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D2.5 -Smart Energy Systems in Oulu

WP2; Task 2.4

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17/10/2020	0.2	VTT	Jussi Kiljander	Overview and description of the Energy Management Agent
01/11/2020	0.3	VTT	Timo Kinnunen	Description of the user interfaces
10/11/2020	0.4	VTT	Roope Sarala	Supermarket Energy Management Agent description
23/11/2020	0.5	VTT	Jari Rehu	Resource interface and Manager components

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12/12/2021	2.0	VTT	Jari Rehu,	Final version for submission

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Abbreviations and Acronyms

Acronym	Description
DEM	District-level Energy Manager
DHWT	Domestic Hot Water Tank
DSO	Distribution System Operator
EMA	Energy Management Agent
FMI	Finnish Meteorological Institute
ICT	Information and Communication Technology
KPI	Key Performance Indicator
LHTES	Latent Heat Thermal Storage
PCM	Phase Change Material
PED	Positive Energy District
SHTES	Sensible Heat Thermal Energy Storage
TES	Thermal Energy Storage

Executive Summary

In this deliverable, the final version of D2.5 - Smart Energy Systems in Oulu is documented. The related task is T2.4 - Smart Energy Systems in PED. The goal of WP2 is to deliver Lighthouse demonstration actions in Oulu. T2.4 focuses on demonstrating technical integration of RES and storages in the different grids of the Kaukovainio PED, including the local heating system, providing heating and cooling on-site. The second big infrastructure is a singular heating and cooling system based on heat pump and geothermal energy and PV panels in the roof, soil storage connected to the district heating (mainly to provide surpluses of energy) and innovative phase transfer liquid tanks. A control strategy employing Building-Level Energy Management Systems is deployed to optimize performance of the buildings in the Kaukovainio district.

1 Introduction

1.1 Purpose and target group

This report constitutes Deliverable "D2.5 Smart Energy Systems in Oulu", which describes the building-level energy management system (BEMS), responsible for control and optimization of building energy performance, including district heating. In addition, BEMS is tasked with communicating their flexibilities up to their district-level aggregator, described in more detail in D2.6.

BEMS is at the core of creating a PED, as it collects and processes information of the building, aggregating information about its energy consumption and production components, as well as processing building automation data. With that information, it is able to forecast its own behaviour and future flexibilities and optimize for maximising given target metric, for example using local production.

In the following sections, different components comprising BEMS are presented. First, an overview of the system is given in Building-level Energy Management System - Overview 152. Section 3 describes Resource Interface and Manager components, which are responsible for interfacing with the on-site metering infrastructure. Section 4 introduces the Energy Management Agent component, delivering forecasting and optimization services to the BEMS. In addition, building-specific implementations of the Energy Management Agent are presented. Section 5 covers site-data services. User interfaces are described in section 6 and use of PCM enhanced TES is presented in section 8. Finally, section 0 concludes the deliverable.

1.2 Contribution partners

The following Table 1 depicts the main contributions from participant partners in the development of this deliverable.

Table 1: Contribution of partners

Partner nº and short name	Contribution
20-VTT	All sections by VTT

1.3 Relation to other activities in the project

The following Table 2 depicts the main relationship of this deliverable to other activities (or deliverables) developed within the MAKING-CITY Project and that should be considered along with this document for further understanding of its contents.

Table 2: Relation to other activities in the project

Deliverable nº	Relation
D2.3	D2.3 Has basic calculations and theory related to PCM enhanced thermal energy storage.
D2.6	D2.6 Presents the details on the district-level energy monitoring and management approach introduced in this deliverable.
D2.9	D2.9 Describes the overall architecture for the Oulu ICT Platform.

D2.8	D2.8 presents the details on the Oulu ICT platform implementation, including communication and deployment views.
D5.7	D5.7 presents the implementation of the monitoring programme in Oulu
D3.20	D3.20 presents the new services and modules of the Groningen ICT Platform

2 Building-level Energy Management System - Overview

This deliverable documents the Building-level Energy Management System (BEMS) functional component of the Oulu ICT Platform. As presented in Figure 1 there is a BEMS component for each building in the Oulu PED area. Each BEMS is responsible for energy management (both electricity and district heating) within a building and providing building's flexibility for district level-energy management. The district level energy monitoring and management approach is presented in more detail in D2.17 and D2.6.

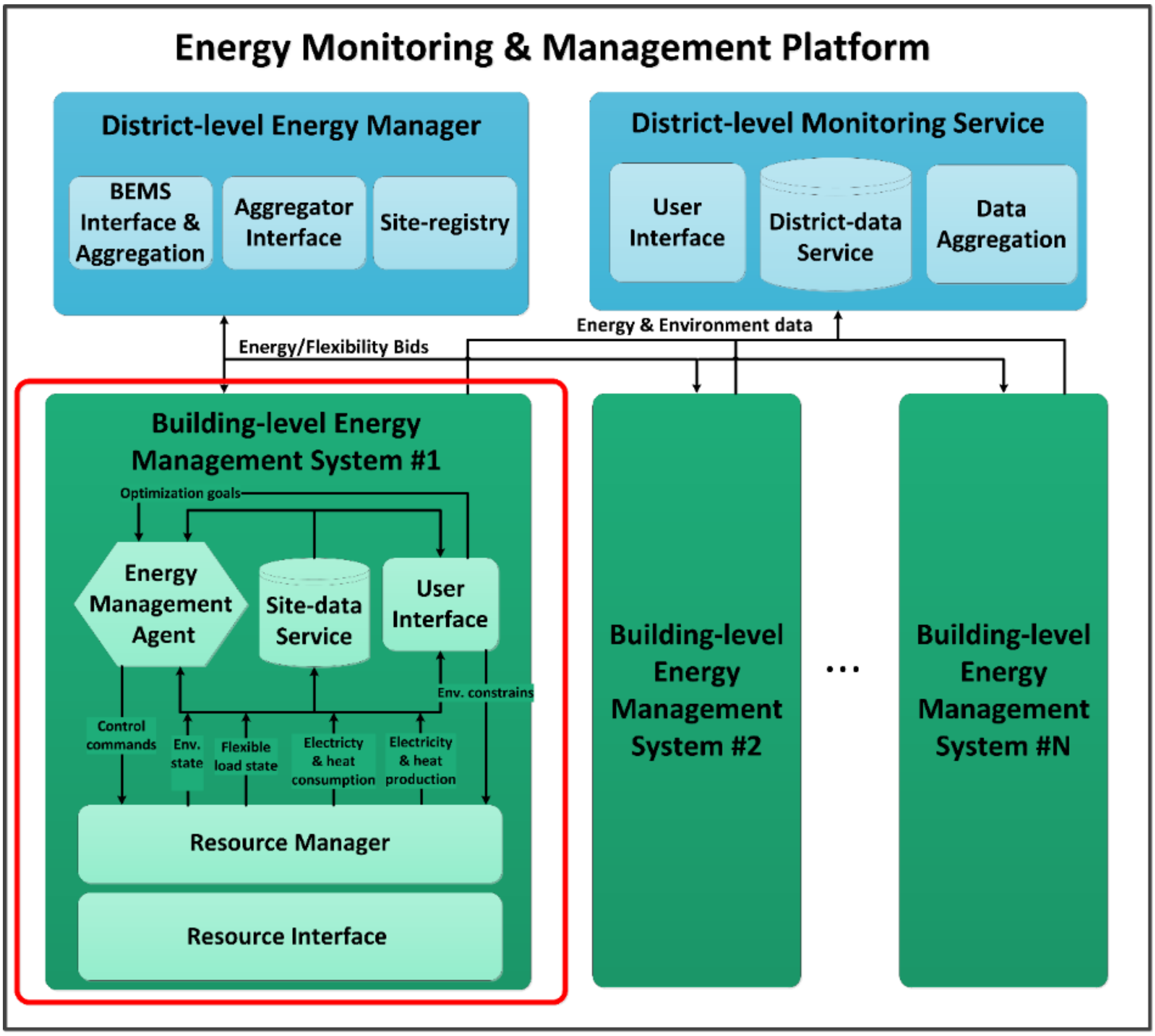


Figure 1. Oulu ICT Platform and the Building-level Energy Management System.

Each BEMS consist of five functional components: Resource Interface, Resource Manager, Energy Management Agent, Site-data Service, and User Interface. The Resource Interface functional component is responsible for interfacing with building management systems (BMS) and site-specific metering infrastructure. The Resource Manager functional component manages resource access and ensures that the control commands issued by the Energy Management Agent respect the constraints (e.g. room temperature) specified for each resource. The Energy Management Agent (EMA) is the functional component that implements the energy management at site-level and provides load and flexibility forecasts to be used for aggregated energy management at the PED-level. The Site-data

Service is responsible for storing site-specific data, including energy and sensor measurements. The User Interface provides End-users with means for monitoring site data.

3 Resource Interface and Manager Components

The Resource Interface functional component is responsible for interfacing with building management systems (BMS) and site-specific metering infrastructure. Resource Interface also offers secured https connection with a SSL certificate, and it routes incoming data messages and data requests to the Site-data Services and Resource Manager as presented in Figure 2.

