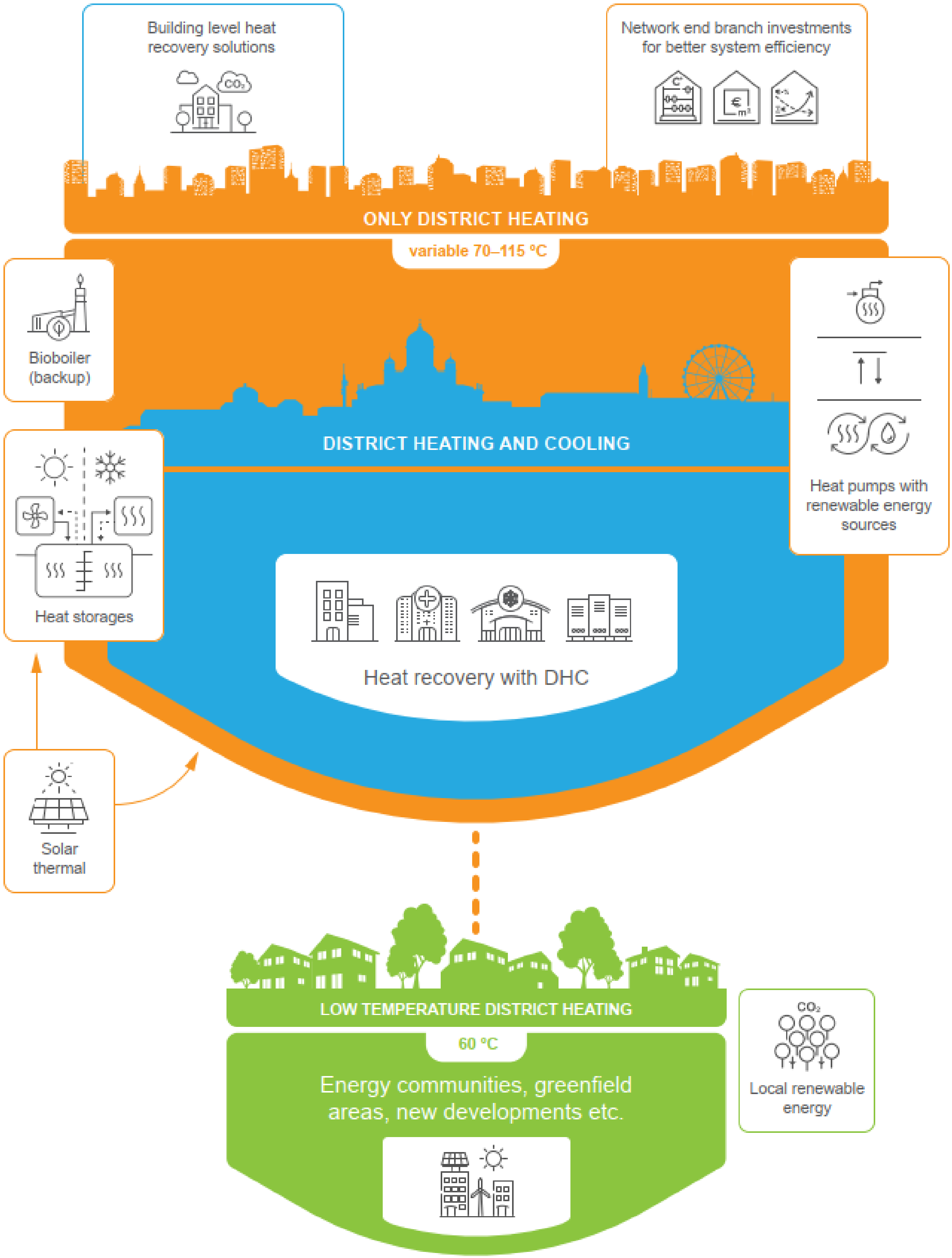
FLEXIBLE FUTURE



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Abbreviations

ASHP	Air source heat pump
BMS	Building management system
CHC	Combined heating and cooling
CHP	Combined heat and power
DC	District cooling
DH	District heating
EIA	Environmental impact assessment
GSHP	Ground source heat pump
HEC	Helsinki Energy Challenge
HFO	Heavy fuel oil
ICT	Information and communications technology
LCOE	Levelized cost of energy
LFO	Light fuel oil
NPV	Net present value
O&M	Operations & Maintenance
ST	Solar thermal
VB	Virtual battery
VBP	Virtual battery platform
WSHP	Water-source heat pump

Summary

The Flexible Future proposal is based on effective utilization of existing energy infrastructures in the city of Helsinki, in particular the thermal networks, added with advanced modern energy solutions.

The decarbonization plan of Flexible Future strongly relies on proven energy efficiency measures, heat storages, heat pumps, and clean heat production technologies. The Flexible Future solution results in significantly lower emissions in heat production and minimized biomass use (compared to existing plans of Helen). All proposed solutions are feasible, expandable, and scalable. Flexible Future pays attention to integration of the solutions to provide an optimal outcome. Therefore, advanced ICT-solutions, such as artificial intelligence-based heat energy management and control are employed to create a Virtual Battery Platform to balance the heat consumption demands with the heat production including the effects of decentralized heat sources. The approach enables extensive harvesting of waste heat streams in Helsinki to save and complement heat production.

The working principle of the Flexible Future solution is illustrated in cover page showing the district heating (DH) and district cooling (DC) networks serving the buildings and other thermal uses. Flexible Future considers three different types of areas in the city: the central parts of the city (e.g. city center), new communities and residential areas of future Helsinki, and the remote parts of the city (‘tail’).

In the city center, dominated by a dense older building stock and commercial buildings, the district cooling network provides not only chilled water (mainly in the summer), but also recovers the surplus heat and feeds it to the district heat network for use in the other parts of the network. Most of all heat demand will be linked to the district heating network, which presently works in one way only, i.e. heat is supplied from central plants to the consumers. In the Flexible Future solution, the DH network is turned into a more active role, serving both prosumers feeding heat into the network and consumers using the heat.

The proposed new DH strategy relies on prosumer-type approach and more decentralized DH production envisaged particularly in the new residential areas of Helsinki, but also in the outskirts of the city, which are not easily served by the central plants, necessitating high delivery temperature of heat in the winter. This would mean in practice harnessing as much local waste heat as possible and complementing existing peak boiler plants with heat pumps for base load generation or constructing new heating centers in the ‘peripheric’ parts of the network. In this way, delivery temperatures could be lowered, which not only reduces network losses but would facilitate integration of new sustainable heating technologies. The future trend may be low-temperature energy communities, which would be mostly self-sufficient through their own heating solutions but would be still be connected to the main DH network of Helsinki, providing backup services and take-up of surplus heat. Active use of thermal storage, e.g. water tanks or rock caverns, to compensate for possible demand & supply mismatches, thus minimizing new back-up investments and upgrading the quality of the local heat sources.

An optimized energy solution (“Flexible Future”) compatible with the current energy system as well as with the criteria set by HEC was determined by carrying out a thorough analysis of all potential opportunities both on the consumption and on supply side. Flexible Future consists of centralized (mainly existing) and de-centralized (mainly new) technologies which are integrated with a so-called Virtual Battery Platform. Platform provides the service and control required for the flexible and effective use of the good number of different heating solutions, both on demand and supply side. Our solutions assume that Helen's current investment plans will be implemented and coal-fired plants of the existing production fleet are shut down according to the published schedule.

The main heating solutions proposed by the Flexible Future are the following:

- Building level energy efficiency and heat recovery measures;
- Large-scale heat pump schemes;
- Solar heating systems;
- Helen´s existing and planned heating solutions (except for Tattarisuo and Patola).

Building level heat recovery solutions are tailored for different building types and residential areas. Heat recovery systems with heat pumps connected to the district heating network, regardless of the method of implementation, have a huge potential and are key elements in the Flexible Future solution for the majority of carbon-free heat supply. An interesting option for heat recovery is the district cooling network, but also the traditional property-specific heat pump system as well. The implementation method depends to a large extent on to what extent the heat recovery solutions in district cooling become more common and how business models are shaped. The indicative heat recovery potential to DH network is presented in Figure 1.

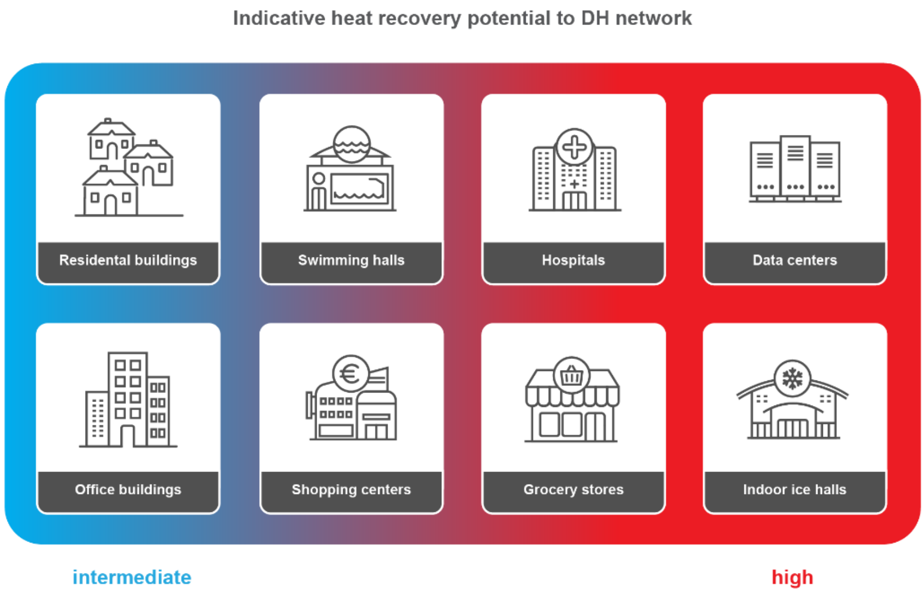


Figure 1. Potential for different heat sources.

From a business perspective, there are already existing models for heat recovery implementation and operation such as Helen's district cooling and building level CHC heat pump service providing cooling to buildings and recovering heat into DH network, and increasingly, real estate owners are investing in their own heat pump systems which enables them to recycle waste heat and reduce purchased heat.

Flexible Future anticipates that business models will be evolved in future as follows:

- Heat recovery by using district cooling is a great model and it can be made even more effective by restructuring the pricing to be more attractive to customers.
- There will be models and services that helps building owners (mainly residential) to procure and implement heat recovery solutions on their own but using e.g. the support of outside technical design and procurement specialists.
- Carbon neutrality will be targeted in new development areas for residential and commercial buildings, and one option to arrange this is a competitive tendering process for selecting a dedicated energy operator for providing a comprehensive energy service for the area.
- Third parties will provide customer-end heating and cooling and even indoor comfort as a service. Service shall be specified and reproducible by building type. Winning solution might require prefabricated components, series production units, smart operation and maintenance with flexibility to optimize system performance etc. Nothing prevents also Helen to provide such a service.
- Digitalization and platform economy will increase in the future enabling new ways for flexible heat trading, service provisioning and minimizing peak-power usage.

Large-scale heat pump solutions would be employed in various locations along the district heating network, with different types of primary heat sources to be applied. An innovative solution proposed is a multi-story open-air heat recovery unit connected to heat pumps, which presents a large-scale heat pump application for limited space. Geothermal heat in form of deep-heat well would be employed as well.

Solar heat collectors are envisioned to be used on floating bed on the seaside bays of Helsinki to enable large-scale use of solar heat. Land-based solar thermal systems are an alternative to the floating systems, if necessary.

Cost-effectiveness combined with carbon savings potential and reduction of biomass-based heat production were the main factors in sizing the proposed solutions in Flexible Future. The future plans of Helen have been taken into account except for seeking actively other energy sources than biomass to replace the use of coal. The overall Flexible Future solution in 2030 is presented in Figure 2. The technical performance parameters for the new capacities are the following:

- The total annual energy savings of the building-level heat recovery measures add up to 1,005 GWh when fully implemented;
- 0.4 km² of solar thermal collectors are installed with a yearly heat output of 177 GWh. The system employs existing and planned heat storage facilities (Mustikkamaa, Kruunuvuorenranta). A single large-scale array would bring the biggest economy-of-scale benefits, but the system can also be divided into multiple smaller arrays around the city.
- New heat pump capacity of 180 MW will be build based on air-to-water or geothermal heat sources. The yearly heat output is 1,050 GWh. Air-to-water heat pumps are slightly more cost-effective than geothermal ones, but the situation may change in coming years and therefore the final heat pump solution may be some combination of both technologies.

