Smart Salt City

FINAL ENTRY (SUMMARY)

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SaltX Technology AB: Corey Blackman, Eric Jacobson, Magnus Ekblad, Lars Croon, Michele Pressiani, Pankaj Gujarathi, Carl-Johan Linér, Nadia Amirpour, Boo Ljungdahl

Rebase Energy: Ilias Dimoulkas, Sebastian Haglund, Mihai Chiru

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Nomenclature

DES	Delocalised Energy Storage
DH	District Heating
FOPE	Forecasting and Optimisation Engine
HP	Heat Pump
TCES	Thermochemical Energy Storage Technology
TES	Thermal Energy Storage

Summary of Proposed Solution

1.1 THE SMART SALT CITY

Our solution melds the beauty of novel energy storage and artificial intelligence with commercially available energy technologies. We fashion a new **smart** energy system for Helsinki implemented with a viable deployment strategy based on optimal system sizing and, increased demand side management through several incentive models. The solution proposes **salt**/mineral-based thermochemical energy storage technology (TCES). This utility-scale energy storage solution employs a novel surface-enhanced material that augments the robustness and reliability of the salt allowing for it to be used in industrially available sub-components useful for stationary energy storage but also giving rise to the possibility moving the energy geographically. Additionally, we present an artificial intelligence-based optimisation engine (FOPE) that allows for introduction of innovative local flexibility markets that unlocks demand control. Thereby, substantial emissions reductions can be made without breaking the bank. The proposed solution is heavily based on scientific simulation results with hourly granularity.

1.2 HEAT DECARBONISATION AND RENEWABLE ENERGY CITIES

Helsinki (and several other cities) has goals to reduce fossil fuel-based energy use and most to move towards renewable energy. This has seen good movement and laudable success towards the greening of electricity systems but doing the same for heating has been a bit more difficult. This, on one hand, has been due to the significantly higher heating demand compared to electricity demand in many colder climates. On the other hand, it is due to the vast diversity of heating systems coupled with the lack of general awareness (and interest) as it pertains to heating technologies compared to electricity/power systems[1]. We see that making a dent initially and then fast tracking to deep decarbonisation will require a multidimensional and multi-technology approach. This would see the use of electricity from renewable sources, from renewable heat and industrial waste heat sources, and the use of utility-scale storage technologies that mitigate the differences between the intermittency of energy supply and the daily, weekly, and seasonal changes in energy demand. We also consider the reduced awareness of heating demand and efficiency considerations with strategies to engage and incentivise the general population. Deployment must be fast and controlled but also large enough to be impactful whilst ensuring flexibility, security, and reliability of the district heating system. Additionally, interconnection and operational optimisation of the heat generating and heat consuming devices, forecasting of energy generation and energy demand, as well as the end-consumer behaviour changes (i.e., nudging) are all part of this holistic solution. A solution that though geared towards the specifics of the city of Helsinki, its fundamentals are applicable to most cities which have district heating networks and even those with more distributed and/or community-based heating systems.

1.3 THE TRANSITION

The roadmap for the decarbonisation of heating in Helsinki considered primarily the shutdown of coal plants by 2029 and the goals of Helsinki city in the upcoming 15 years to reduce greenhouse gas/CO_2 emissions of the heating system by 80% [2]. The decommissioning of the coal fired plants, whilst significantly reducing the CO_2 emissions (responsible for 53% of the emissions in DH in 2019 [3]) basically removes reliable baseload heating and electricity capacity. Current plans are to replace this with heat pumps, renewable energy, heat procurement and biomass energy. The solution of our proposal has thus sought to be compatible with current heating system development plans but push boundaries of innovation to meet the timelines involved but also ensuring energy security, adequate generating plant redundancy, and overall cost-effectiveness. The proposal actively avoids implementing new biomass energy plants but sees that the existing ones can continue to be utilised over their remaining lifetime.