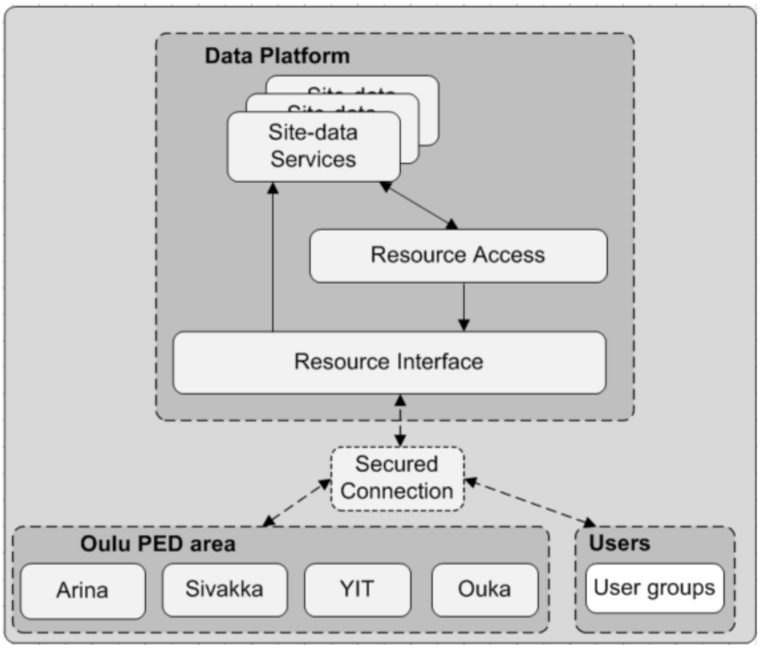


Figure 2. Resource Interface connections.

3.1 Supermarket

All relevant measure points of building automation and energy meters data are collected to database. The building automation data contains process data also. Process data contains heating and cooling measure and control data. Energy data contains all electricity energy, heating energy, geothermal energy and produce district heating energy. The data collection for the system architecture is shown in Figure 3.

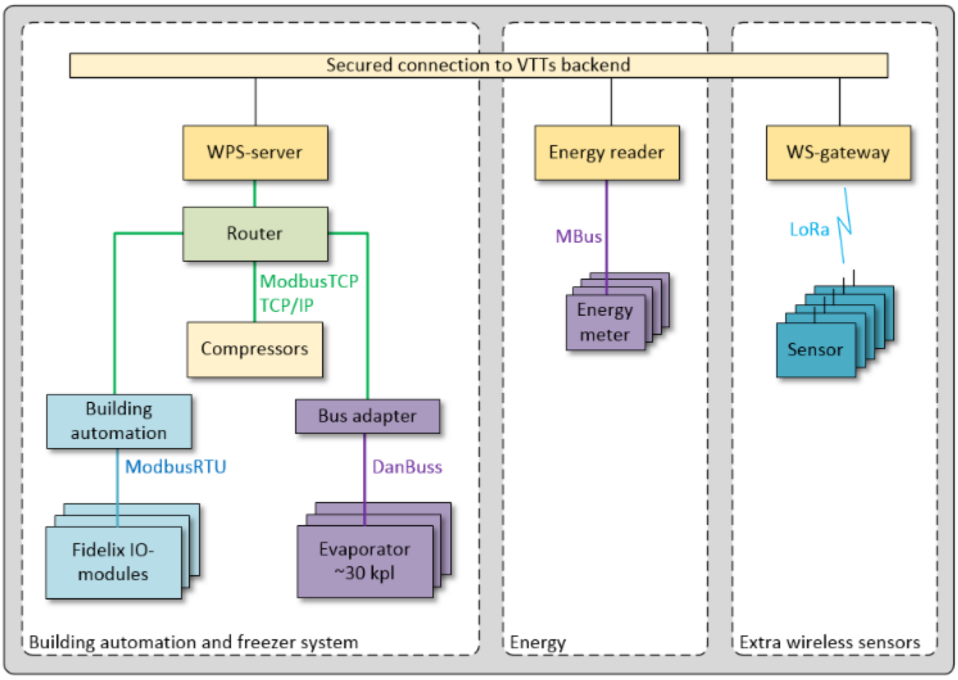


Figure 3. Architectural view of the Data collection system.

The supermarket's energy system includes several electrical loads and the largest main load is a compressor package. The compressor package produces the necessary cold and heat for the supermarket. The compressor package produces cold for freezers and refrigerators. Both cold (cooling) systems include three compressors, two fixed and one frequency converter controlled. Heating energy is generated with the same compressors. The Compressors produce heating energy for hot water and heating boiler as well as district heating. The Energy system is shown in Figure 4.

Figure 4. Architectural view of the Energy system.

The Supermarket's energy system includes several sub-meters so we can know the consumption of large loads. Electrical load includes e.g. Cooler equipment (melting system), HPAC-system, kitchen appliances, lighting, car heating, defrost cables and other small loads. Some loads can be control for different times, but some cannot be affected. The supermarket energy system includes also the solar panel system.

Figure 5. View of the power data on a sunny spring day.

Figure 5 shows electrical power measurements on a sunny spring day. We can see that during a sunny day the solar panels power exceeds the total consumption except for short spikes.

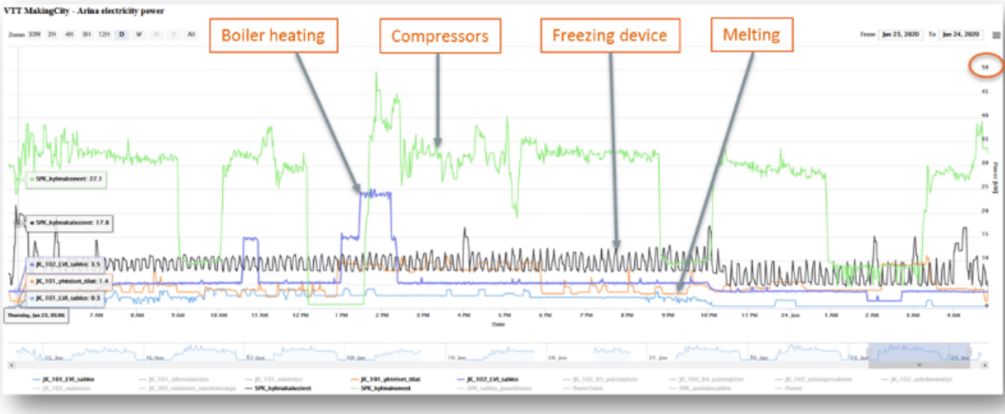


Figure 6. View of the loads that can be control to different time.

Figure 6 shows the electrical power measurements of large loads. These loads can be control to different times.

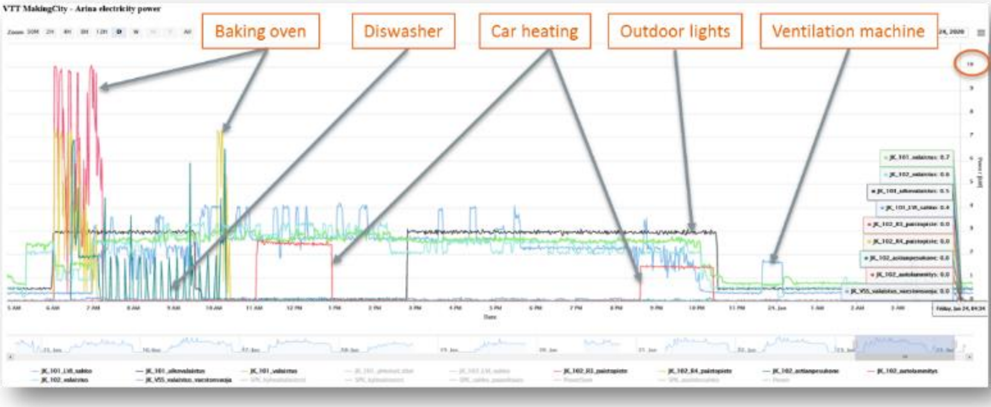


Figure 7. View of the loads that cannot be control to different time.

Figure 7 shows the electrical power measurements of quite large loads. These loads cannot be control to different times. We need to consider the timing of these loads when planning timing to the controllable loads.

Figure 8. Dashboard view of the Heating and Cooling system.

The monitoring system includes several different visualizations that based on the collected data. One dashboard view is shown in Figure 8.

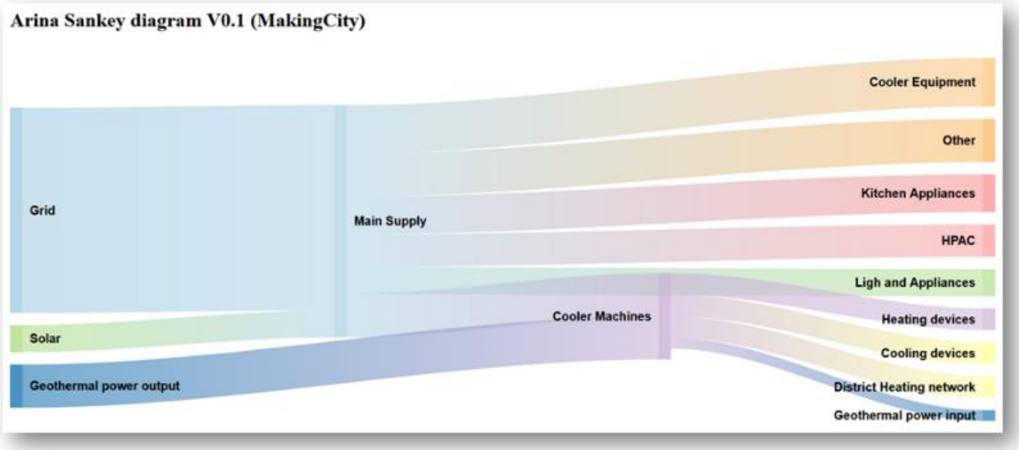
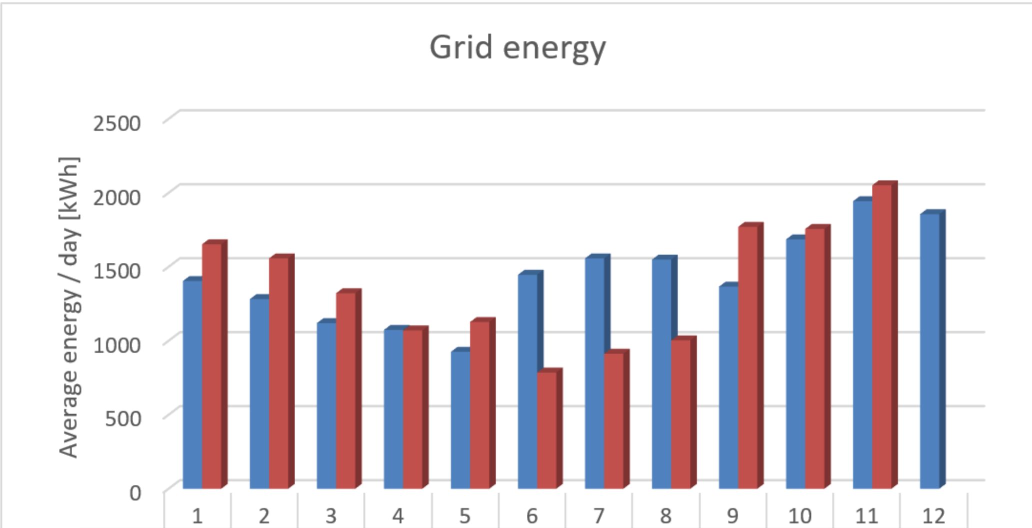


Figure 9. Sankey diagrams view of the loads.