The proposed new measures and technologies above will provide 40% of all heat production in Helsinki by 2030. Figure 2 shows the impacts of the proposed solutions on the heat profile in 2030. Energy efficiency measures and building heat recovery contribute with a fairly constant effect over the year. Most of the solar thermal output concentrates to summer. The summertime production shares indicate that there could be room for more solar thermal production, but this may be limited by the availability space.

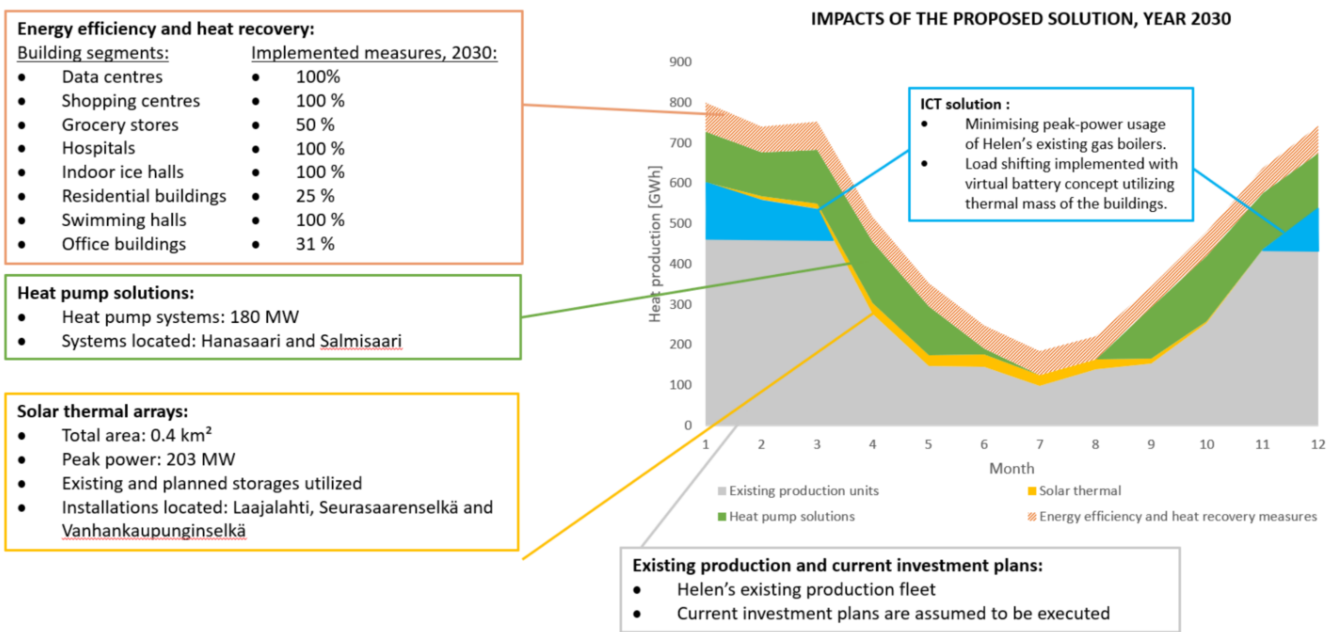


Figure 2. Impacts of the proposed solution in year 2030.

A Baseline scenario was created for comparison, by modelling the annual heat production with Helen's perceived production plants and thermal storage capacities for years 2020–2040.

In the Baseline scenario, the annual CO_2 emissions from heat production would be 0.46 $MtCO_2$ in 2030. In Flexible Future, the emissions would drop by 36% compared to the Baseline (see Figure 3).

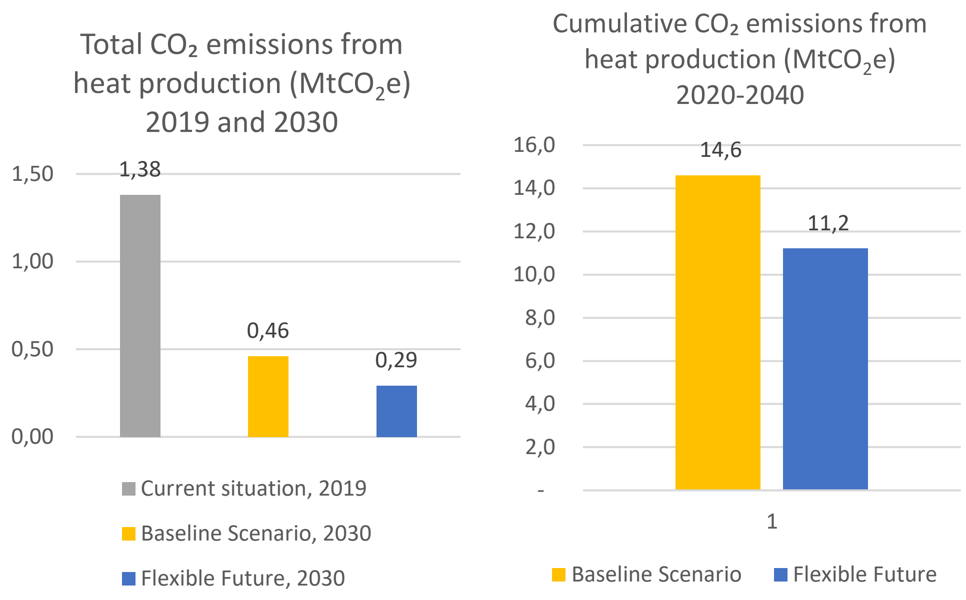


Figure 3. Total CO_2 emissions, 2030, and cumulative, 2020-2040, CO_2 emissions from heat production.

The cumulative investment cost of the Flexible Future is 719 M€ for the period 2020-2040. The energy weighted LCOE was 30.1 €/MWh, ranging from 25 to 65 €/MWh.

All the low-carbon measures proposed by Flexible Future will be implemented by 2029 whereafter the Vuosaari CHP plant would be the by far biggest fossil fuel consumer and source of emissions in Helsinki energy system. Flexible Future is based on infrastructure solutions (e.g. DH network, comprehensive IoT platform) which facilitate flexible introduction of new capacities and measures as and when new low carbon technologies mature and are commercially acceptable. It is anticipated that e.g. biogas/biofuels, hydrogen and nuclear solutions may reduce natural gas consumption at Vuosaari and eventually replace it completely, possibly already before 2040 or thereafter. At this point of time, however, Flexible Future is built on proven solutions but remains open for the future options.

1 Climate Impact

The Flexible Future proposal provides the following environmental benefits compared to Baseline Scenario:

- By year 2040, the Flexible Future would save in total 23% in the cumulative emissions
- Starting from 2030, the specific CO_2-eq emissions per heat unit would be 36-50% less compared to Baseline Scenario, and approximately 70% less compared to year 2020 level
- The Flexible Future reduces the need for biomass by almost 78%, 1.9 Mt, and the demand of natural gas by 35%, 14000 GWh, between 2020-2040

The Flexible Future proposal provides the following environmental benefits compared to Baseline Scenario:

The Flexible Future proposal is based on an analysis and optimization of the solutions following a 3-step procedure:

- starting with broad surveying of potential low- or zero-carbon solutions
- followed by narrowing down the available options to the most cost-effective ones, and
- finally choosing the solutions best compatible with the criteria set by the Helsinki Energy Challenge and current situation and investment plans in Helsinki.

All relevant technical, financial, and environmental parameters have been considered and included for various capacity and system options analyzed. Different restrictions and limitations are taken into account, e.g. those related to the operation and dynamics of the energy system, limitations with different heat sources for the heat pumps, available space for the heat generation solutions, realistic implementation possibilities of the building-level energy efficiency and heat recovery measures, etc. The simulation and optimization work have yielded as an output the energy, emission, and resource impacts and balances, which are then used to define the optimum scenario best compatible with the criteria set by the HEC.

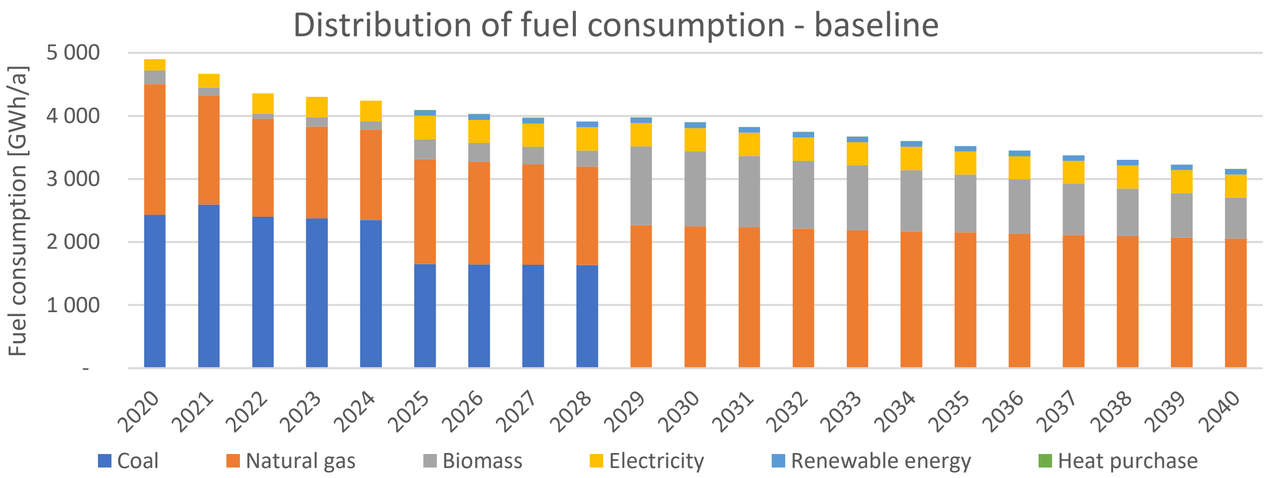
The key assumption included the simulation were the following:

- All current plant investment and decommissioning decisions by Helen are assumed valid, with the exception of Tattarisuo and Patola biomass boiler plants. These plants are assumed to be built in the baseline scenario by the end of the 2020s to replace coal-fired production but in the Flexible Future proposal they are not needed, and the plants are not built.
- The current operational strategy of the heat generation plants of Helen is used as the baseline in the simulations, i.e. the model is calibrated so that its results for 2019 match with the actual production shares of the existing plants;
- CHP plants are modelled as separate units, while boiler plants by fuel type and heat pumps (separated into existing and new) were dealt with as aggregated capacity units;
- The proposed building-level energy efficiency measures and heat recovery solutions are incorporated in the simulations as a decrease in the heat demand with the resulting increase in their electricity consumption accounted for.
- All production units have type-specific real fuel efficiency values;
- The CHP plants are assumed to be off-line for a one-month maintenance in the summer. Other production units have shorter maintenance periods;
- Realistic output power adjustment, minimum load and start-up/shut-down time assumptions for the production units were used;
- Salmisaari coal-fired CHP plant is assumed to be fully decommissioned by 2029.

Figure 4 shows the annual distribution of fuel consumption for the Baseline Scenario and the Flexible Future for 2020-2040. Carbon emissions are calculated based on annual fuel consumption using the emission factors by Statistics Finland.[1]

[1] https://www.stat.fi/tup/khkinv/khkaasut_polttoaineluokitus.html

The use of coal is eliminated in both scenarios by the year 2028 but in Flexible Future the usage is already somewhat lower starting from 2023 (Figure 4). The Flexible Future reduces the need for biomass by almost 1.9 Mt and the demand of natural gas by 14000 GWh between 2020-2040, a reduction of 78% and 35%, respectively.