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[1] https://www.hel.fi/static/kanslia/energy-challenge/heating-system-in-helsinki.pdf

[2] https://www.hel.fi/static/liitteet/kaupunkiymparisto/julkaisut/esitteet/HNH2035_en_summary_14022019.pdf

[3] https://www.helen.fi/en/company/energy/energy-production/origin-of-energy

The Transition Plan: This considers that heat production from coal needs to cease as soon as possible. The current district heating (DH) system in Helsinki uses various fuel-based technologies to cover the heat demand. These are coal-fired combined heat and power (CHP) plants, gas-fired combined cycle CHP plants and heat-only boilers with various types of fuel. There are also a few heat pump (HP) units and thermal energy storage (TES) units (hot water accumulators). Our plan would decommission the coal-fired combined heat and power (CHP) plants and replace them with power-to-heat technologies: heat pumps and electric boilers. Heat pumps to serve as the baseload energy source with the heat pumps being able to draw on low temperature energy sources from sea water, ground source & geothermal systems as well as waste heat and solar energy sources where needed/possible. Much effort has been placed on considerations of where the low temperature energy would be sourced, potential environmental impacts as well as the inevitable increase in electricity demand caused by this technology that couples the (renewable) electricity sector to the heating sector. This results in a reasonable capacity of installed heat pumps given the conditions at hand. To meet capacity and redundancy requirements, direct electric boilers also form part of the solution, though not as efficient as heat pumps, their simple design, quick deployment, and flexibility make them an important component of the overall solution. The proposal also includes renewable heat generation from the sun and heat import from the neighbouring waste incineration plant.

One of the main challenges with weaning ourselves off of fossil fuel-driven systems is their dispatchability; one can generate heat and/or electricity whenever and wherever needed and modulate that generation at the demand of the end-users. To create the same level of dispatchability for renewable energy sources we propose two forms of thermal energy storage. Short-term, low to medium temperature thermal energy storage (TES) in the form of large hot water tanks and underground water filled pit stores. These TES would provide resilience in the heating system by being able to charge when electricity and/or heat are cheap and (over)abundant. They would then be appropriately discharged to meet peak demand and any short-term fluctuations in demand. For longer term energy storage considerations as well as considerations for high demand periods, in winter months, high temperature utility-scale thermochemical energy storage systems (TCES) are proposed. TCES are charged by cheap electricity when renewable electricity is abundant and discharge high-quality steam as necessary during peak demand, to provide both heat and electricity as desired as well as to shift large amounts of energy from one period to another; weeks or even months later, with minimal losses. The TCES's capability to produce high temperature heat during peak demand times minimises the use of the electric boilers to prime (i.e., increase the output temperature) of the heat pumps which have limited outlet temperatures (especially when heat source temperatures are low). Additionally, TCES can produce electricity using existing steam turbine infrastructure. Though not able to produce the same level of capacity of electricity that the current coal-fired combined heat and power plants produce, it can provide some electrical energy into the grid reducing peak electric demand in Helsinki and potentially reduce the need for additional electricity transmission line capacity into Helsinki.

These technological solutions have been chosen to minimise technology deployment times whilst maximising CO_2 reduction impact, solution cost-effectiveness, reuse of existing infrastructure, and flexibility of system interactions. The solution seeks to ensure a smooth transition with minimal disruptions and a long-term sustainable heating system for Helsinki. To reduce capital intensive investments, we employ an advanced forecasting and optimisation engine (FOPE) that can interoperate and complement existing, and even potential future technical solutions, via open hardware and software interfaces in the district heating system. FOPE estimates the marginal cost and emissions level of heat generation at any given time which allows cost-effective dispatch of heating units, including calculating price flexibility in local heat markets. This in turn provides data to incentivisation schemes and strategies for demand side management reducing the need for 'peaker' plants. Our data-driven approach means that FOPE can provide decision support for (i.e., Helsinki-based generating and energy use assets) when and how to operate, while getting more intelligent over time as more data is collected. The application of heat demand response in the buildings is also considered using either local energy saving initiatives such as automated controls and connected devices [4]. Electric load management based on real-time scheduling can reduce peak energy use by up to 46% in households [5]and by 5-10% in commercial buildings [6]. Heating peak demand can be reduced by 68% if occupancy detection, monitoring of ventilation, heating and lighting systems are implemented [7]. We however take a conservative (or rather pragmatic) approach in the demand response management implementation assuming 5% peak heat demand reduction possibilities.

The main generating plant used in this solution, namely: heat pumps, electric boilers, TES and TCES are topped up with the planned biomass boiler plant and heat procurement from a nearby waste incineration plant. Existing natural gas ‘peaker’ plants are kept for resilience and redundancy of heat generation but would typically only operate during particularly cold periods. The increase in electricity usage would thus require the build out of more solar electric and wind power systems to provide emissions-free electricity. Figure 1 shows the evolution of heat generation energy as the proposed solution is deployed showing the individual contributions of the various heating technologies. Figure 2 and Figure 3 show projected demand curves for 2030 for high and low peak demand scenarios respectively.