Figure 9 shown is one example of several different visualizations that shown Supermarket power flow in Sankey Diagram view.

3.1.1 Supermarket energy comparison

The normalised grid energy consumption of each month (total energy consumption / days in month) of the supermarket building has been compared in Figure 10 for year 2020 and 2021.



	1	2	3	4	5	6	7	8	9	10	11	12
2020	1404	1282	1120	1074	926	1447	1557	1549	1366	1686	1944	1856
2021	1653	1557	1322	1070	1127	786	913	1003	1771	1757	2051	

Figure 10. Supermarket grid energy consumption from two previous years.

The normalised solar energy production of each month (total solar energy production / days in month) of the supermarket building has been compared in Figure 11 for year 2020 and 2021.

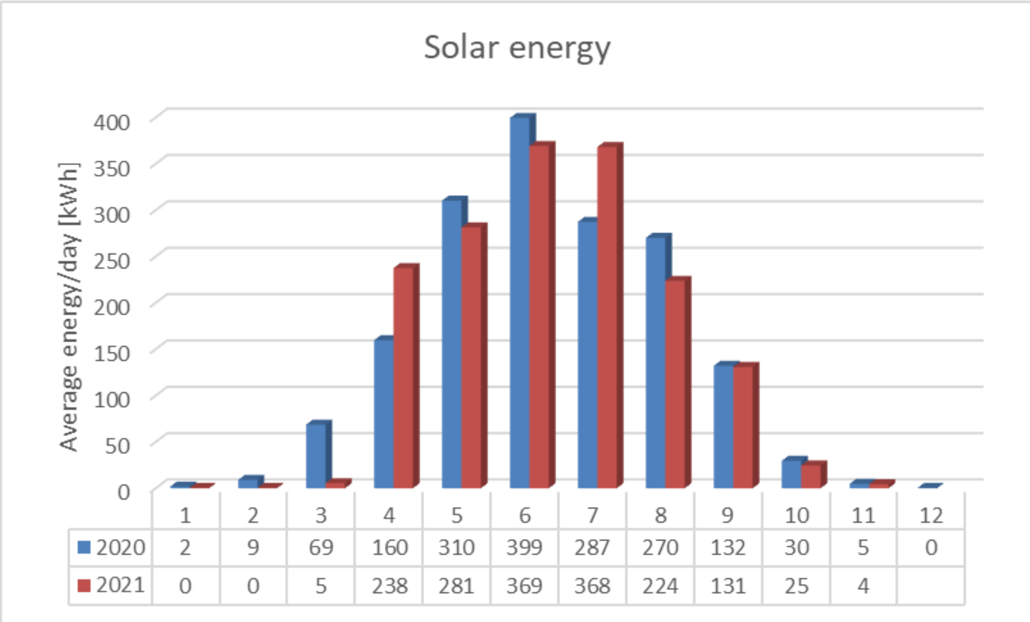


Figure 11. Supermarket solar energy production from two previous years.

The normalised compressor energy consumption of each month (total compressor energy consumption / days in month) of the supermarket building has been compared in Figure 12 for year 2020 and 2021.

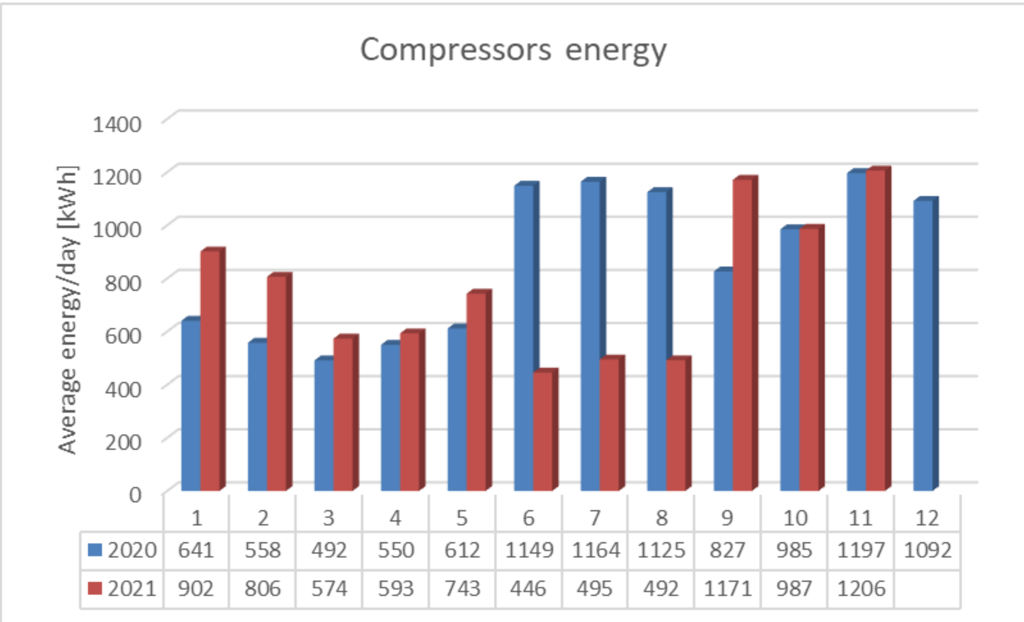


Figure 12. Supermarket compressors energy consumption from two previous years.

The normalised district heating production of each month (total district heating production / days in month) of the supermarket building has been compared in Figure 13 for year 2020 and 2021.

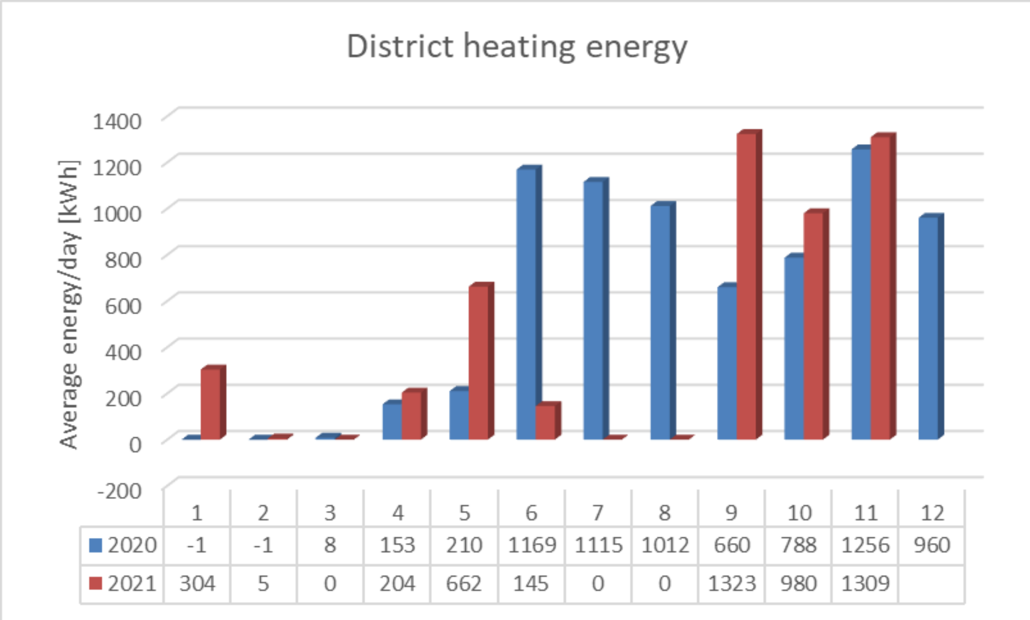


Figure 13. Supermarket district heating energy production from two previous years.

The normalised heating consumption of each month (total heating consumption / days in month) of the supermarket building has been compared in Figure 14 for year 2020 and 2021.