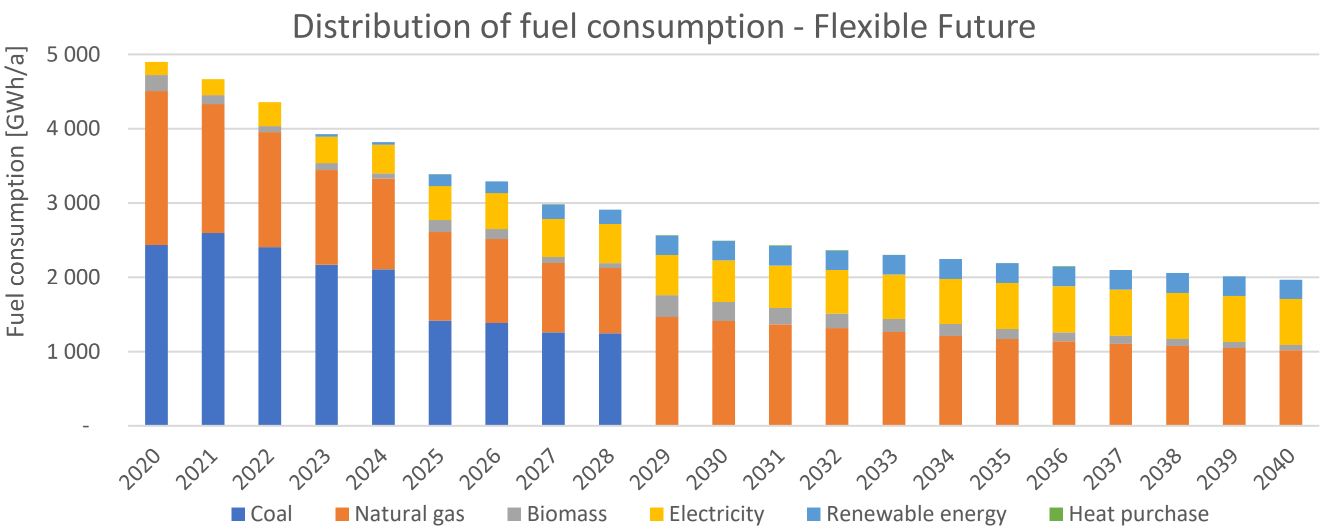


Figure 4. Fuel use. (a) Baseline Scenario, (b) Flexible Future Proposal.

The annual CO_2-eq emissions from heat production for the Baseline and Flexible Future scenarios are presented in Figure 5; total tons of CO_2-eq emissions per year as well as specific emissions per heat production (in tCO_2e). Emissions in the first three years of the calculation are identical in both scenarios since the first new proposed capacity is introduced only from 2023 onwards.

The difference in specific emissions between the Baseline and Flexible Future in year 2030 is 36%; mainly due to replacing some of the Vuosaari CHP production with zero/low-carbon solutions introduced by the Flexible Future. The main emission source in 2035 is the Vuosaari CHP plant: in the Baseline Scenario its emissions are 0,46 $MtCO_2/a$ (total 0,46) and in the Flexible Future 0,27 $MtCO_2/a$ (total 0,29).

Helen's emission factor for district heat was 198 gCO_2e/kWh in 2019 and 76.3 gCO_2e/kWh in the Baseline Scenario in 2030. In Flexible Future, the emission factor drops to 48.6 gCO_2e/kWh by 2030, representing a reduction of 73% compared to 2019 figure. By year 2040, the Flexible Future would save in total 23% in the cumulative emissions compared to the Baseline (Figure 5).

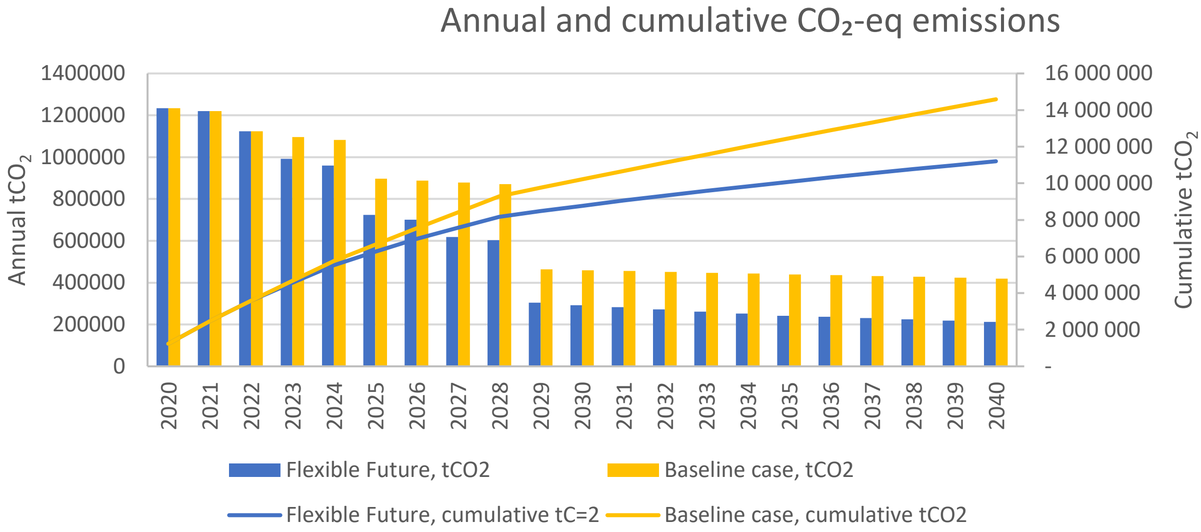


Figure 5. Annual and cumulative CO_2-eq emissions.

The current investment plan of Helen relies mainly on natural gas and biomass as the main fuels. The biomass is handled with an emission factor of 0 kgCO_2e/MWh (assuming that biomass is fully climate sustainable). Despite this, the Flexible Future proposal is capable of delivering notable emission reductions.

However, biomass burning in reality does cause CO_2 emissions and if this should be accounted, as debated among scientists, this would lead to major increase in CO_2 emissions in the Baseline Scenario but almost 80% less in the Flexible Future. In any case, it is most likely that substantial amounts of wood chips would need to be imported, which could have adverse local environmental effects. [2] [3].

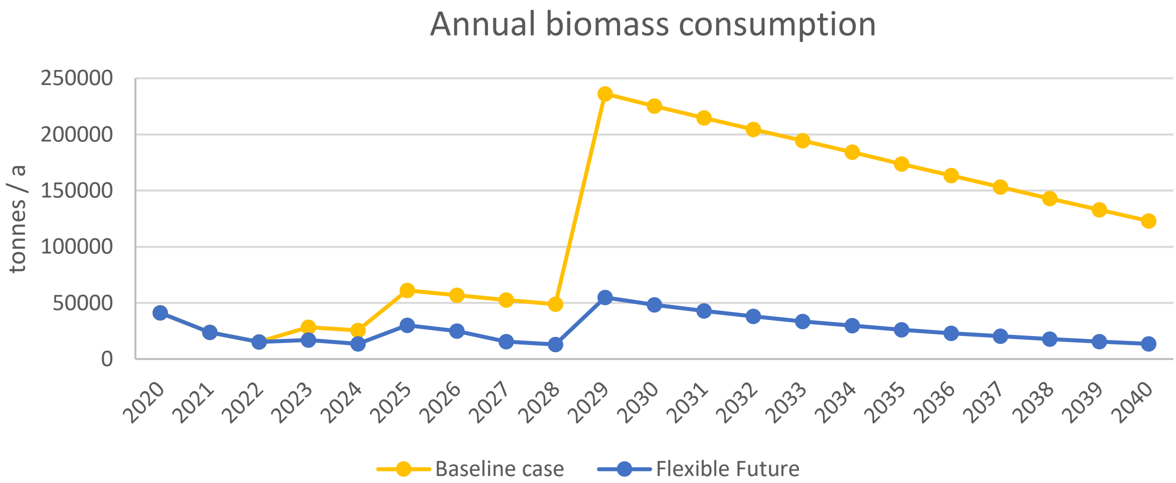


Figure 6. Annual biomass consumption in the proposed solution and in the baseline scenario.

[2] Ramage et al. 2017. "The wood from the trees: The use of timber in construction. Renewable and Sustainable Energy Reviews. https://www.sciencedirect.com/science/article/pii/S1364032116306050

[3] Tuontihake korvaa kotimaista haketta. 11.5.2020. Promaint. https://promaintlehti.fi/Alan-Uutiset/Tuontihake-korvaa-kotimaista-metsahaketta

2 Impacts on natural resources

Flexible Future would

- Result in significant lifetime conservation of fossil fuels and biomass resources
- Focus on smart energy efficiency solutions, the most sustainable approach in terms of natural resources
- Maximise the use of existing infrastructure thus avoiding unnecessary investments and minimize material usage
- Recognize the land use restrictions, focus on existing sites where possible and would be flexible in terms of locations and land areas

The Flexible Future would utilize the heat infrastructure existing in Helsinki to the maximum, as appropriate, thus minimizing the use of new construction materials, further land and investment costs. This applies especially to Helen's comprehensive DH network which provides a good basis for introducing new low carbon heat options with minimum costs and as importantly, maintaining the reliability of supply at all times.

The main materials needed for construction and installation of the energy technologies in this Flexible Future are basic construction materials such as concrete and glass, and ordinary mineral commodities such as aluminum, steel and copper. No precious or critical materials are needed. No harmful refrigerants are used. Most of the materials embedded in the technologies can be recycled. The total material use may be in the range of 4,000 tonnes. [4]

The Flexible Future saves major energy resources and fuels, as it employs renewable energy sources, waste heat, and energy efficiency measures. The electricity employed for the Flexile Future is assumed low-carbon (emission factor 30 kgCO_2/MWh) in line with the presumption given in the assignment.

About 100,000 to 200,000 tons of biomass can be saved annually from 2029 onwards compared to the Baseline Scenario with a total saving of over 1.9 million tons during 2020-2040. The remaining biomass usage would consist mainly of chipped forest fuel, industrial wood residue or clean recycled wood (according to the information shared by Helen during the EIA process). Avoiding construction on combustion-based plants (e.g. Tattarisuo) would also reduce the impacts on local environment and natural habitat. The sulphur- and nitrogen dioxide as well as particle emissions, hydrogen fluoride-, hydrochloric acid and mercury emissions would drop in proportion to saved biomass.

During 2020 to 2040, the Flexible Future would save 14000 GWh of natural gas. Most of the natural gas used in Helsinki originates from Russia [5]. In 2019, Gasum Ltd. conducted a study on the environmental impacts of natural gas extraction in Russia. The main environmental impacts relate to non-renewable fossil resource use in general and to treatment of waste and wastewater in Russia. Extraction also causes changes in the soil and vegetation. These changes, in turn, can cause both direct and indirect adverse impacts on biodiversity. [6] [7] The Baltic connector gas pipeline will provide alternative routes for gas from the Baltic countries, with possible lower environmental impacts.

The large-scale solar thermal collector field would require some 0.4 square kilometres of space. Therefore, placement along the seaside in blocks would be a land saving solution and minimize landscape impacts.

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[4] Benjamin Greening et al. Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK. 2012 Elsevier Ltd doi:10.1016/j.energy.2012.01.028

[5] Maakaasumarkkinat. Energiavirasto. https://energiavirasto.fi/maakaasumarkkinat. Viitattu 21.9.2020

[6] Gasum: Environmental Study 2019. Pöyry. https://www.gasum.com/globalassets/vuosiraportointi/green-finance/final_gasum_environmental-study_october2019.pdf

[7] Onshore Oil and Gas Development. EHS Guidelines. IFC. https://www.ifc.org/wps/wcm/connect/8eb48de5-748e-4d62-bcfe-40814dee7f0f/Onshore+Oil+and+Gas+Development+EHS+Guideline+-+clean+draft+revised+version.pdf?MOD=AJPERES&CVID=lIWn.4z

Placement of solar collectors on land would be technically possible also, as well as utilizing large uniform rooftop areas for more decentralized installations.

The air source heat pumps (ASHP) would be located either within existing industrial areas or at the Hanasaari plant site inside a building, also minimizing the impact of noise on the surroundings. These areas have already been assessed in this regard. The Figure 8 outlines possible locations for Flexible Future solutions. It also shows the facilities planned by Helen.