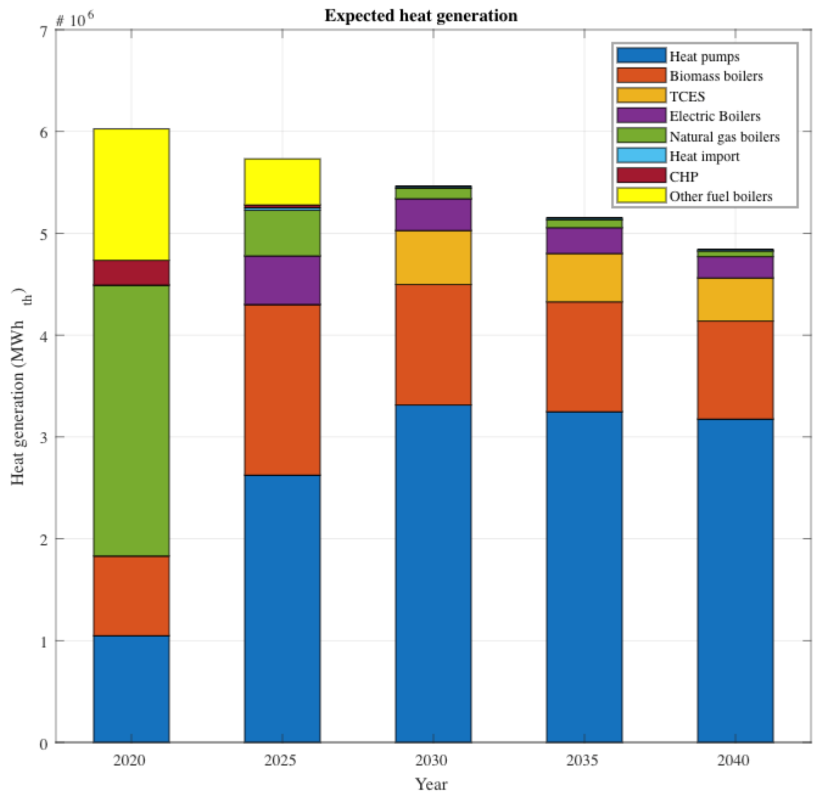

Figure 1 - Energy Balance for the Transition Plan

[4] See for example https://sunamp.com/, https://nest.com/, https://www.netatmo.com/en-eu/energy
[5] https://www.sciencedirect.com/science/article/abs/pii/S0378778814001248
[6] https://www.osti.gov/servlets/purl/889248
[7] https://iopscience.iop.org/article/10.1088/1742-6596/1343/1/012055