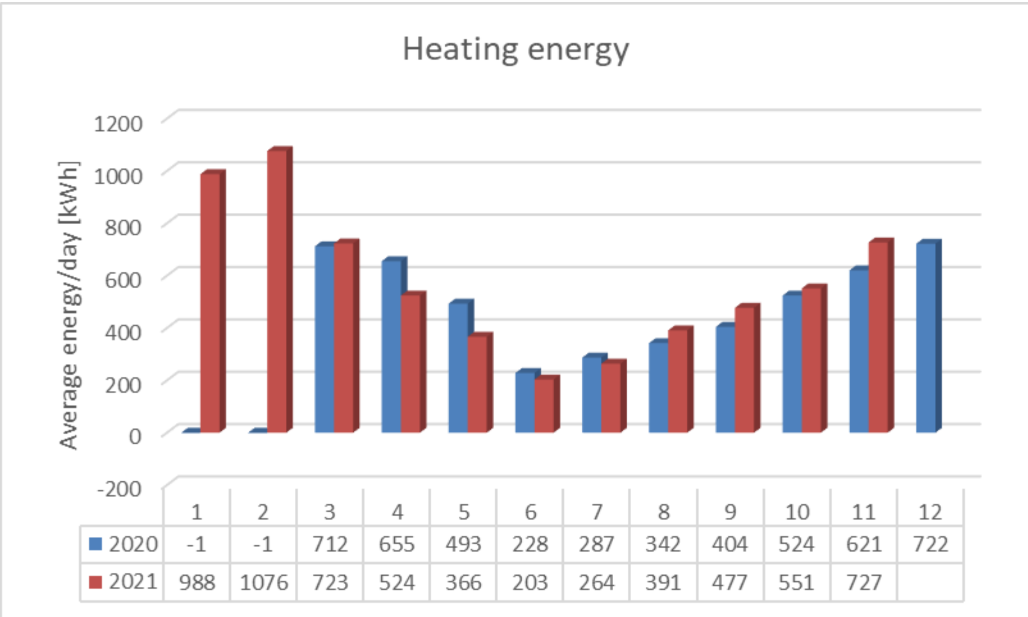


Figure 14. Supermarket heating energy consumption from two previous years.

The supermarket is installed with energy monitoring, control hardware add-ons. The supermarket is producing district heating energy since April 2020. The first test period of the district heating production was between April to December 2020 (nine months). In addition, the district heating production process was modified between January to August 2021 and the production started again in September 2021 as seen in Figure 13.

The analysis results shows that the district heating production process has increased the efficient by 24% as seen in Figure 15. The production (power of the compressors) is set to maximum, but so that no gas cooler required. The heating system of building is using extra energy generated all time. The summer 2021 was exceptionally hot. The district heating energy production was not needed and was operating in minimum energy mode (no district heating energy production at all). However, extra energy was needed for extra cooling and drying (air drying requires cooling and heating energy).

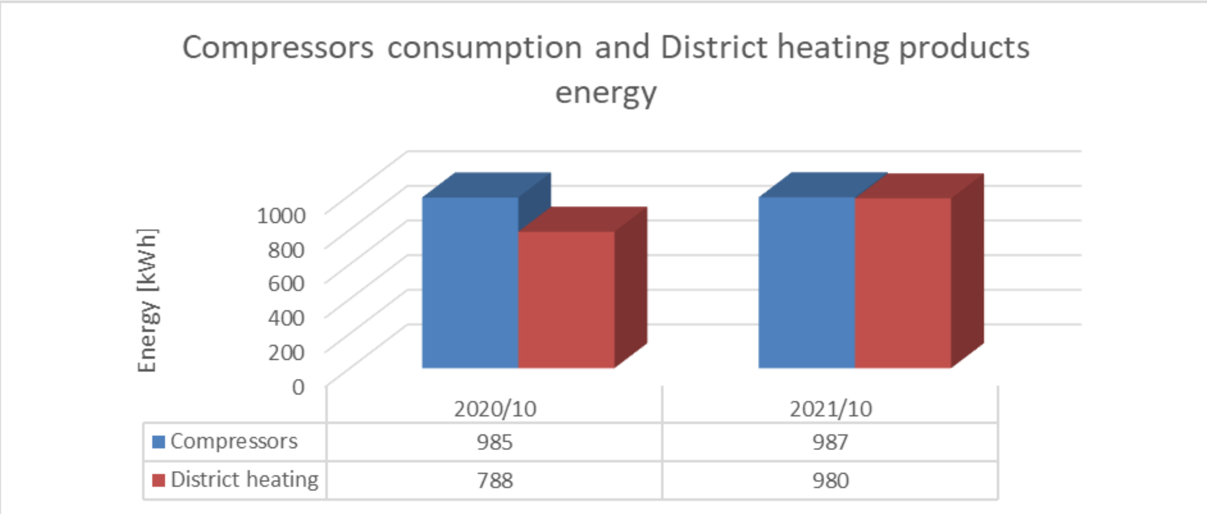


Figure 15. Supermarket district heating energy production and compressors energy consumption.

3.2 Sivakka buildings

All relevant measure points of building automation, heating automation and apartment sensors collected to database. The building automation data contains wastewater recovery system and HPAC-system and apartments temperature and humidity data. Heating automation data contains district heating system and heat pump system data. The heating system include the heat pump that uses as input exhaust air energy or district heating return energy. Heating system can be uses also district heating in the normal way, if the heat pump power is not enough. The electricity energy of the apartment measuring from the energy meter blinked LED. The data collection for the system architecture is shown in Figure 16.

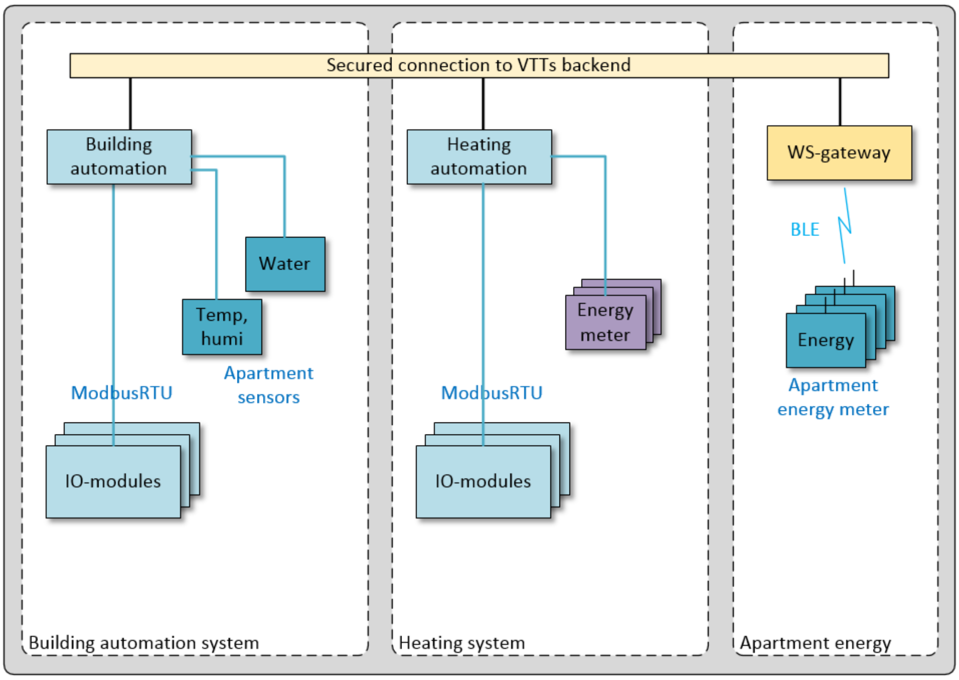


Figure 16. Architectural view of the Data collection system.

3.2.1 Sivakka 1, Vaskitie

Sivakka 1 building is equipped with Hörgfors FiksuGST heating system, which include a heatpump that can use input energy from recovered air from exhaust or return energy from district heating. The heatpump uses that input energy to generate heating and hot water energy. If the heat pump is not capable enough in extreme weathers then district heating can be used. This building also has wastewater recover system that is used for hot water preheating. The solar penal capacity on this building is 11 kWp as shown in Figure 17.

Figure 17. Sivakka 1 building with 11 kWp solar panels

3.2.2 Sivakka 2, Jalohaukantie

Sivakka 2 building is also equipped with Hörgfors FiksuGST heating system, which include a heatpump that can use input energy from recovered air from exhaust or return energy from district heating. The heatpump uses that input energy to generate heating and hot water energy. If the heat pump is not capable enough in extreme weathers then district heating can be used. This building also has wastewater recover system that is used for hot water preheating. The solar penal capacity on this building is 23.5kWp as shown in Figure 18.

Figure 18. Sivakka 2 building with 23.5 kWp solar panels

3.2.3 Sivakka 3, Hiirihaukantie

Sivakka 3 building is also equipped with Hörgfors FiksuGST heating system, which include a heatpump that can use input energy from recovered air from exhaust or return energy from district heating. The heatpump uses that input energy to generate heating and hot water energy. If the heat pump is not capable enough in extreme weathers then district heating can be used. The solar penal capacity on this building is 16 kWp (assembled on the wall) as shown in Figure 19.

Figure 19. Sivakka 3 building with 16 kWp solar panels assembled for wall.

3.3 YIT building

YIT building (Figure 20) is also equipped with Hörgfors FiksuGST heating system, which include a heatpump that can use input energy from return energy from district heating. The heatpump uses that input energy to generate heating and hot water energy. If the heat pump is not capable enough in extreme weathers then district heating can be used.

Figure 20. Supermarket and YIT 1 building.

4 Energy Management Agent

4.1 Approach

The EMA functional component is responsible for optimizing energy (heat and electricity) within a site by controlling flexible resources to maximize End-user benefits. The End-user benefits are represented as a reward function that can be customized for each site. The interaction between EMA and relevant external systems is presented in Figure 21.