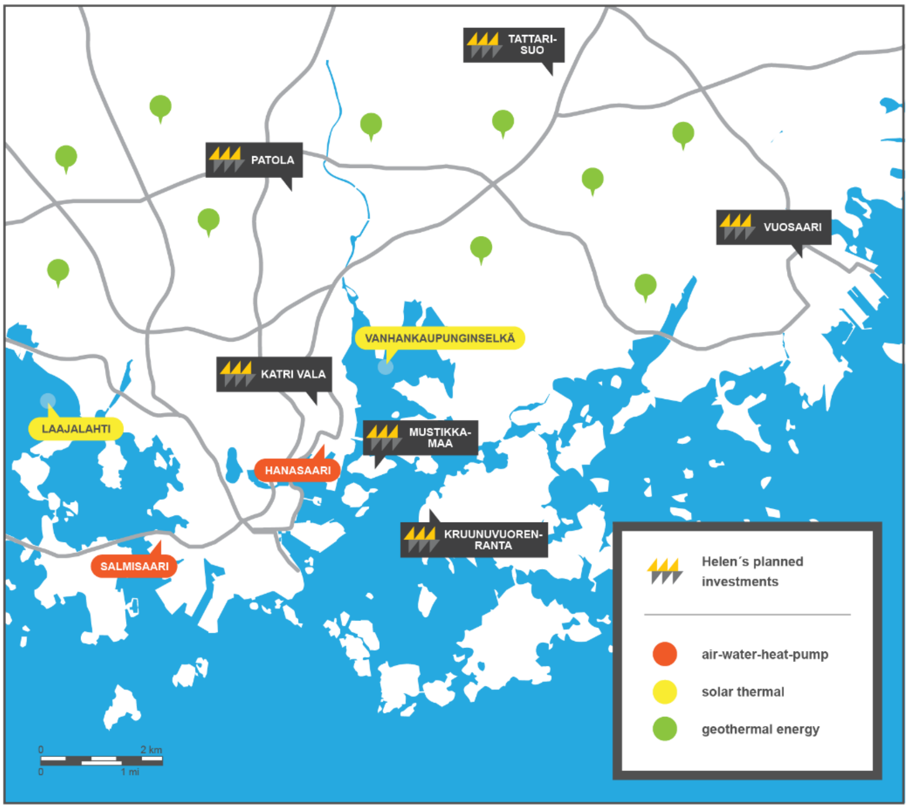


Figure 7. Possible location for Flexible Future solutions.

3 Cost impact

- The cumulative investment costs in the Flexible Future scenario for the period 2020-2035 amount to 719 M€
- The energy-weighted LCOE of Flexible Future is 30.1 €/MWh
- The cumulative NPV of Flexible Future costs about 3,100 M€ in total which is about 10% higher compared to Baseline. For comparison, Flexible Future would save in total 23% in the cumulative emissions during the same period.
- Even a slight increase in the price of biomass and CO_2 emissions or a decline in renewable energy technology makes the investment more profitable

<u>Analysing the cost-efficiency of potential solutions</u>

The cost impact of potential energy efficiency and heat generation options was analysed in detail and the levelized cost of energy (LCOE) was calculated for each option in order to facilitate the selection of the most cost-effective solutions. In the cost calculations, a 20-years lifetime with 4% interest were used. In determining the LCOE, the investment, replacement, electricity and other O&M costs plus taxes were taken into account. The energy-weighted LCOE was 30.1 €/MWh, ranging from 25 to 65 €/MWh for different solutions analysed, as presented in Figure 9.

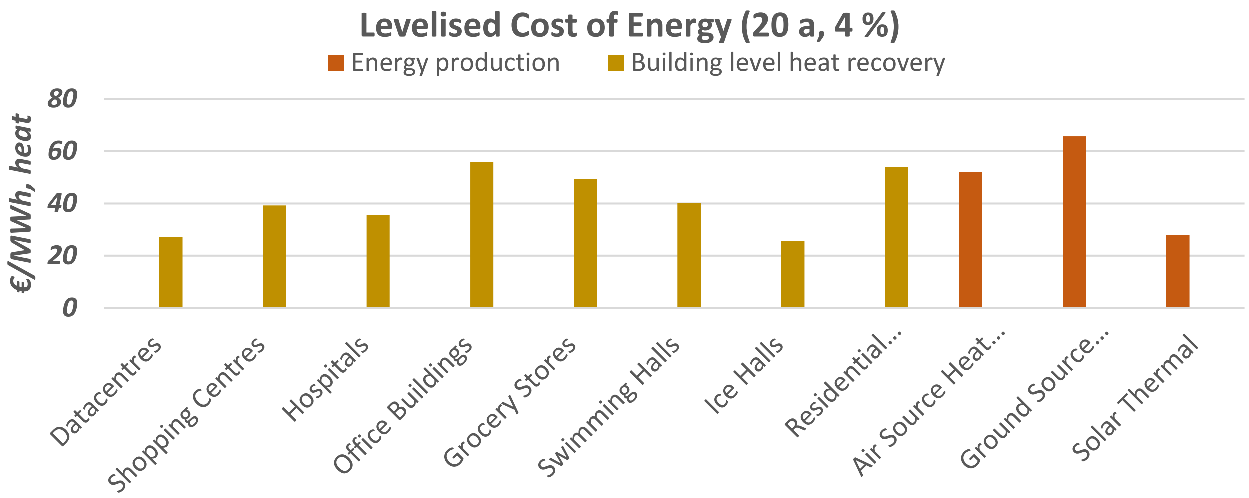


Figure 8. LCOE of the different measures included in Flexible Future.

The results show that the energy efficiency and waste heat recovery measures in ice halls, data centers and hospitals were the most cost-efficient options to reduce the heat demand in Helsinki (25-35 €/MWh). Office buildings and residential buildings were the most expensive demand side solutions, although they showed the largest heat reduction potential. In grocery stores, the cost of the employed solutions varies a lot depending on size and type of stores. The LCOE presented in Figure 9 is the weighted average for all grocery stores.

Solar thermal had the lowest LCOE of the reviewed heat production technologies. With the production volume used, solar thermal could make use of the existing and planned thermal storage capacity in Helsinki.

The LCOE of the heat pump systems (ASHP and GSHP) was almost double that of the solar thermal, but they offer a year-round production option with fewer limitations to space requirement. The ASHP is slightly cheaper than the GSHP. The final heat pump scheme may therefore be a combination of both depending on technological and market developments in the coming years. Another potential solution is a water-source heat pump (WSHP) using the sea water as heat source, e.g. Helen is already building such a system at the Vuosaari plant site. However, since the current cost level of the ASHP is lower, the presented solution and simulation results are based on ASHPs. Substituting ASHP with GSHP is analyzed in the sensitivity analysis section to consider future technological and market development of deep geothermal well systems.

Investments

The cumulative investment costs in the Flexible Future scenario for the period 2020-2035 amount to 719 M€, excluding the investments already included in the Baseline. The annual investments are shown in Figure 10, considering the investment phasing and lead times. Most of the investments take place during years 2021–2028. The investment costs of an ICT system consist of deployment, licenses, O&M, cloud costs, and field device costs, however, as a whole they are only a nominal part of the costs of the entire scenario.

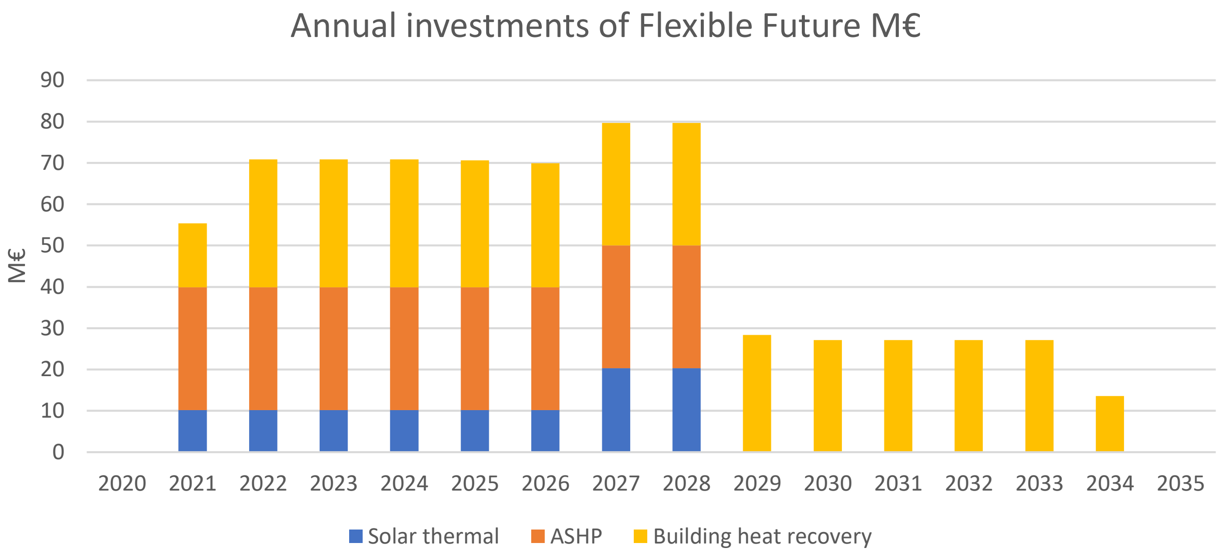


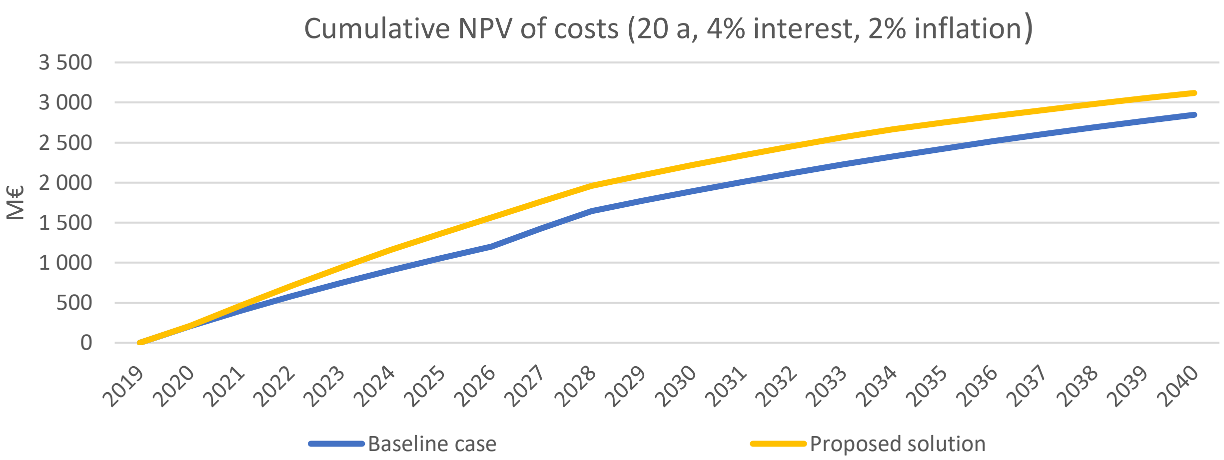
Figure 9. Annual investment costs related to the implementation of the Flexible Future Scenario.

Net Present Value (NPV) analysis

Discounted annual costs and the cumulative NPV (20 years, 4% interest rate) of the Flexible Future proposal and the Baseline Scenario are presented in Figure 11.

Investment costs common for both scenarios are excluded from this NPV comparison. Thus, the Baseline Scenario NPV includes only the operational costs. The investment costs of 200 M€ from building the Tattarisuo and Patola biomass plants are included in the NPV of the baseline scenario.

The Flexible Future NPV includes the phased investment costs as shown in Figure 10, the annual operational costs and possible replacement costs that occur during the 20-year calculation period.