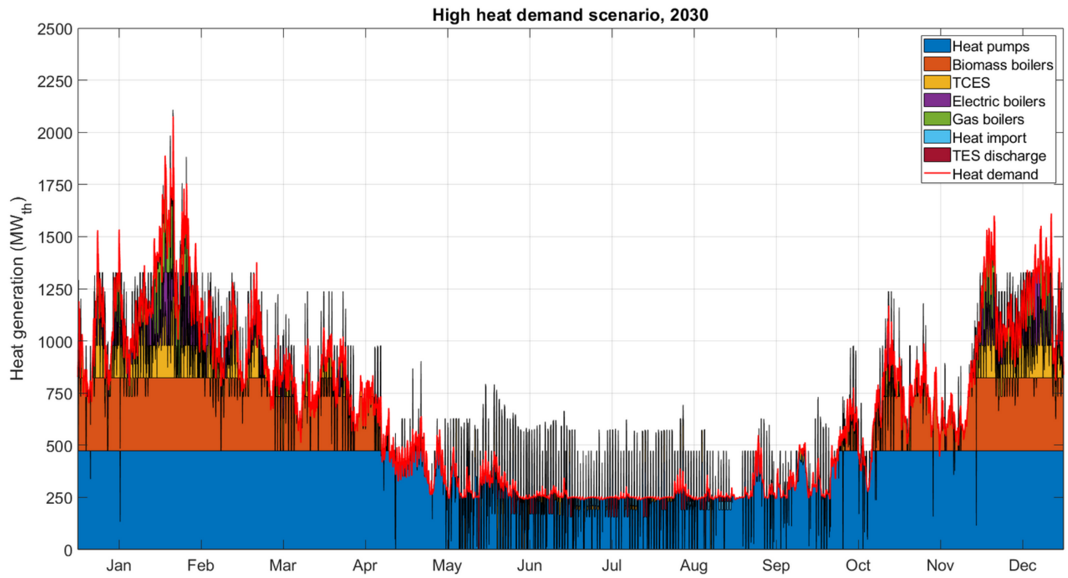

Figure 2 – Projected heat demand curve for 2030 for high peak demand scenario (implementing forecasting).

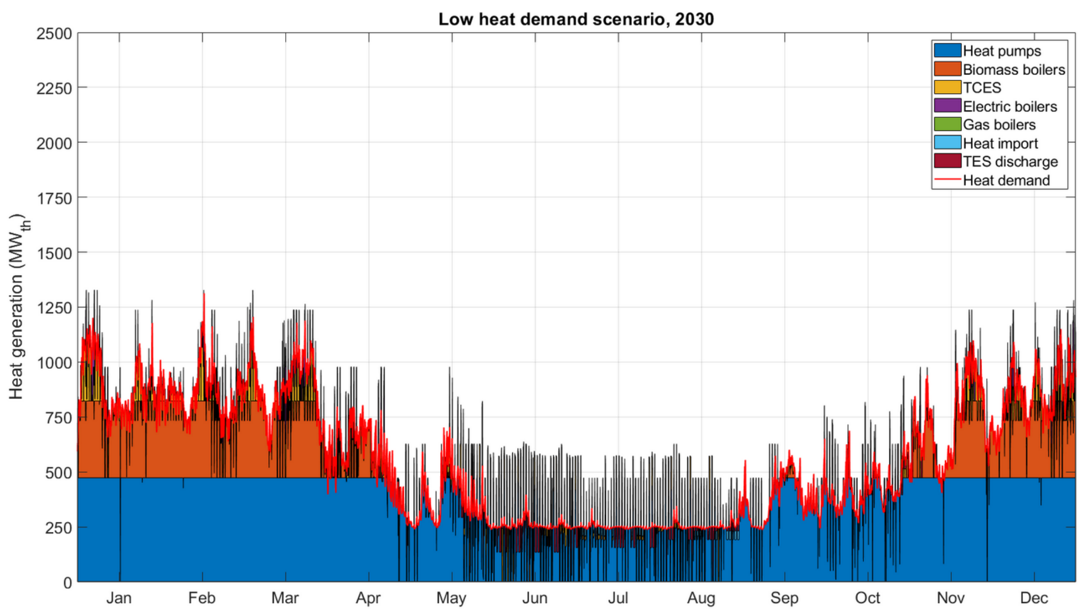

Figure 3 - Projected heat demand curve for heat demand for 2030 for lower peak demand scenario (implementing forecasting and demand side management).

1.4 THE TECHNOLOGIES

The proposal sets out paths to decarbonisation using various heating technologies. These technologies can be broken down into:

- *Standard technologies* that are mature and widely commercially available and critical for rapid deployment of the plan as well as reduced risk and improved cost-effectiveness of the solution.
- *Ground-breaking technologies* that are currently near to commercialisation and should be commercially available for deployment within 5 years. These technologies are key enablers of the transition with important attributes not present in standard technologies.

1.4.1 Standard Technologies

Heat Pumps: Large (MW-scale) electrically powered centralised heat pumps are used to upgrade low temperature heat from seawater and geothermal/ground sources to the temperatures required in the district heating network. Given that Helsinki has already implemented a large proportion of waste heat recovery from datacentres and water treatment, the proposal considers the availability of the aforementioned low temperature sources and the costs involved with harnessing this heat as well as the location and footprint of the necessary installations. Additionally, the design of the system interconnections was considered allowing for the TES to also be used as a low temperature heat source maximising the usable energy content of these thermal stores. The heat pumps also provide district cooling during the summer where any excess heat is used to charge the TES thus these units are efficiently operated year-round. Heat pumps were chosen due to their technological maturity and their flexibility to exploit different streams of low-grade thermal energy which could include other sources not directly considered but with high potential for expansion of today's systems into the future such as industrial waste heat, heat from waste and sewerage water as well as heat from underground train tunnels. Additionally, smaller scale heat pumps are incentivised for the recovery of waste heat from datacentres and other sources.