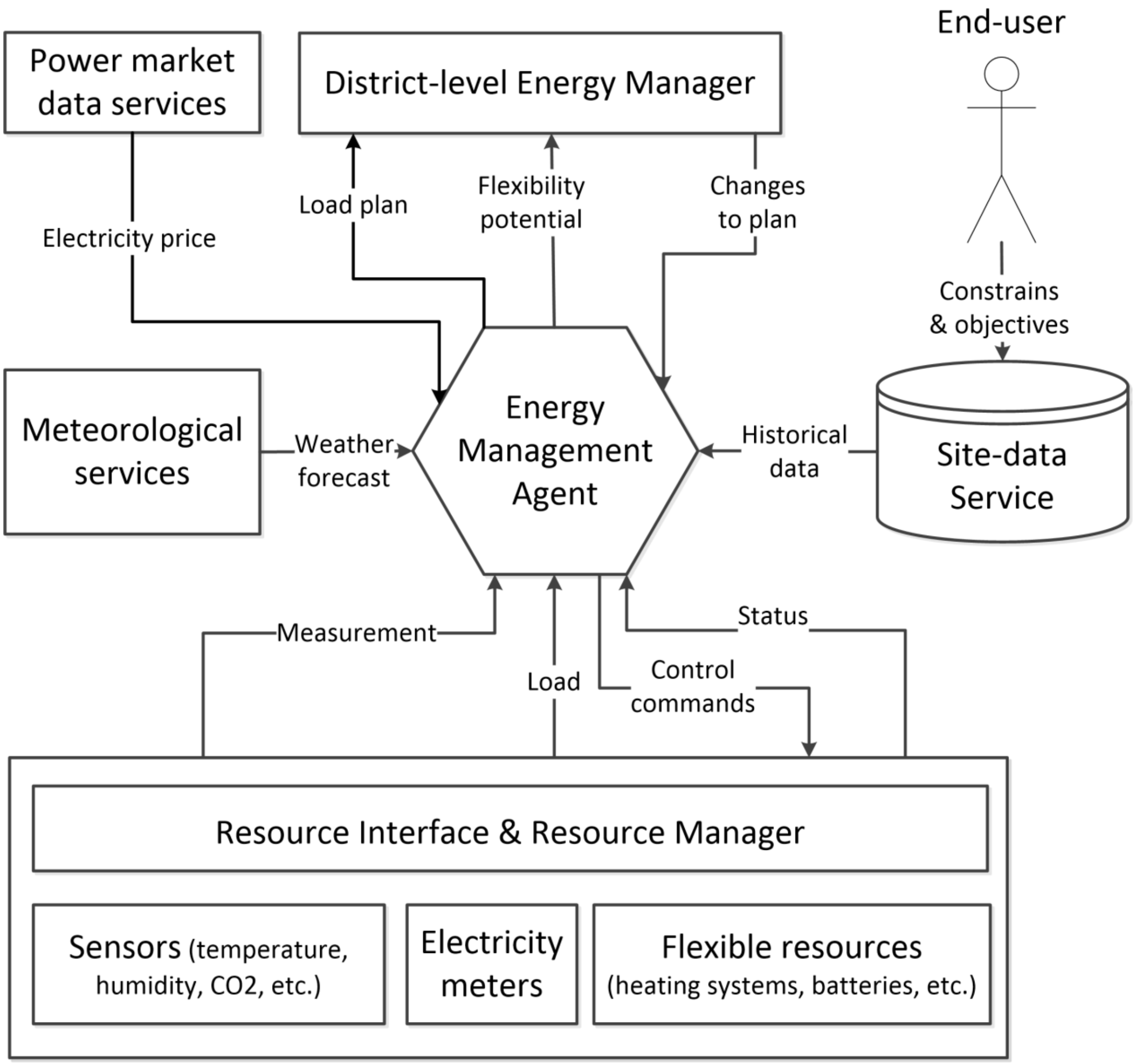


Figure 21. Context view of the Energy Management Agent.

As illustrated in Figure 21, EMA interfaces with BEMS components, including the Resource Interface & Resource Manager, and Site-data Service, as well as following external systems: Power market data services and Meteorological services. EMA also provides a building-level flexibility management interface (for both electricity and district heating) for the District-level Energy Manager (DEM) component (to be described in more detail in D2.17 and D2.6). EMA interfaces with Resource Interface & Resource Manager components in order to 1) collect real-time data about the building environment and energy consumption, 2) and to control flexible resources. Site-data Service provides EMA with historical view on the data collected via the Resource Interface component. Weather forecasts are obtained from meteorological services and electric price data is provided by *Energy market data services* such as the one offered by Nord Pool.

Internally the EMA consists of two type of functional components as illustrated in Figure 22.

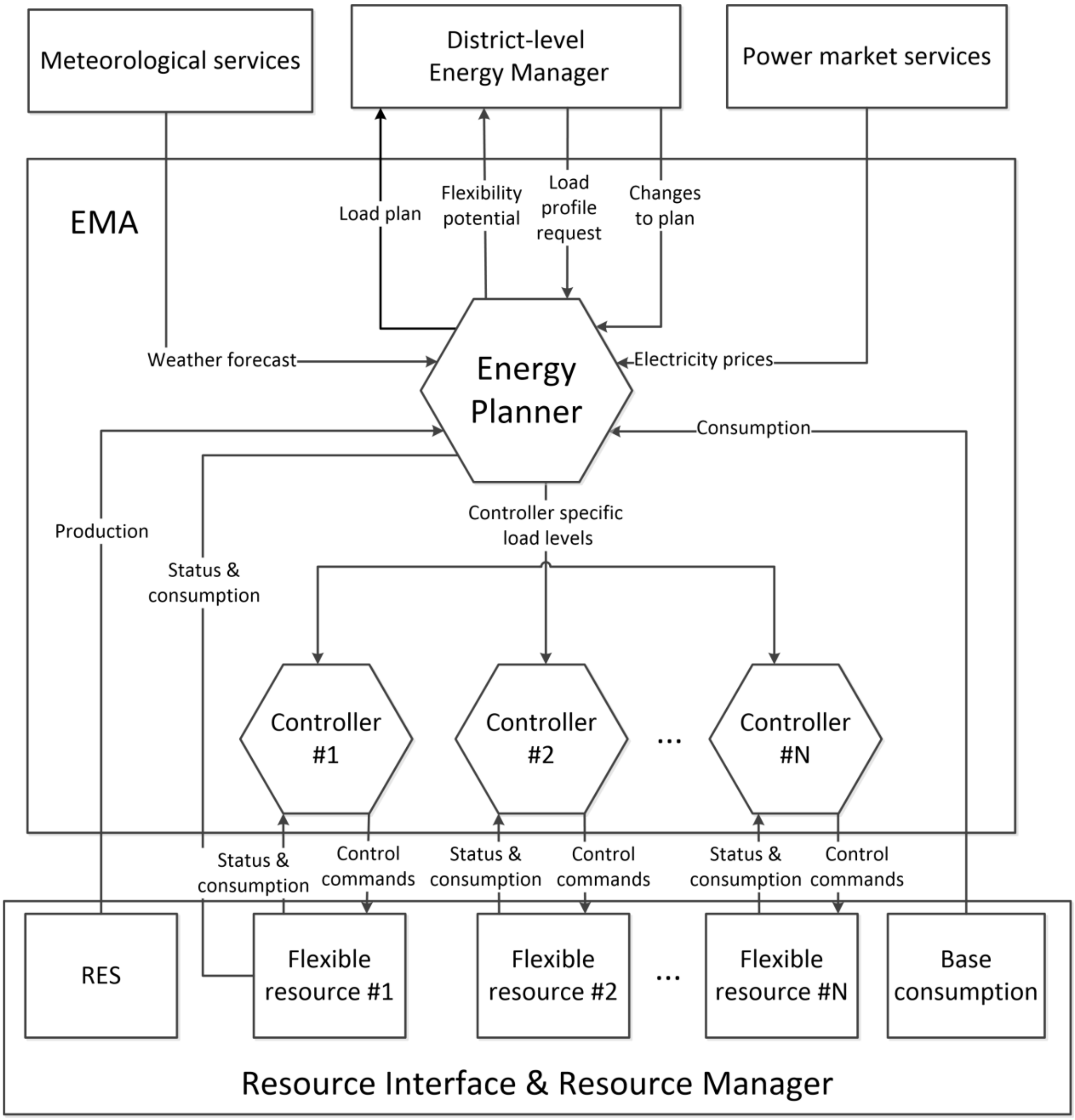


Figure 22. Functional view of the Energy Management Agent.

The Energy Planner plans and manages flexibility within the site. Its functionality consists of five main steps:

1. At fixed intervals, the Energy Planner provides a load plan for both electricity and district heating to the District-level Energy Manager.
2. At fixed intervals, the Energy Planner sends flexibility potential message to the District-level Energy Manager.
3. Whenever a flexibility is activated by the DEM, the Energy Planner modifies the internal load plan accordingly and informs the Controllers about changes in their individual load plans.

There is a Controller component for each flexible resource type within a site. A Controller is responsible for managing flexible resource according to a load plan provided by the Energy Planner.

The approach for implementing the EMA, illustrated in Figure 23, is based on model-based planning and control.