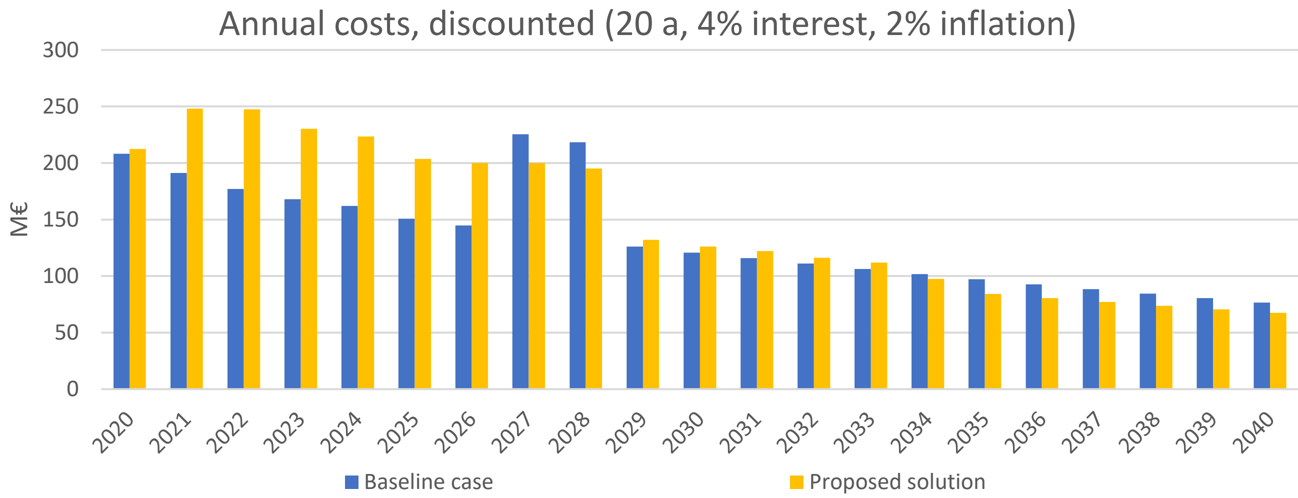


Figure 10. NPV of investment and operational costs for Baseline and Flexible Future. Investment costs common for both scenarios are not included.

During the 2020-2040 period, the cumulative NPV of the Flexible Future proposal costs roughly 3100 M€ in total which is about 10% higher compared to Baseline. For comparison, Flexible Future would save in total 23% in the cumulative emissions during the same period.

Sensitivity analyses were conducted to better understand the impacts from uncertainties on future technology costs, fuel prices etc. The following sensitivity analyses were performed:

- Ground source heat pump technology was used to replace the proposed ASHP capacity. Currently GSHP deep geothermal technology (circa 2 km deep wells) is still in piloting phase with relatively high costs but increasing competition and technological developments are anticipated to decrease the costs in the near future. Here we investigated the impact with borehole investment at 100%, 75% and 50% of current investment cost level. The results in Table 1 show that a lower GSHP borehole investment cost would make a relatively small difference in the total 20-year NPV, but already a 25% decrease in borehole costs would make GSHP almost as cost-effective as ASHP.
- ASHP investment costs could also potentially decrease with an optimized heat pump setup. The current scheme consists of two heat pumps in series; one for heat recovery from outside air and the other to boost output temperature to reach temperature of the district heat network. Using special industrial-type ammonia heat pumps this process may be run with a single unit, almost halving the investment costs. Table 1 shows that this could save close to 100M€ in investments but having a smaller effect on the NPV of all heat.
- The solar thermal plant investment depends on the site where it will be installed. The possible uncertainty in installation and mounting costs were analysed assuming 25% and 50% higher investment costs. Table 1 shows a minor raise in the NPV of heat in this case.
- The development of biomass fuel prices includes uncertainties. In the current price growth scenario, biomass price will increase moderately between 2020–2030 from the current 20€/MWh to 25€/MWh (around + 2%/a). Reflecting possible stricter international and national regulations and demand increase, we checked the effects of 4% and 6% per annum price increase for the baseline. Table 2 summarizes the results. Table 2 shows that the development of biomass prices has a significant impact on the economics of the baseline case. With a 6%/a price increase, the overall NPV of the proposed solution is very close to the Baseline Scenario.

Table 1. Sensitivity of the NPV against investment costs of various heat production technologies.

	Investment costs, M€	Total Flexible Future investment, M€	LCOE, €/MWh, heat	NPV versus Baseline Scenario
ASHP +/-0%	237.6	719.0	30.1	9.6 %
ASHP -50%	118.8	600.2	29.0	5.8 %
GSHP +/- 0%	369.1	850.5	31.1	13.7 %
GSHP-25%	276.8	758.2	30.4	10.8 %
GSHP-50%	184.6	665.9	29.6	7.9 %
ST +/- 0%	101.7	719.0	30.1	9.6 %
ST + 125%	127.1	744.4	30.3	10.4 %
ST +150%	152.5	769.2	30.5	11.2 %

Table 2. Summary of sensitivity analysis on biomass price development

Biomass price scenario	Biomass price 2020-2040 €/MWh	Flexible Future NPV against Baseline Scenario
Helsinki Energy Challenge Scenario	20.0 - > 30.0	9.60 %
Biomass +4%/a	20.0 -> 43.8	7.40 %
Biomass +6%/a	20.0 -> 64.1	4.60 %

<u>Annual O&M costs</u>

The annual O&M costs of heat production for Flexible Future are lower than for the Baseline Scenario (Figure 12).

The costs included here consist of variable and fixed operating costs and the losses in profits from power sales due to decrease in CHP power production compared to the Baseline Scenario. Fuel costs decrease in the Flexible Future compared to the Baseline Scenario, but the savings are offset by the reduction in power sales. Fuel prices and associated costs used in the calculations are based on current prices and 2030 prices given by HEC, accounting for estimated annual fuel-specific price development for 2020 to 2030 and 2030 to 2040.

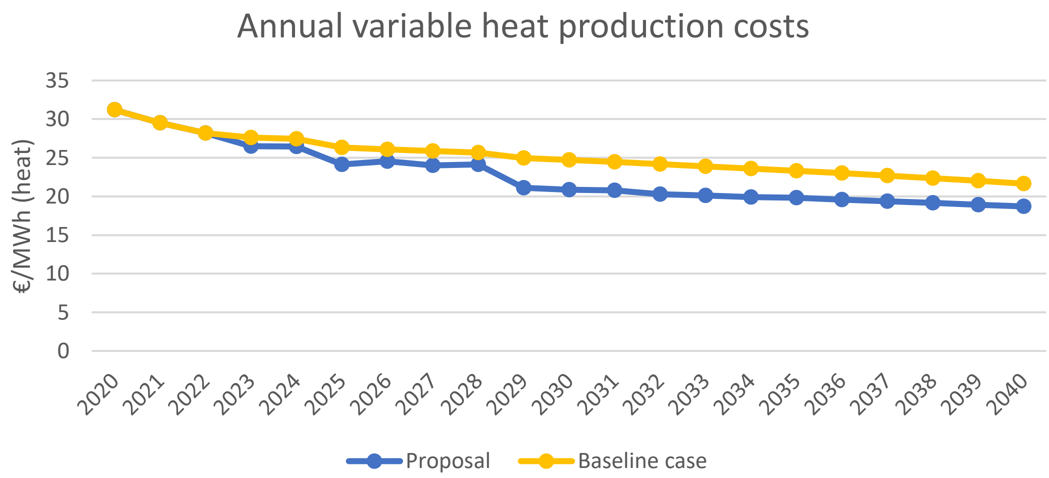


Figure 11. Annual O&M costs of heat production for the proposed solution scenarios and the Baseline scenario.

4 Implementation schedule

- Commissioning new energy plants require city planning, EIA processes, technical design and construction. Existing sites would be used when possible.
- The implementation of required investments is fully completed by 2029 with exclusion that some building types such as offices, residential buildings and grocery stores will continue implementation phase until year 2035
- Solar thermal and ASHP production technologies are targeted to have full capacity ready by 2029.

The lead time for commissioning of new energy plants is generally long, starting from possible changes in city planning, and including the time needed for the EIA environmental permit processes, technical design, procurement and construction. Flexible Future would use existing sites and buildings when possible, but flexibility may be needed from Helsinki's side to allocate space for the energy production plants in the city planning.

The estimated implementation schedule of the Flexible Future proposal assumes that the implementation of required investments is fully completed by 2029, including all new production capacity as well as the majority of the building-level energy efficiency measures. It is unrealistic, however, to expect all building-level measures to be fully implemented by 2029 for some building types, therefore it is estimated that implementation of offices, residential buildings and grocery stores will continue until year 2035. The main risk factors include lack of funds, potential support requirements for building-level solutions and technical obstacles regarding proposed new technologies. Active promotion with targeted support and campaigning will play a key role in reaching these implementation goals.

A summary of the phasing of the implementation by building type is shown in Table 3. A simplified approach was used at this stage: the annual additions in savings/heat recovery and investments are the same each year over the phasing period. A two-year investment lead time is taken into account in the phasing and the total investment is divided equally between these two years, i.e. the capacity introduced at the beginning of year 3 will result in an investment cost that is 50% of the total capacity investment for both year 1 and year 2. It is assumed that investments can start already in 2021 and the first building-level solutions are thus introduced in 2023. After 2023 the savings/heat recovery capacity increase annually in accordance with the presented phasing schedule until full implementation is reached.

Table 3. Summary of the implementation of building-level solutions.

Building type	Implementation phasing, years	Total Energy savings/heat recovery impact, GWh/a	Total investment costs, M€
Shopping centres	8	46	8.8 M€
Office buildings	13	279	171.2 M€
Data centres	5	174	4.2 M€
Swimming halls	8	49	5.2 M€
Ice halls	5	23	2.5 M€
Grocery stores	13	77	41.8 M€
Residential buildings	13	340	139.8 M€
Hospitals	8	17	6.2 M€

As to the energy production technologies, the solar thermal field would need a 0.4 km² total solar collector area, but a total space of 2 km² space was reserved here to enable flexibility for placements. It was estimated that the current Salmisaari and Vuosaari storage tanks along with the Mustikkamaa storage to be introduced in 2021 will be sufficient for solar heat storage due to relatively small contribution on the total heat demand of the district heat network.

The introduction of both solar thermal and ASHP plants is phased similarly to the building-level measures. For these production technologies, the target is to have full planned capacity ready by 2029 when the Salmisaari coal-fired CHP plant is due to be decommissioned. A 2-year lead time is used for the production technology investments as well as a similar 50/50 division of investment costs between the leading time years. Both solar thermal and ASHP capacity phasing is envisioned to be divided into four stages with capacity increasing every other year. A summary of the cumulative annual capacity introduction and total investment costs are shown in Table 4 below.

Table 4. Cumulative introduction of solar thermal and ASHP capacity

	2023	2024	2025	2026	2027	2028	2029	Total investment costs
Solar thermal	0.1 km^2	0.1 km^2	0.2 km^2	0.2 km^2	0.3 km^2	0.3 km^2	0.4 km^2	102 M€
ASHPs	50 MW	50 MW	100 MW	100 MW	150 MW	150 MW	180 MW	238 M€

5 Implementation feasibility

- All solutions can be realized with current know-how.
- Total investment of Flexible Future is 719 M€. Most of the new investments can be located within existing infrastructure.
- Air water heat pump installations require estimated 18,000 m2, but this can be further reduced using multi-storey alternatives. Geothermal pumps would locate in existing industrial zones and would require only 0.2 km2.
- 0.4 km2 solar collectors are suggested to be divided into several smaller locations to avoid harmful effects to local flora/fauna/landscape.
- DH peak power periods are further reduced by averaged 20% and maximum 47% with an ICT solution which controls and balances energy usage by using virtual agent-based demand control and profiling algorithms.
- Owner of the ICT system will be able to simulate and predict DH network loads based on defined assumptions and external inputs.

Technology and space requirements

From a technology feasibility point of the view, the Flexible Future proposal is based on proven technologies and thus represent a high implementation feasibility. All building-level energy efficiency and heat recovery solutions can be realized with current know-how. The large-scale heat pump solution is a scaled-up of similar small-unit solutions that already exist. Solar heating is also a well-known technology, although assembling the arrays on seabed is a somewhat newer aspect and necessitates more careful the execution. Therefore, a contingency plan for construction of land has also been proposed. Our solar thermal employs experience from large-scale solar thermal DH plants from Denmark, Sweden and Central Europe, where this technology is commercially available[8]. Of the suggested technologies, geothermal heat pumps are the most novel technology with experience accumulating from several pilot plants in Finland. In the solution, the geothermal pumps are, however, represented only as an alternative or complementary to air-to-water heat pumps.

Regarding space requirements most of the new investments can be located within existing power plants or industrial areas. Hence, the disturbance of the environment or local habitants is likely to be small as these areas have already been assessed to be fit for their purpose, which is expected to ease the necessary permitting processes. The building-specific energy efficiency solutions have no harmful effects on the buildings. While some of the technologies presented may be novel, all of them can be deemed as culturally and ethically appropriate in the field of Finnish district heat production, from which the population has ample experience. The placement of the technologies would need support from Helsinki City Planning, but the measures needed would not go over the standard permitting procedures. In the next, specific space requirements and their feasibility is discussed in more detail.