The proposed solution focuses on replacing existing CHP plants with heat pump installations where existing land, facilities and heating and electrical grid connection infrastructure improves financial feasibility. With the added benefit of revenue for the plant operator from both the sale of heat and cooling. Given the new developments are minimal and there would be no major facility or operational changes, the use of this technology is also deemed legally, administratively, culturally and ethically feasible.

Electric Boilers: These MW-scale units will also be used to provide heating directly with electricity. Unlike heat pumps, they do not require a low temperature heat source allowing for greater flexibility as it pertains to installation sites. Given their lower efficiency compared to heat pumps they are foreseen for use mostly when heat pumps cannot meet the required demand or when favourable electricity rates are available for charging the TES. Additionally, electric boilers can provide the high district heating network temperatures required during peak demand (i.e., very cold weather).

Thermal Energy Storage (TES): The proposal employs large tanks and pit stores to store hot/warm water at viable locations. These cost-effective short-term (several hours or days) thermal energy stores would be used to mitigate the intermittency of increased renewable electricity in the grid (i.e., fluctuating electricity prices) as well as short peaks in demand and/or fluctuations in capacity. The TES units will be designed for stratification of temperature layers to allow efficient charging and discharging by tapping into the right temperature level for district heating delivery and also for charging using different heat generation plant or being used as a low temperature heat source. Many TES also have the added duty to modulate pressure differences in the district heating network, a feature that was considered but whose benefit was not quantified monetarily.

Solar Thermal System: Solar thermal collectors were also considered where large ground mounted plant installations could provide heat during summer directly to the district heating network or alternatively deliver heat to a TES.

1.4.2 Ground-breaking Technologies

Thermochemical Energy Storage (TCES): These systems can store thermal energy as chemical energy in reaction products. The energy is stored based on a reversible reaction involving the breaking and reforming of chemical bonds. This involves an endothermic energy storage process which heats $Ca(OH)_2$ separating it into its constituent reactants (CaO & H_2O). The reactant materials can then be stored separately at room temperature and atmospheric pressure providing (essentially) lossless energy storage for an unlimited length of time. Heat is released via an exothermic reaction from the recombination of the reactants. The TCES is charged by surplus/low-cost renewable electricity and dispatched as high temperature heat (up to 450°C) when needed. The discharge of the TCES can be months later (i.e., summer to autumn/winter energy shifting) since this utility-scale storage does not incur major thermal loss penalties (as opposed to TES).

The TCES system considered for the proposed solution uses abundant, recyclable, energy dense limestone-based material whose surface enhancement is part of a breakthrough innovation. The TCES would basically replace coal and other fossil-fuel based assets with the renewable and rechargeable 'salt fuel', $CaO/Ca(OH)_2$.

The discharged energy is in the form of high temperature steam (with quality similar to fossil-fuel fired boilers) lending to its potential retrofit into existing combined heat and power plants. The setup thus avoids stranding viable heat generating plant assets with focus on retrofit of plants by replacing the boilers with charging and discharging units. This large-scale thermochemical energy storage is central to ensuring heat can be adequately dispatched to meet demand at the lowest cost versus emissions level.