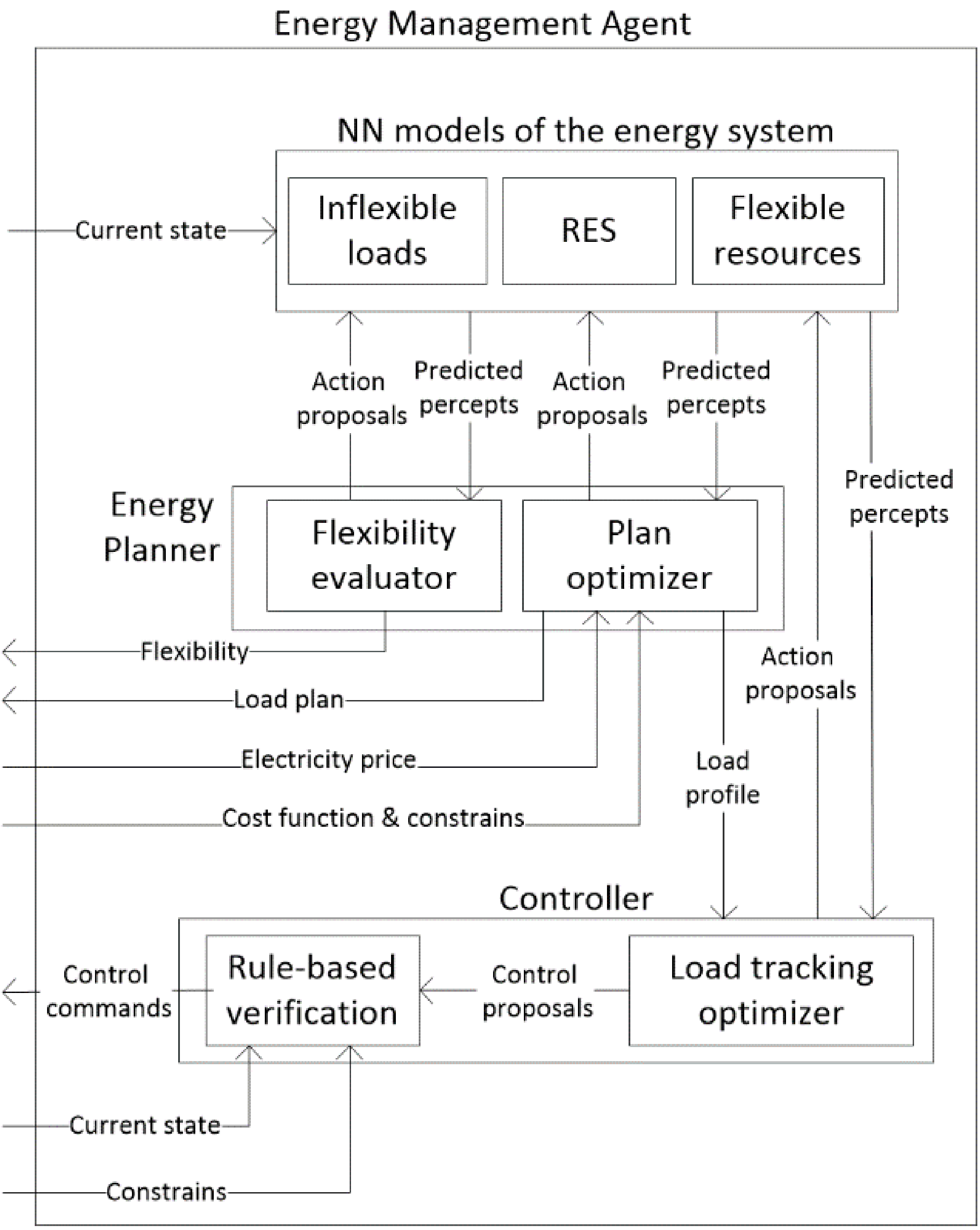


Figure 23. Model predictive with ANNs for building energy management.

The Energy Planner utilizes model-based optimization for finding an optimal control policy for the flexible resources. The optimization target of the Energy Planner for making the load plan can be presented as follows:

$$\max_{a_1,\ldots,a_T} \sum_{t=1}^{T} r(s_t, a_t) \qquad (1)$$
$$s.t.\ s_t = f_f(s_{t-1}, a_{t-1}) + f_g(s_{t-1,}) + f_d(s_{t-1,})$$
$$s_{min} \leq s_t \leq s_{max}$$

,where r is the reward function, s_t is the state of the system, and a_t is the action. The s_{max} and s_{min} are possible constrains (e.g. min and max values for indoor temperature). The f_f, f_g and f_d represent models (e.g. Artificial Neural Networks) for flexible resources, power generation and inflexible demands, respectively. The approach developed for Oulu PED area combines data based modelling with physics to model f_f, f_g and f_d for different sites. Details will be provided in section 4.2.

Different types of optimization methods can be used for Model Predictive Control (MPC). These methods can be divided into two main groups: derivative-based methods and gradient-free methods. Derivative-based methods are more efficient, but require a model that is differentiable model such as an ANN. However, even with ANNs there are problems with exploding and vanishing gradients [1] in long optimization horizons. Consequently, gradient-free methods such as Genetic Algorithms (GA) [2][3], Particle Swarm Optimization (PSO) [4][5] have been so far more popular for ANN-based energy optimization in buildings.

Either open loop or closed loop control (i.e., MPC) can be used for making the load plan. In MPC new load plan is made at every time step whereas in open loop control a plan is made once per length of the load plan. This design choice is a trade-off between the accuracy of the load plan and optimality of the energy management.

The controller can be implanted either with MPC or more traditional control logic such as proportional-integral-derivative (PID) controller. MPC is the preferred approach if the plant (i.e., system to be controlled) has complex and time-varying dynamics and/or there are long delays in the control. When MPC is used the controller only requires model(s) of the flexible resource it is controlling. Same model as used by the Energy Planner can be typically used for control. The objective of the Controller is to follow its load plan. It is defined as follows (2):

$$\min_{a_1,\ldots,a_T} \sum_{t=1}^{N} \left(E_t - \hat{E}_t\right)^2 \qquad (2)$$
$$s.t.\ s_t = f_f(s_{t-1}, a_{t-1})$$
$$s_{min} \leq s_t \leq s_{max}$$
$$\hat{E}_t \in s_t,$$

where E_t is the energy in the load plan, $\hat{E}_t$ is the energy consumption predicted by the model f_f, and s_t is the state of the system including the energy consumption.

4.2 Building specific instances

4.2.1 Supermarket

Inflexible loads in the building are composed of mainly refrigeration, lighting, heating demand, and hot water heating. A large compressor system is responsible for delivering power to the refrigeration and heating systems of the store. It is further separated into heating and refrigeration circuits each with their own set of compressors. These circuits are connected via complex set of carbon dioxide (CO_2) carrying pipes and valves. This system is automatically controlled by the building automation system. Main controllable loads are found in the heating circuit where it is possible to control district heat production, hot water heating cycles and power delivered in the store heating circuit. Moreover, energy storing flexible resources in the building include refrigeration system, where it is possible to change the temperatures of the refrigerators and freezers (within limits) and water boiler used for heating the building. Additionally, the thermal mass of the building can be seen as a flexible resource. The supermarket also houses large PV production capabilities that are in summertime able to produce more than necessary energy needed to run the store.

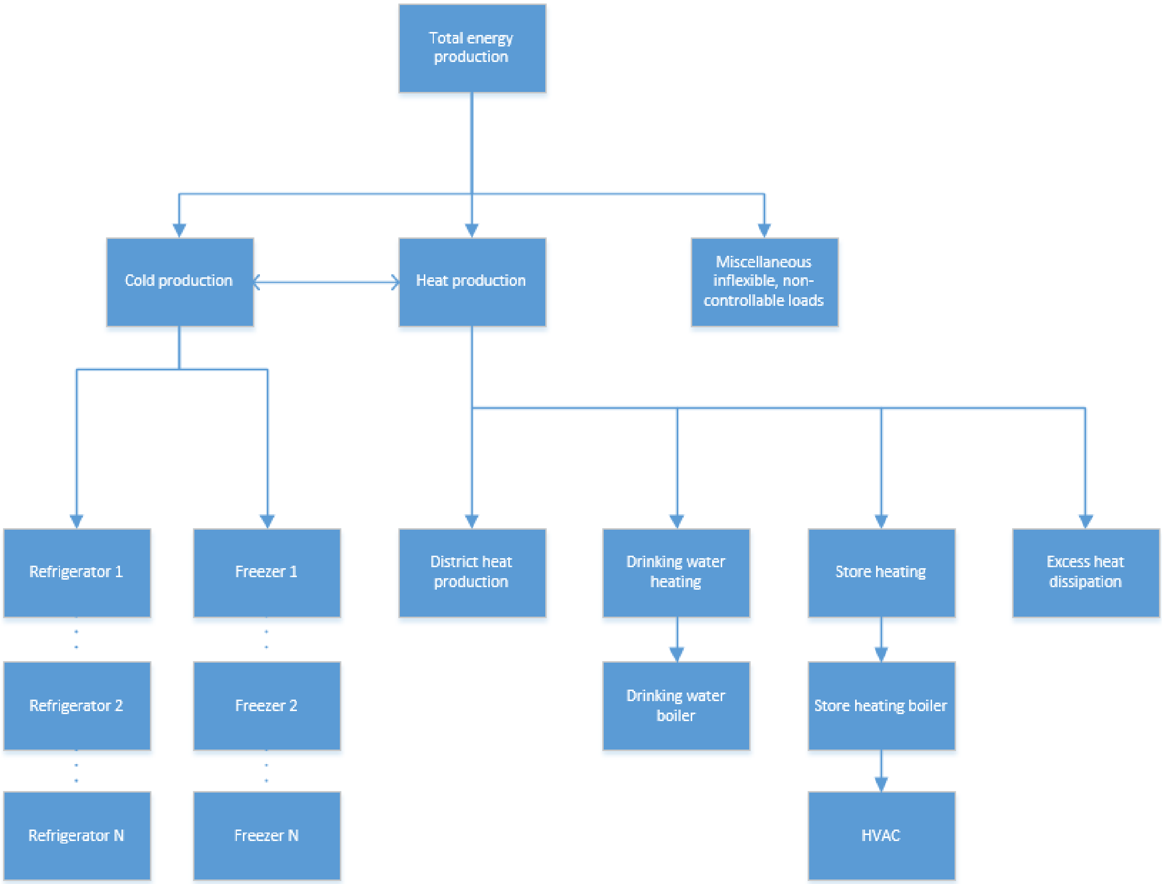


Figure 24. Schematic description of the various energy components and their relations in the supermarket.