An ASHP plant can be easily built to a single site. Here a total capacity of 180 MW was proposed, but it could consist of several sub-units. The outdoor units of this capacity require a space of 11,500 m2. The installations can be located either inside existing industrial areas or in a new industrial hall-type of a construction that could be made to replace e.g. the Hanasaari plant. The total space requirement of the heat pump plants is estimated to be around 18,000 m2, but the total required land area can be reduced by using dedicated multi-storey buildings for the outdoor and heat pump units as shown in Figure 13.

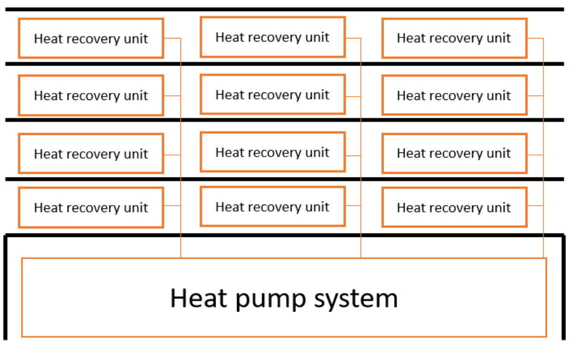


Figure 12. Illustration of an air-water-heat-pump heating plant.

[8] https://task52.iea-shc.org/Data/Sites/1/publications/SDH-Trends-and-Possibilities-IEA-SHC-Task52-PlanEnergi-20180619.pdf https://task52.iea-shc.org/Data/Sites/1/publications/IEA-SHC-Task52-STC1-Classification-and-Benchmarking_v02.pdf

The geothermal pumps with deep boreholes present novel technology regarding the depth of the boreholes which would be 1-2 km instead of conventional 300–400m deep boreholes. The necessary drilling know-how is improving through the several pilot plants been built in Finland. The GSHP sites could be located in existing industrial zones or outskirts of the city. Covering 10% of Helsinki heat demand with GSHP would require around 0.2 km2 of land area.

For the solar thermal arrays, the placement necessitates careful consideration as some of the otherwise feasible bay and seaside areas in Helsinki are also partly Natura 2000- protected areas. The arrays are therefore suggested to be divided into several locations to avoid harmful or irreversible effects on the local flora, fauna and marine landscape. The total technical potential was estimated as 2 km2 of solar collectors' field when utilizing the existing and planned (Mustikkamaa) thermal storage capacity of the district heat network, amounting to a 1083 GWh/a potential, which corresponds to 16% of Helsinki's total heat demand. Options for location would be to use the seaside surroundings of Laajalahti, Kuusisaari, Seurasaarenselkä and Vanhankaupunginselkä for the solar thermal plant as floating thermal collectors. However, as solar thermal plants typically have a 3:5 ground area to collector area ratio, the Flexible Future is limited to a 0.4 km2 area only. The arrays are suggested to be divided into several locations to avoid harmful or irreversible effects to local flora, fauna and marine landscape. Placement to the land area would also be feasible. If solar heating

The heat pumps in our solution use electricity and the given Helsinki Energy Challenge's electricity emission factor expects greener electricity in the future. Helsinki's electricity production is likely to include the following: increased solar electricity production in the city, as indicated by the City of Helsinki's plans for its new properties (mandatory photovoltaics), wind power growth (Helen's investments, also outside the city) as well as Vuosaari CHP which will continue in operation according to current plans.

Cost impacts

The Flexible Future proposal as a whole is cost-competitive compared to the Baseline Scenario. The heat production technologies are economically feasible. As to the building-specific heat recovery and energy efficiency measures, average costs for each building type were assessed. In practice, the cost-effectiveness may vary within a group. For this reason, the full potential of these measures was NOT used in the Flexible Future as some of the projects could be economically feasible not until later stage, in particular for office buildings, grocery stores and residential buildings. The implementation of the measures may be easier for buildings/sites with less stakeholders. In the case of shopping centers, offices, grocery stores and residential buildings, the implementation phasing is ambitious, which is why active promotion with targeted support and campaigning will play a key role in reaching these implementation goals.

The price of CO_2 emissions (ETS) was pre-determined in the Helsinki Challenge to 34 €/tCO_2, which we consider too low as the price is already now in January 2021 at a level of 34.5. Considering the EU policy goals for reducing carbon emissions by at least 55% by 2030 and reach carbon neutrality by 2050 means an even much higher CO_2 price. This will improve even more the financial feasibility of the present Flexible Future. The total investment of the Flexible Future was 719 million €, which as such is well financeable.

Business models for building heat recovery solutions

One of the key elements of Flexible Future solution is heat recovery from cooling operations and other waste heat sources from buildings. That heat can be recycled back to a building but also into district heating network if heat demand in a building at certain moment is lower than recoverable heat.

Technically heat can be recovered either by using building level heat pumps or with the aid of district cooling network and centralized heat pumps. Direct heat recovery in buildings enables higher energy efficiency as heat can be recovered at lower temperature level compared to heat recovery by using the district cooling and heating system. In both cases, approximately same amount of heat can be recovered in total.

Existing cases and experience of team Flexible Future proves that heat recovery solutions are very attractive for the buildings with the highest potential for heat recovery (Figure 1 illustrates potential for heat recovery) such as data centers, indoor ice halls and grocery stores, and there are already existing market based business models.

In contrast, heat recovery from residential buildings is more challenging. From energy operator perspective, single residential building is small and heat recovery potential is low compared to efforts required for heat pump system implementation and service contracts etc. In other hand, property owner might reduce significantly its purchased heat by installing e.g. heat pump system which circulates excess heat from warm exhaust air back into building's heating circuits. Market for building level heat pumps is shattered, there are plenty of manufacturers and contractors but not service providers who would optimize the system and make purchasing easy for building owners. It is almost mission impossible for building owners (in Finland, usually housing cooperatives which have amateur boards) to compare different technologies and manufacturers, and to procure complete optimized system by themselves. All that might reduce harnessing full potential of residential buildings' heat recovery and lead to inefficient systems.

The following business models for heat recoveries already exist:

- District cooling, in which the supply boundary between energy operator and its client is at cooling sub-station located in building. Energy operator sells cooling to the clients based on specific cooling tariffs (typically similar structure compared to district heating). Helen is a district cooling operator in Helsinki
- Building level heat pump system owned and operated by the building owner. In this case, excess heat which is not recycled within the building can be sold into district heating network. This model works for buildings connected to district heating network (does not require cooling network).
- Building level heat pump system owned and operated by an energy operator. In this case the operator typically prices heating and cooling as a whole. This model works in district heating networks. Helen has a service (CHC) based on this model.

In order to realize waste heat potential effectively in future, it requires further development of business models. Flexible Future sees business models evolve as follows:

- Heat recovery by using district cooling is a great model and it can be made even more effective by restructuring the pricing to be more attractive to customers, especially for those with highest potential for heat recovery as they can see investments for own heat pump solutions more viable.
- There will be models and services that helps building owners (mainly residential) to procure and implement heat recovery solutions on their own but using e.g. the support of outside technical design and procurement specialists. E.g. City of Helsinki has published such a service (https://www.hel.fi/uutiset/fi/kaupunkiymparisto/helsinki-kaynnistaa-energiarenessanssin)
- Carbon neutrality will be targeted in new development areas for residential and commercial buildings, and one option to arrange this is a competitive tendering process for selecting a dedicated energy operator for providing a comprehensive energy service for the area.
- Third parties will provide customer-end heating and cooling and even indoor comfort as a service. Service shall be specified and reproducible by building type. Winning solution might require prefabricated components, series production units, smart operation and maintenance with flexibility to optimize system performance etc. Nothing prevents also Helen to provide such a service.
- Digitalization and platform economy will increase in the future enabling new ways for flexible heat trading, service provisioning and minimizing peak-power usage. ICT platforms can serve as two directional marketplaces, and further, support vendors in creating value and savings to customers and energy providers alike. Centralized marketplaces can be extended to serve several cities and energy communities on a single platform in the future.

Smart energy system by IoT platform

Reducing peak power periods and for controlling the district heating system and its marketplace, an ICT system for virtual battery management is defined by Flexible Future. Using an available and existing industrial grade IoT platform introduces quality and service guarantee to the proposal. An ICT system architecture is shown in Figure 14. Our Flexible Future proposal is based on the idea of decentralizing and balancing the energy load with the possibilities offered by ICT on a large scale. ICT platform allows averaged 20% and maximum 47% reduction in peak power periods by using virtual agent-based demand control and virtual battery profiling algorithms[9]. In the initial deployment phase, the profiling and load shifting can be implemented by utilizing existing knowledge of heating systems, making the system consisting of simulation and evaluation of building thermal consumption. The accuracy of the system can be improved with various measurement data. Even site-specific measurement data is already available for a wide range of buildings and residences in the Helsinki region and coverage will increase all the time in connection with, for example, heating renovations. Additionally, the city of Helsinki provides also wide range of open measurement data already and there are also many other data sources like weather forecast provided by Finnish Meteorological institute. Forecast scenarios as well as building profiles can also take advantage of these metrics. Systems based on measured data and, for example, weather forecast information have been in place already for many years, so technology and data reliability are self-evident.

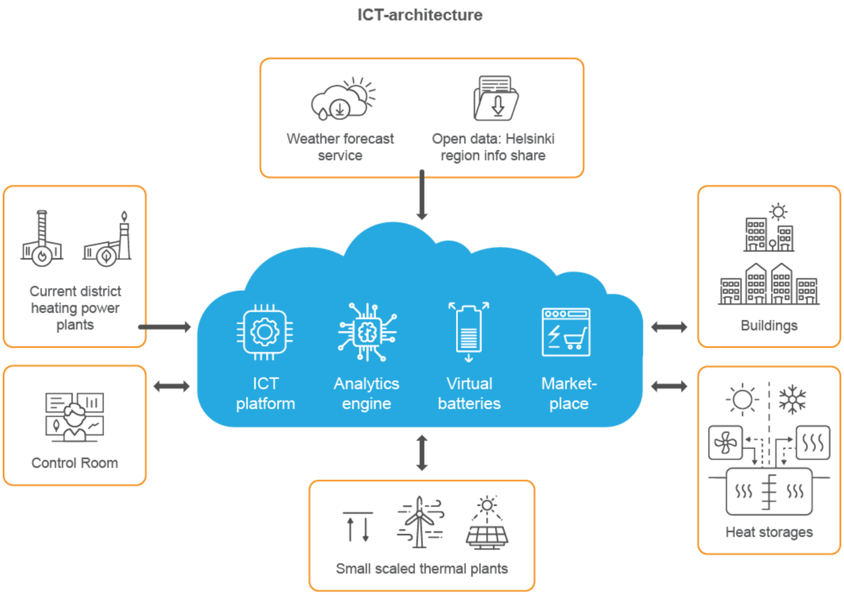


Figure 13. ICT system architecture.

In an ICT system we can decentralize and balance energy use using a platform for virtual energy storage (virtual battery). The main idea of the platform is to monitor, calculate, and simulate the thermal energy used, circulated, stored, and produced in buildings and the heat accumulators in the network.

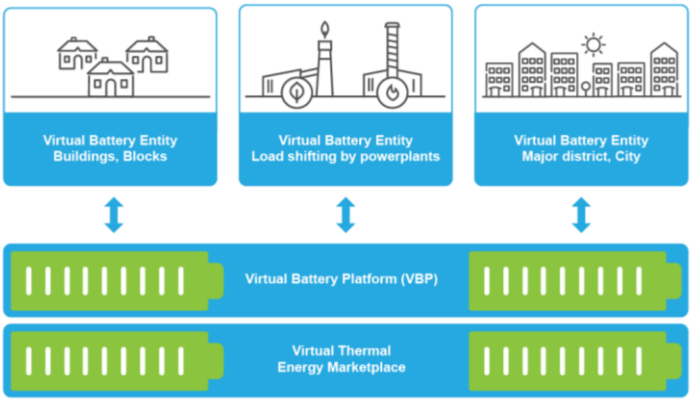


Figure 14. Virtual battery platform..