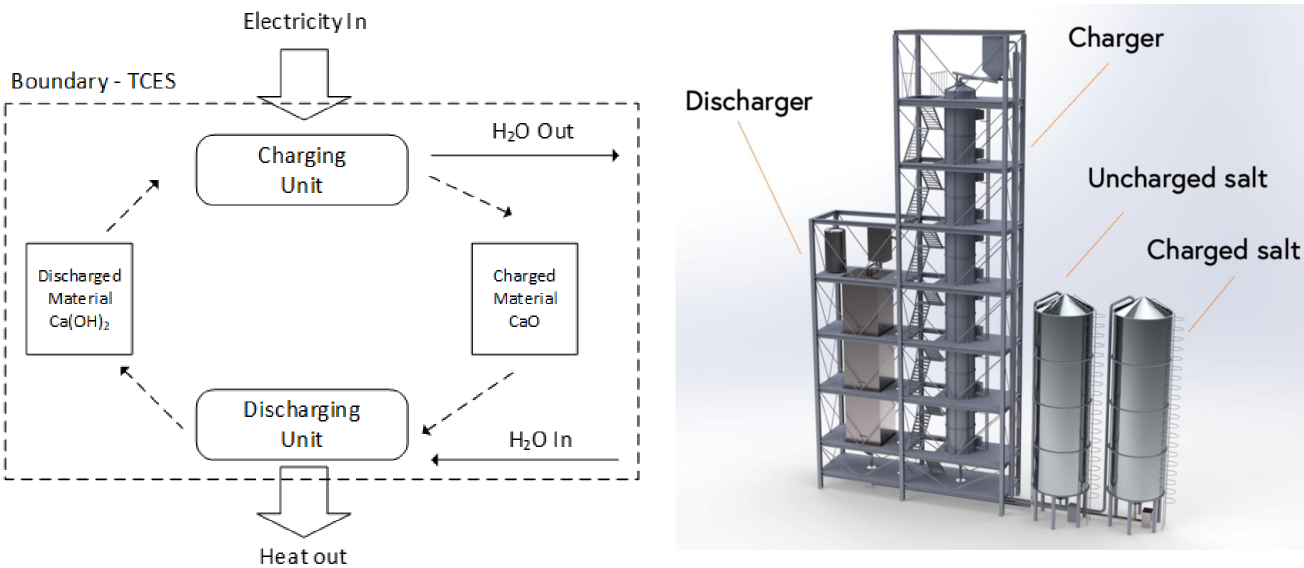

Figure 4 - Schematic of the main components and functioning principle (left) and a plant rendering of TCES (right)

The TCES is charged and discharged based on energy market prices and demand signals and provide heating at high enough temperatures to meet peak district heating temperatures. Additionally, electricity can also be produced using the existing power blocks already installed at the combined heat and power (CHP) plants to maximise the flexibility of the energy system.

Forecasting and Optimisation Engine (FOPE): The proposal includes an AI-driven forecasting and optimisation engine incorporating several data sources, such as meter values from heat/power consumption and production, weather forecasts and energy market information. The optimisation engine is adaptive and supports interoperability with existing or future optimisation systems, tools, and data streams. The system would work via open hardware & software interfaces in the district heating system also considering Helsinki's open district heating policies. FOPE is driven by machine learning-based energy demand and supply forecasts as well as power plant simulation and optimisation that is used to estimate the marginal cost of heat generation at any given time. The marginal cost can, for example, inform energy and flexibility pricing in the heat markets and by that incentivise demand side management. FOPE would automatically send demand reduction signals to the Building Management Systems (BMS) of buildings and systems that have committed to a demand reduction program which would have an impact on peak demand and the need for many 'peaker' plants. FOPE is designed for flexibility of different inputs on the operation of the various heat generation plants and technologies, including both centralised and distributed supplies of heat and/or electricity. This system would be key to the district heating system operator that optimises heat production, distribution, and consumption.