Modelling of the system is divided into multiple sub-models, based on the physical structure of the building and functionality of the components. This is done in order to reduce complexity of the model, to facilitate easier and more accurate model evaluation, testing and development, and identification of key components that need more attention in modelling. The sub-models are depicted in Figure 24. In Figure 25, an example on artificial neural network architecture is shown for simultaneous training and inference of the different sub-models. These sub-models could also be trained individually which increases training time but could add to model accuracy. In addition, physics-based constraints and other techniques are implemented on top of the ANN model to increase model performance.

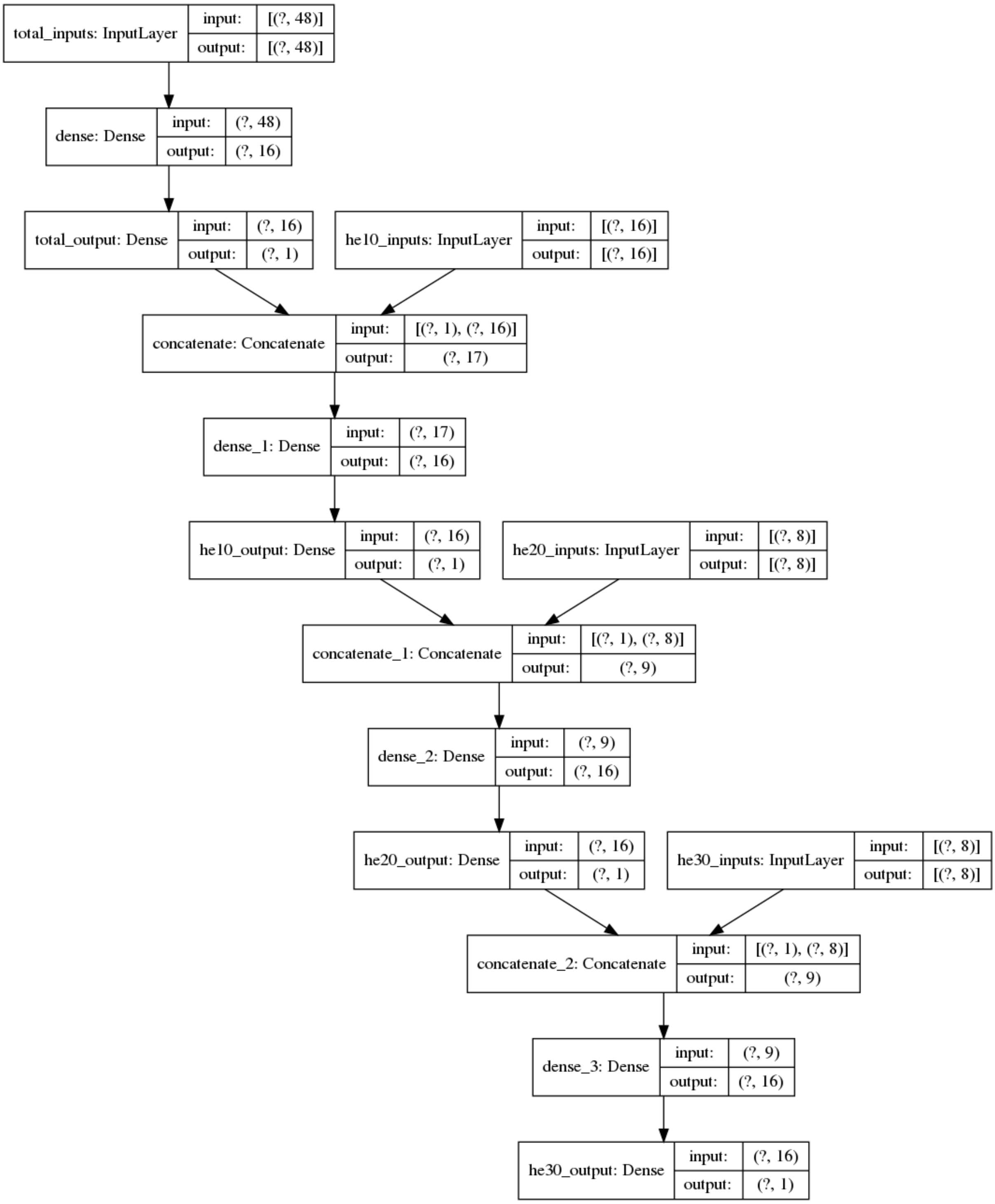


Figure 25. An example of the ANN model structure when it is trained in a single pass. The model predicts variables in sequential order, which are then fed as inputs to subsequent models.

In the following section, modelling approach is presented for each of the components of the system.

4.2.1.1 Total heat generation

Modelling total heat generation is a complex task as it is affected by not only control signals given to the system but also the power consumption of each component, which again are dependent on heat generated. This creates a feedback mechanism between generation and demand. Heat generating compressors will adjust their power based on the demand of the system and limits set by the control values. In principle, the total heat generated is given by

$$P_{gen} = \min\left(\sum_i P_{demand}^i, P_{gen}^{max}\right),$$

where i is the component and P_{gen}^{max} is the maximum power given the control signals.

4.2.1.2 District heat production modelling

The amount of district heating is dependent, other than control signals, on both the production of heat and also the state of the heating network itself. The pressure and the temperature of the incoming district heat varies and this in turn affect power delivered.

4.2.1.3 Hot tap water modelling

As hot water is consumed, it is replaced by cold water and this lowers the temperature of the boiler. Thus, the power required by this component is mostly dependent on human behaviour which is in this case adequately modelled using time and day as inputs.

4.2.1.4 Store heat production and demand

Heat power delivered to store heating purposes is mostly dictated by how much power is available. In addition, the state of the store heating system plays a role. For example, if the boiler is at its maximum temperature, returning water from the heating system might be high already, in which case the temperature difference between CO2 line and store heating line is not very large.

4.2.1.5 Store heating boiler

The main flexible load of the system is large water boiler in the store heating system. Using models for store heating and demand, the boiler state (flexibility) can be modelled linearly using

$$\Delta E_{boiler} = E_{gen}^{model} - E_{dem}^{model} - \epsilon,$$

where ϵ is a loss term for heat dissipation due to thermal conduction and hot drinking water pre-heating.

4.2.1.6 Excess heat dissipation

Modelling heat dissipation is straightforward; given you know the power delivered to other components. Then it is in essence the difference between power produced and used. Or more formally

$$P_{dis} = \left(P_{gen} - \sum_i P^i\right).$$

4.2.1.7 Refrigeration system

Due to the design of the system, heating the store generates surplus power also to cool the freezers and refrigerators, at least in the colder weather. As a result, it is therefore adequate for forecasting purposes to use heating side inputs in modelling refrigeration energy consumption. Small variation may incur from people opening and closing the cold units and from melting cycles of the freezers.

Controlling and optimization of the system is done through manipulating various set points that regulate the actions of the building automation system. A depiction of the different control interfaces is found in Figure 26.

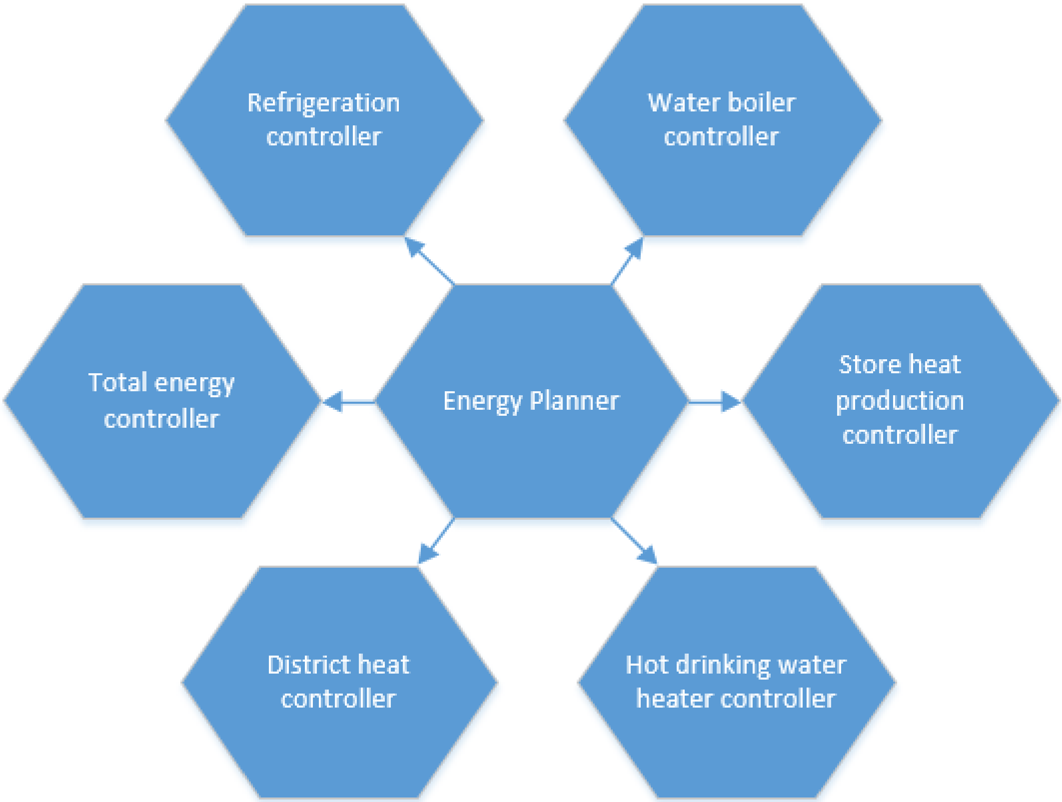


Figure 26. Different control modules identified in the supermarket.