This kind of platform uses agent-based control of thermal energy. Each entity (the entity can be building, block of buildings or even a whole city) of virtual battery can take part in the load shifting and affect the thermal energy consumption by balancing the consumption spikes and drops. To minimize thermal energy consumption, the platform is used to form a consumption profile in advance. Preparing for consumption spikes and drops is done by creating consumption profiles of connected entities in the network. In our proposed technology, forecasting is carried out by profiling buildings, analyzing several measurement data points and taking weather conditions and weather forecasts into account.

Virtual battery (VB) entities consist of layers for individual sensors, buildings, blocks of buildings, districts, cities and powerplants. Each entity is on itself a virtual battery on the platform and data from entities can be connected together to form new levels of virtual batteries. By means of state-of-the-art profiling algorithms

[9] Sarasti Joel 2017. Evaluation of load shifting potential in Espoo district heating network using a model predictive approach https://aaltodoc.aalto.fi/bitstream/handle/123456789/29383/master_Sarasti_Joel_2017.pdf?sequence=1&isAllowed=y

the VB platform will extract different types of cooling/heating behavior groups that share similar consumption and predictability. Profiles are supporting the platform with information from hour-based scale up to year-based scale about the heat usage patterns of the VB entities.

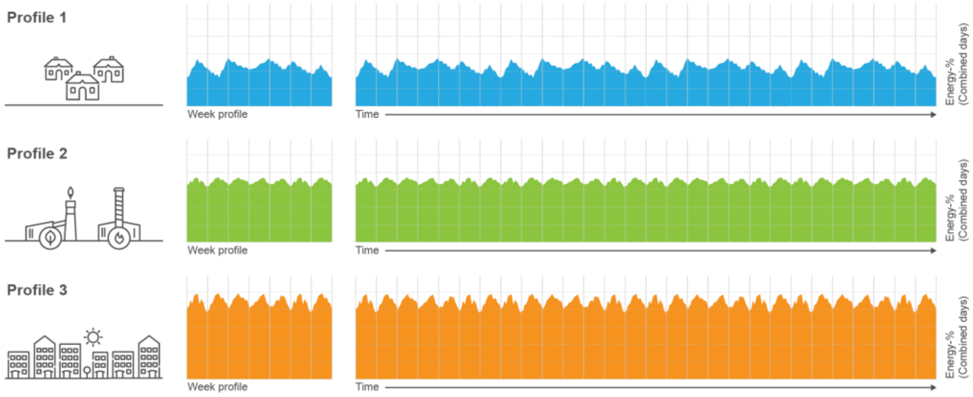


Figure 15. Energy profiling and estimations.

As the long- and short-term profiles are identified, it is possible to feed these profiles to the operations on the VB platform. Operations control the virtual battery entities and groups so that heat energy storing and releasing is dynamically adjusted to the current heat usage and also to the forecasted usage and power peaks to allow load shifting in the system. Operations are additionally integrated with the heat energy marketplace and it can report the demand or surplus of different virtual batteries in the market.

From an economic point of view, harnessing the ICT system for this solution purpose is very appropriate. The platform itself is already available as a working product, only tailoring for the purpose is needed. The product has been used for comparable industrial solutions for many years already, so the quality and service guarantee are clear.

The situational status provided by the platform serves two needs. One is to visualize the total of available resources on the platform and the second is to allow connected entities to share information. ICT platform controls information about heat usage and distribution, status of stored heat in connected entities and information of the energy market place. The platform includes two different levels of marketplaces where potential thermal energy can be stored and released. The lower level is the neighborhood or certain areas that all use the same centralized virtual thermal battery. The higher level then controls the load shifting of the power plants/heat production and low-level systems.

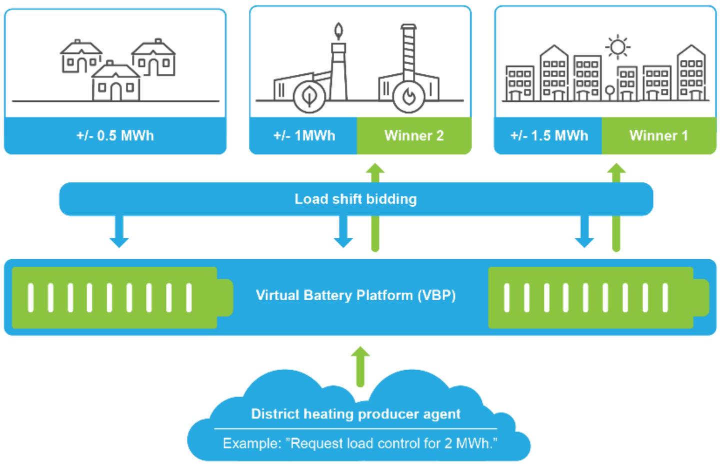


Figure 16. Agent based load shifting.

The ability to use simulations in the ICT platform gives the owner of the system a possibility to plan and prepare for different scenarios in district heating load. We propose a solution that uses virtual profiles to simulate network loads based on defined assumptions and external inputs such as weather forecast or maintenance break information that could affect energy needs. All energy solutions proposed in this application will be connected to the platform and existing compatible producers and consumers can also be added in on the way to increase coverage of balanced thermal energy use.

6 Reliability and security of supply

- Flexible Future does not introduce adverse effects on security heat supply compared to baseline situation.
- Electricity need for heating in Flexible Future is 557GWh/yr and relies on new investments on 400 kV distribution networks planned by Helen.
- Back-up heat can be provided using existing natural gas, HFO and LFO boilers and they should be kept available.

The present Flexible Future makes strong use of versatile energy sources including renewable energy, energy efficiency, waste and ambient heat resources, which all improve the security of supply. The Flexible Future relies much on heat pump technologies, which will require electricity to produce heat. In the Flexible Future, the electricity need for heating would be 557 GWh/a, which is 190 GWh/a more than in the Baseline Scenario. For each unit of power, the heat pump would produce at least 3 units of heat. This additional power requirement does not impose a supply problem and could be met by the present and planned power portfolio of Helen.

Power transmission and distribution networks in Helsinki would be adequate to supply the power to the heat pump schemes. Helen is investing in new 400 kV transmission line from Länsisalmi, Vantaa, to Viikinmäki in Helsinki to respond to future electricity demand. It is assumed that the capacity of the current 110 kV transmission lines will in any case be insufficient in the future.[10] [11]

From DH network point of view, the gradual increase in decentralization of heat generation as proposed in Flexible Future, would reduce the impacts of pipeline failures causing supply interruptions.

Increasing electrification of heat supply needs adequate attention to be paid on resilience of supply, e.g. preparing to possible blackouts due to extreme events. Also, occasionally the availability of natural gas may be at risk due to unexpected events, e.g. such as short-term technical transmission issues or even longer-term political crisis. The heat supply of the capital area must be secured in all conditions, even if the probability to occur would be low.

Therefore, maintaining adequate back-up heat production facilities is necessary, typically to be used under severe peak load conditions in the winter and during unexpected capacity outages, but also for other unexpected events. For “normal” peak load conditions, existing natural gas boilers will top up and secure the reliability of supply. Existing HFO and LFO boilers can also be used as backup. These can supply heat in all situations provided that adequate short-term oil storages are maintained, and oil imports can be secured. During longer term international crisis and possibly fuel imports endangered, even if very unlikely to occur, the boiler capacity fueled by domestic wood biomass would be vital to maintain minimum heat supply level required.

These risks are not only related to the Flexible Future proposal but are typical through electrification of heat production and sector integration.

Helen´s current peak and backup capacity (boilers) are assumed to remain available, while the Flexible Future mainly replaces baseload production. Therefore, the Flexible Future does not have adverse effects on security of heat supply compared to the current situation. On the contrary, introducing more versatile energy sources and decentralized supply will somewhat improve the resilience against interruptions. Furthermore, the Flexible Future is less dependent on fuel imports (other than electricity) and thus risks and uncertainties regarding gas and (large scale international) biomass supply decrease.

[10] Helsingin kaapeliyhteyden ympäristöselvitys. Fingrid. https://www.fingrid.fi/kantaverkko/suunnittelu-ja-rakentaminen/voimajohdot/helsingin-kaapeliyhteyden-ymparistoselvitys/. Viitattu 21.9.2020

[11] Jopa 100 miljoonan investointi: Helsinkiin on tarkoitus tuoda sähköä hirviömäisellä 400 kilovoltin yhteydellä. 6.9.2018. Talouselämä. https://www.talouselama.fi/uutiset/jopa-100-miljoonan-investointi-helsinkiin-on-tarkoitus-tuoda-sahkoa-hirviomaisella-400-kilovoltin-yhteydella/0602b006-e372-35bd-b99b-5f338ec1ce60

7 Capacity

- Full impact of Flexible Future is 2.2 TWh/a
- Proposed measures will contribute 42% of all Helsinki energy production by 2035
- Flexible Future would replace all coal-based production in Helsinki by 2029

Important drivers in choosing and sizing the Flexible Future capacity solutions were cost-effectiveness combined with carbon savings and decreasing of anticipated biomass-based production. The end of coal use in Helsinki by the year 2029 is, however, the most important factor entailing the solutions presented.

The Flexible Future proposal includes new baseload capacity to cover the deficit caused by the decommissioning of coal-fired plants. The full potential impact of Flexible Future is 2.2 TWh/a which is almost as much as the total coal-fired heat production currently. The total newly implemented heat supply capacity would consist as follows:

- 180 MW of centralized heat pumps,
- 254 MW of solar thermal (0.4 km2 of solar collectors)
- 145 MW of building-level solutions from energy savings/heat recovery (In 2030 105MW, 2035 145MW)

The envisaged new production capacities and the overall heat generation in 2030 is presented in Figure 18. In total, the proposed new measures and technologies will contribute 42% of all heat energy production in Helsinki by 2030. The peak load periods are estimated to decrease by averaged 20% and maximum 47% due to efficient use of energy efficiency and demand side management facilitated by the proposed Virtual Storage Platform ICT system.

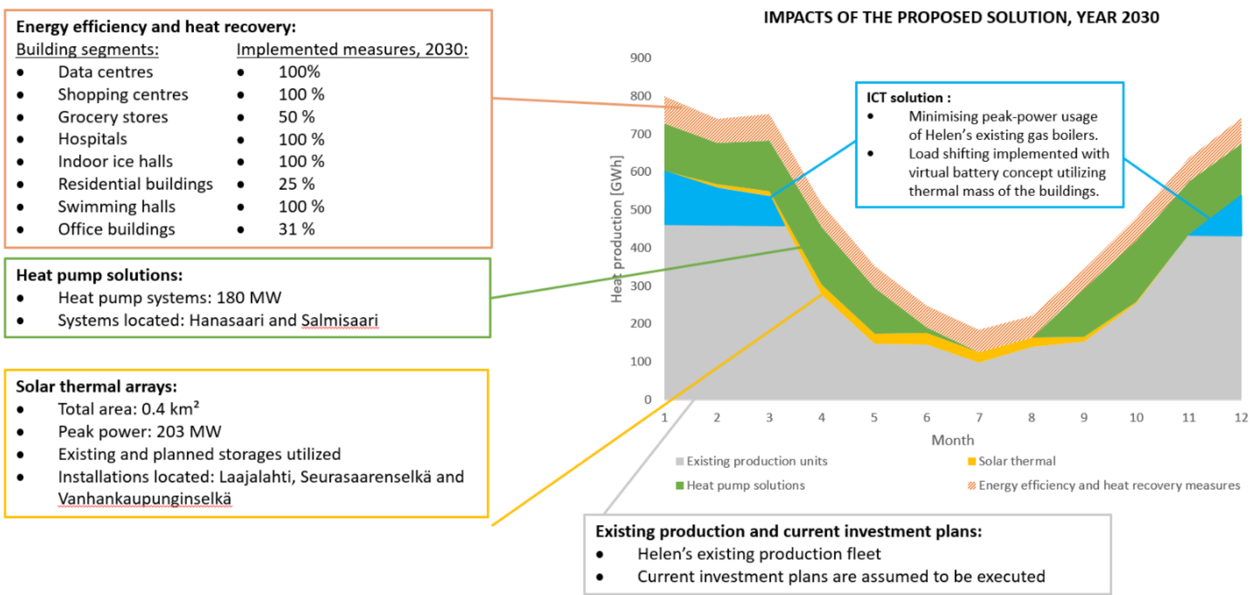


Figure 17. Proposed solution to the Helsinki Energy Challenge.