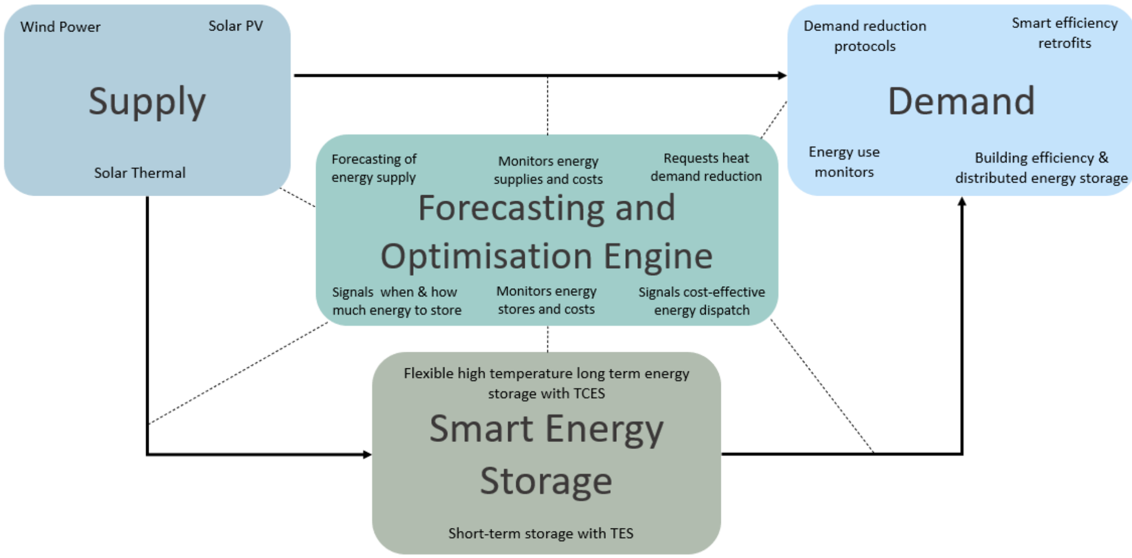

Figure 5 - Schematic showing interaction between Forecasting and Optimisation Engine (FOPE) and Helsinki Heating System

Delocalised Energy Storage (DES): This is a variant of the TCES technology, where like the standard TCES, has separated charging and the discharging units. However, in the case of DES, the charging unit is installed at a location with high temperature waste heat or excess electricity that can charge the salt material. The charged material is then transported by existing rail (or ship where possible) lines to a plant on the outskirts of the city which is home to a unit dedicated to the discharge of the salt material to produce district heat. The discharging plant would house one or several discharging units and two storage silos; one for discharged material and one for charged material, the material functioning essentially as a rechargeable fuel.

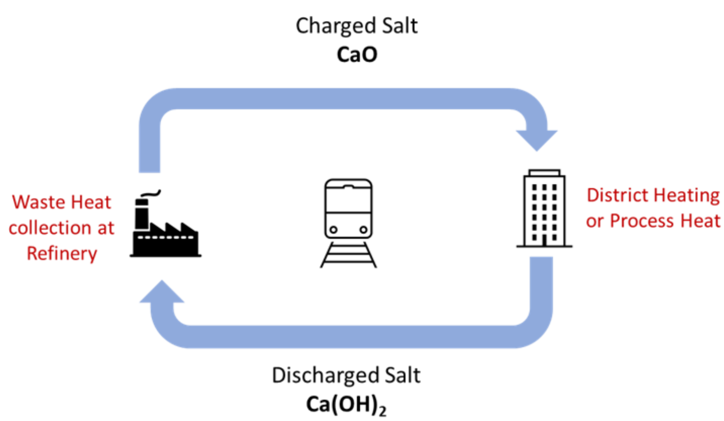

Figure 6 - Delocalised Energy Storage (DES)

This system setup in its essence allows for the storage and transport of waste heat from remote locations into the city, exploiting existing infrastructure with no requirement for major permanent infrastructure.

1.5 DEMAND SIDE MANAGEMENT STRATEGY

Demand side efficiency and management is one of the key areas in achieving a fully decarbonised heating system in Helsinki. The most efficient kWh is the one that was never produced. In addition, the future heating system needs to be highly adaptive to avoid fossil-fuel based heating and allow for sector coupling (heat and electricity) with increasing amounts of intermittent renewable energy integrated into the power system.

Several innovative companies that provide AI-based building management systems and energy aggregation are already established in the market[8]. Building energy optimisation has the potential to reduce energy consumption by up to 30% and improve building connectivity and flexibility[9]. The technical solutions are there, what is needed is the right incentive structure to unlock this potential at scale.

Flexibility on the demand side has proven to be difficult to accomplish without thoughtful and appropriate incentive measures. We propose a three-step approach to increase heating system demand side flexibility in Helsinki:

1. Behavioural demand response.
2. Dynamic local demand response market.
3. Long-term bilateral demand response commitments.

In the first step, we intend to educate the demand side of the issue through actively uploading education material (also as targeted video ads) on social media platforms like Facebook and Instagram. We believe that it is essential that this information finds its way to the end-user, therefore meeting them where they are present. One of the goals of these videos is to encourage end-users to download the free Helsinki smartphone app. In the smartphone app we will provide a CO_2-intensity signal and forecast[10]. The CO_2-intensity signal allows us to send (opt-in) push notifications that inform the end-users some hours in advance about upcoming high carbon heating periods. This gives end-users the opportunity to adjust their energy consumption behaviours accordingly. The CO_2-intensity signal could also be integrated with their own smart home heating management solution through an Application Programming Interface (API), which would allow for a completely automated workflow. End-users would get continuous feedback regarding CO_2 saved through their manual or automatic actions.

Behavioural demand response has the potential to reshape the demand profiles to be more correlated with carbon free heat production. However, research has shown that it is difficult to reach deep penetration through non-monetary demand response measures. Therefore, we propose a second step where a local dynamic heat flexibility market is implemented in Helsinki. These types of markets already exist for electricity flexibility[11]. With days to a week's notice, the district heating provider can purchase demand side flexibility from the demand side and thereby avoid increased carbon emission and marginal costs associated with fossil-fuel based heat production. The market mechanism can be one-sided or two-sided. The marginal price of flexibility that a rational district heating provider should accept from demand flexibility providers can be calculated using the same optimisation engine developed in this proposal to calculate optimal heating scenarios. These markets are usually referred to as local energy markets (LEM). In Figure 7 a flow diagram is presented of a potential structure, where energy aggregators sell flexibility to the district heating utility allowing it to reduce peak demand. The structure would also be compatible with the evolution of local energy markets for energy communities that allow the trade of heat locally.

While local flexibility markets have the potential to reduce yearly operating hours of e.g., peaker boilers, their ability to decrease capital investments in peaker plants is limited because of the fully voluntary market participation. Therefore, to avoid capital investments, multi-year bilateral demand flexibility agreements are needed. These agreements are more complex by nature and therefore we propose to focus on larger heat consumers within the business to business (B2B) segment as main flexibility providers. Education and transparency on the district heating provider website as

[8] See for example nuukasolutions.com, vibeco.fi/en and leanheat.com.
[9] See for example https://www.energy.gov/eere/buildings/about-commercial-buildings-integration-program
[10] Such a signal is already provided for electricity by the Finnish TSO Fingrid.
[11] See for example nodesmarket.com or coordinet-project.eu.

well as continuous updates and webinars on platforms such as, for example, LinkedIn can promote acceptance and participation.

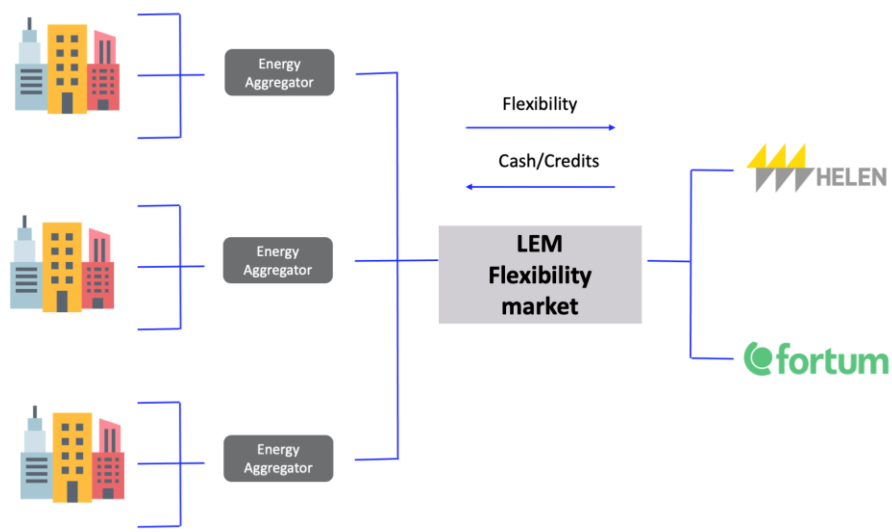

Figure 7 - Potential Structure of Helsinki Energy Flexibility Market

1.6 THE KEY BENEFITS

The proposal has the benefit of being timely to deploy by using a mix of standard commercially available technologies with more innovative ground-breaking technologies balancing the risk and reward of the solution. The proposed solution seeks to exploit existing infrastructure which adds to the speed and cost-effectiveness with which deployment can occur. Simultaneous to the roll out of new heat generation plant, the development of the interfaces and data input for the FOPE can occur. The proposal focuses on large-scale systems to maximise the impact of the transition and considers novel energy storage technology that would provide full control to the city of Helsinki for its implementation. We strive for flexibility of the solution to link many different energy sources, thermal and electric alike, giving rise to a more integrated and widespread energy flexibility market. Considering the difficulties of planning for the future, especially with the many changes that can happen suddenly (for instance in the case of the pandemic); changes in living and workspaces, adaptability and futureproofing are key ingredients of our proposal.