The Baseline Scenario against which the Flexible Future is compared to assumes that the heat demand in Helsinki drops to 5.6 TWh due to energy efficiency measures and improvements. These results were obtained through hourly simulations of the heat using the growth scenario presented in the background material. In the Baseline heat demand is reduced through heat recovery / energy efficiency measures in the buildings, which are summarized in Table 5. Share implemented column represents the situation when measures are fully implemented from 2035 onwards.

Table 5. Different building level solutions for heat demand reduction.

Building type	Heat reduction potential, GWh/aGW	Share implemented, %	Heat reduction implemented GWh/a	Description of solutions
Data centres	-174	100%	-174	Heat recovery to DH network from cooling with heat pumps.
Shopping centres	-46	100%	-46	Heat recovery from space cooling, grocery store cooling and exhaust air with heat pumps. Recovered heat used within the building.
Hospitals	-17	100%	-17	Heat recovery to DH network from space and equipment cooling with heat pumps
Office buildings	-559	80%	-279	Renovation of zone dampers and air flow controls, exhaust air heat recovery, supply air unit renovation, radiator network balancing, BMS control optimisation, heat recovery from space cooling with heat pumps.
Grocery stores	-96	80%	-77	Heat recovery to DH network from refrigeration and space cooling equipment with heat pumps.
Swimming halls	-49	100%	-49	Heat recovery from exhaust air and wastewater with heat pumps.
Indoor ice halls	-29	100%	-23	Heat recovery to DH network from refrigeration equipment with heat pumps.
Residential buildings	-908	40%	-340	Heat recovery to DH network from exhaust air and wastewater with heat pumps.

The potential of the heat production solutions of the Flexible Future is large and only a fraction is employed in practice due to the different constraints. The potential of the heat pumps would be 14000 GWh/a, half from ASHP and the other half from GSHP, which is well beyond the annual total demand of Helsinki. The potential of solar thermal is slightly over 1000 GW/a limited by space and storage requirements, or ca 15% of the demand.

ASHP heating power and efficiency is affected by the ambient temperatures, which results in variable thermal power and efficiency both decreasing with decreasing outdoor temperature. The ASHP operation is limited to -15 °C, below which the ASHP units are turned off. The optimal ASHP capacity was decided through simulating the annual heat production for 2030 against the Baseline Scenario choosing a capacity which yields the most benefits for the best cost-effective. This yielded a total of 180 MW ASHP capacity. GSHP operation is not limited in the winter by temperature and could provide a steadier production than ASHP.

An ASHP plant can be easily built to a single site, whereas geothermal heat is limited by suitable space in Helsinki, which would favor deep wells instead of conventional 300–400m deep boreholes. Deep geothermal is also capable of producing peak heating.

A 2-year lead time is used for the production technology investments in the Flexible Future and a 50/50 division of investment costs between the leading time years. Both the solar thermal and ASHP capacity phasing is envisioned to be divided into four stages with capacity increasing every other year. A summary of cumulative annual capacity introduction is shown in Table 6 below.

Table 6. Sequence of production technology capacities of the Flexible Future proposal (cumulative values).

	2023	2024	2025	2026	2027	2028	2029
Solar thermal	0.1 km²	0.1 km²	0.2 km²	0.2 km²	0.3 km²	0.3 km²	0.4 km²
ASHPs	45 MW	45 MW	90 MW	90 MW	135 MW	135 MW	180 MW

Figure 19 shows the annual distribution of heat production for the Baseline Scenario and Flexible Future for 2020-2040. The Flexible Future proposal would replace all coal-based heat production in Helsinki by 2029 in accordance with Helen's plans. For short peak heat demand periods in the winter, existing and planned peak plants by Helen are employed.

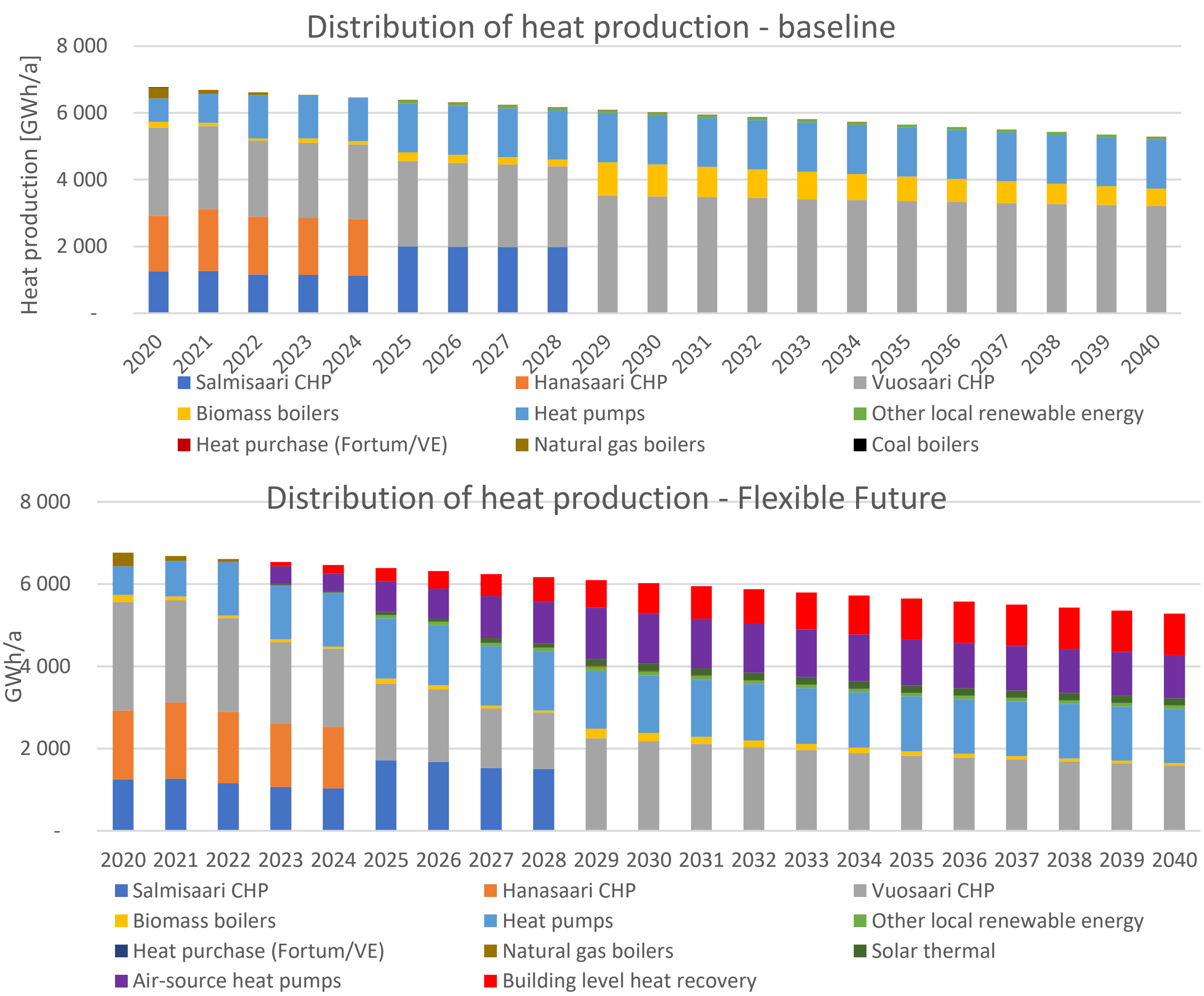


Figure 18. Heat production by production type. (a) Baseline Scenario, (b) Flexible Future Proposal.

The degree of utilization of existing heat production capacity in the Flexible Future proposal in 2030 is shown in Figure 20. Fossil-fuel capacity remains unused. The presented solution is also easily extensible, e.g. in case biomass or natural gas plants need to be replaced.

The capacity used in 2030 vs. existing capacity is as follows:

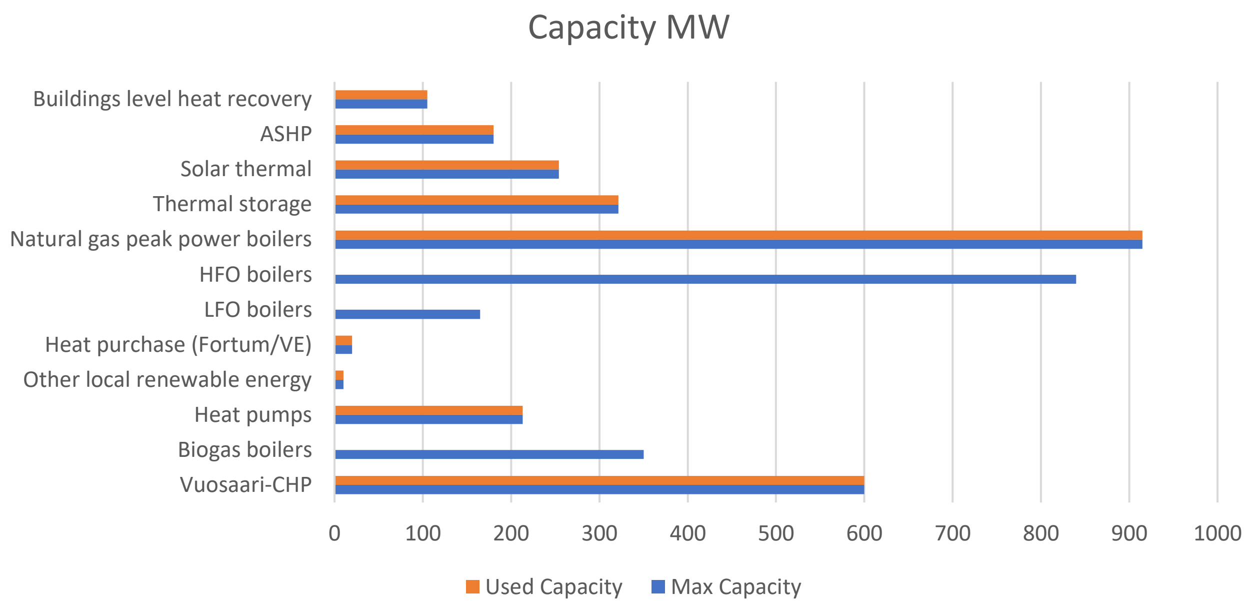


Figure 19. Utilization degree of existing heat production capacity in 2030.

The main assumptions in the capacity calculation and analyses were the following:

- Existing production capacities, planned new production capacity as well as shutdown of certain existing fossil-fuel-fired plants are considered. Information on new production capacity was acquired from Helen´s website.
- Existing and planned thermal storage integrated into the district heating system are considered in the modelling;
- Hanasaari B coal-fired CHP plant is to be phased out by end of 2024. Salmisaari B and Salmisaari A coal-fired plants in 2028. In the modelling it is assumed that these two plants will be shut down instead of converting them into biomass-fired production units;
- The merit order of production is based on minimizing the operational costs, but the new proposed heat pump capacity is placed before the CHP plants. The new heat pumps operate around the year.
- Air-to-water heat pump production is limited to around 60 °C output temperature. The hot water is further superheated with another set of heat pumps which are connected in series with the air source heat pumps. The maximum temperature level of the heat production system is 90 °C;
- The amount of existing peak and backup boilers (biomass, natural gas and fuel oils) in the district heat network at present is assumed to be sufficient in the future;
- Decided and planned changes in production capacity by Helen include:
  - Heat production capacity of the Katri Vala heat pump plant will be increased to 123 MW and the cooling production capacity to 82 MW;
  - Vuosaari heat pump plant (13 MW district heating and 9.5 MW district cooling), which uses the power plant's own cooling water and seawater as heat sources;
  - Share in nuclear power Olkiluoto 3 ca 1 TWh /a (electricity);
  - Nearly 12 GWh thermal energy storage at Mustikkamaa with 120 MW unloading and charging capacity;
  - Renovation of hydropower plant in Kymijoki, annual power production of 32 GWh will increase by 18%;
  - Kruunuvuorenranta low-temperature seasonal heat storage concept;
  - Vuosaari biomass boiler plant (260 MW) in 2023;
  - Patola and Tattarisuo biomass boiler plants (120 MW and 130 MW respectively) by 2029 (both still in feasibility planning stage);
  - Shutdown of Hanasaari coal-fired CHP plant by 2024 and Salmisaari CHP plant by 2029.