4.2.2 Residential buildings

Building heating systems are the main flexible resources in the apartment buildings located in the Oulu PED area. The buildings contain advanced heat supply that combines heat pumps and district heating. Heat pumps and district heating are also used for heating the domestic hot water (DHW) of the buildings. Inflexible loads in the apartment buildings are composed mainly of appliances in the apartments, common area lighting, and heating of domestic hot water.

The whole building model consist of following five types of models: total district heating demand, total electricity demand, indoor temperature, and space heating. The total demand models for district heating and electricity, are implemented with machine learning (ML). The ML models are described in more detail in section 4.2.2.1. The indoor temperature and space heating models provide predictions of the buildings flexibility. These models are implemented by combining physics and linear models. These models are further elaborated in section 4.2.2.2.

4.2.2.1 Machine learning models for baseline load forecasting

Python programming language is used for implementing the machine learning models. The modelling framework developed in the project utilises Tensorflow 2.0 [6] with Keras API [7] and scikit-learn [8] for searching the best models for each forecasting tasks.

The implemented machine learning framework searches best models for DH, and total electricity consumption and RES generation among following type of models: linear, Support Vector Regression (SVR) and Artificial Neural Network (ANN). For SVR radial basis function (RBF) and sigmoid function kernels are used in the model search. The ANNs are evaluated with different amount of hidden layers and neurons. Adam optimizer [9], ReLU activation and mean squared error loss are used with all ANNs models.

In addition to different ML methods and hyper-parameters introduced above, the developed ML-framework searches the best model from different input features, which can be specified in a configuration file. Possible input features utilized in the model search include outdoor temperature (forecast) for the target period, lagged target values with different lag windows, and temporal features such as hour, day of the week, and holiday. Various encodings for input features were also utilized in the model search, including, sin-cos transformation for cyclic data, one-hot encoding, and scaling.

All the models were trained to forecast the next 24 hours (i.e., lead time of 0 and forecast length of 24 hours) with update frequency of one hour (i.e., a sliding window where a new forecast is made every hour). Different times were used for training and validating the models, depending on the amount of data available for each building. Many buildings did not have a good amount of data yet available so the ML-models will be re-trained and deployed during the next two years.

From apartment buildings, we have collected most representative data set for the Sivakka 1 building, located in Vaskitie 1. The models achieved a good performance for both district heating and electricity baseline forecasting. The test period root mean square errors (RMSE) for DH and electricity were 7.4 kW and 1.5 kW, respectively.

Figure 27 - Figure 29 illustrate forecast (orange) against the measured district heating consumption (blue) in a selected time frame from the test period. Figure 30 - Figure 32 represent the electricity forecast against measured load in a selected period from the test period.

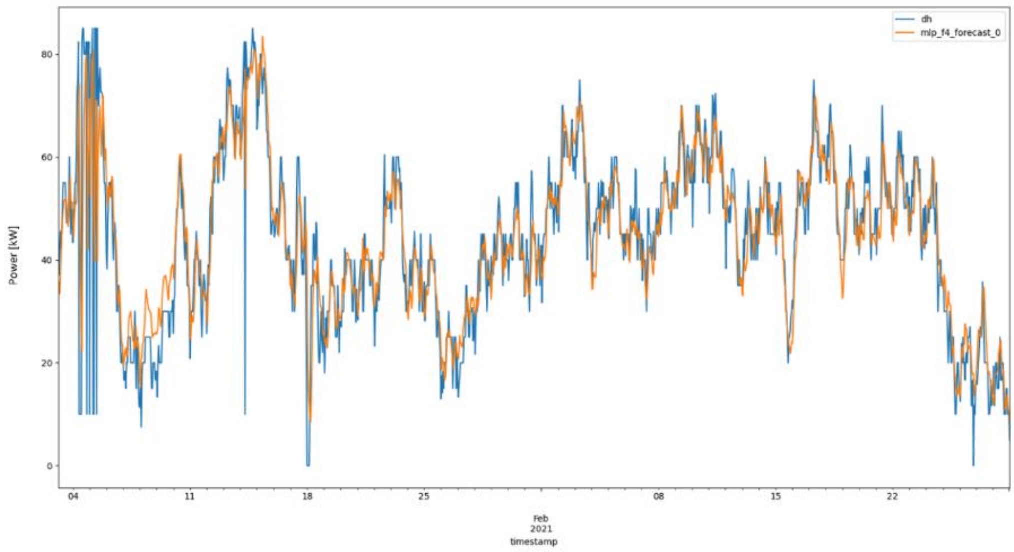


Figure 27: District heating load forecast for 1-hour ahead. Forecast in orange and measured load in blue. Results are represented for a slice of the test period in January - February 2021.

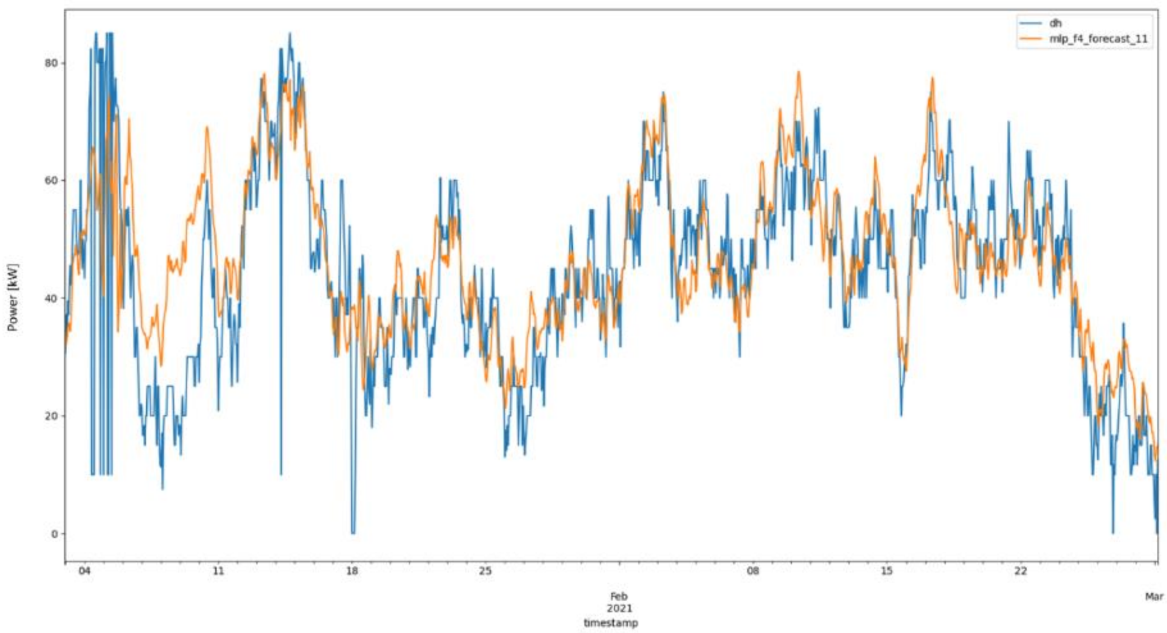


Figure 28: District heating load forecast for 12-hour ahead. Forecast in orange and measured load in blue. Results are represented for a slice of the test period in January - February 2021.

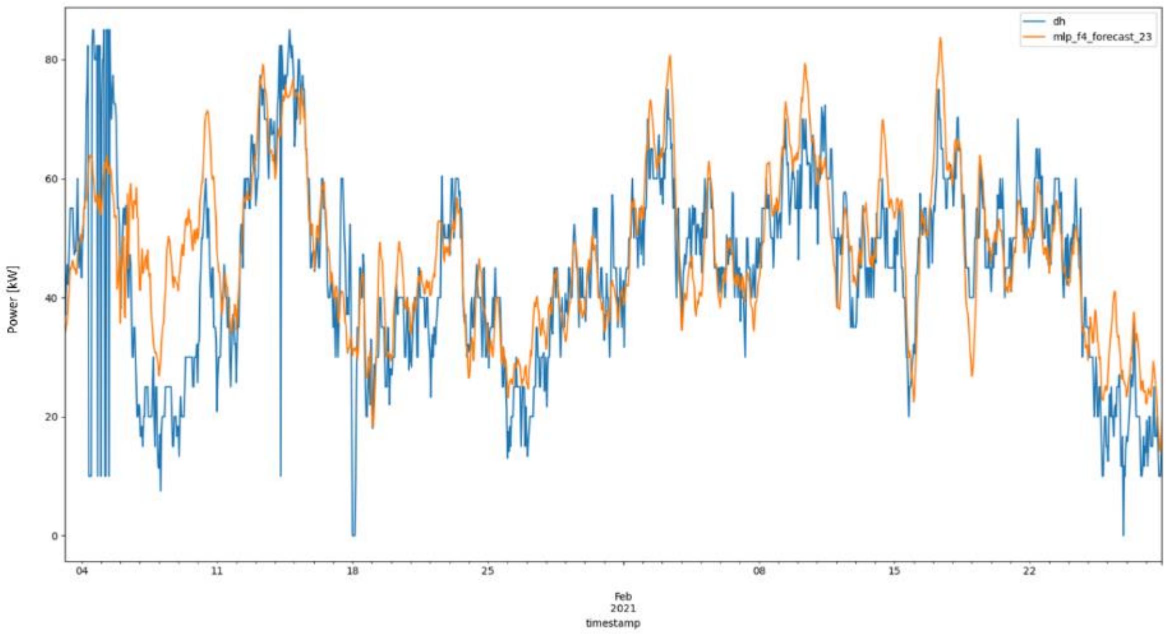


Figure 29: District heating load forecast for 24-hour ahead. Forecast in orange and measured load in blue. Results are represented for a slice of the test period in January - February 2021

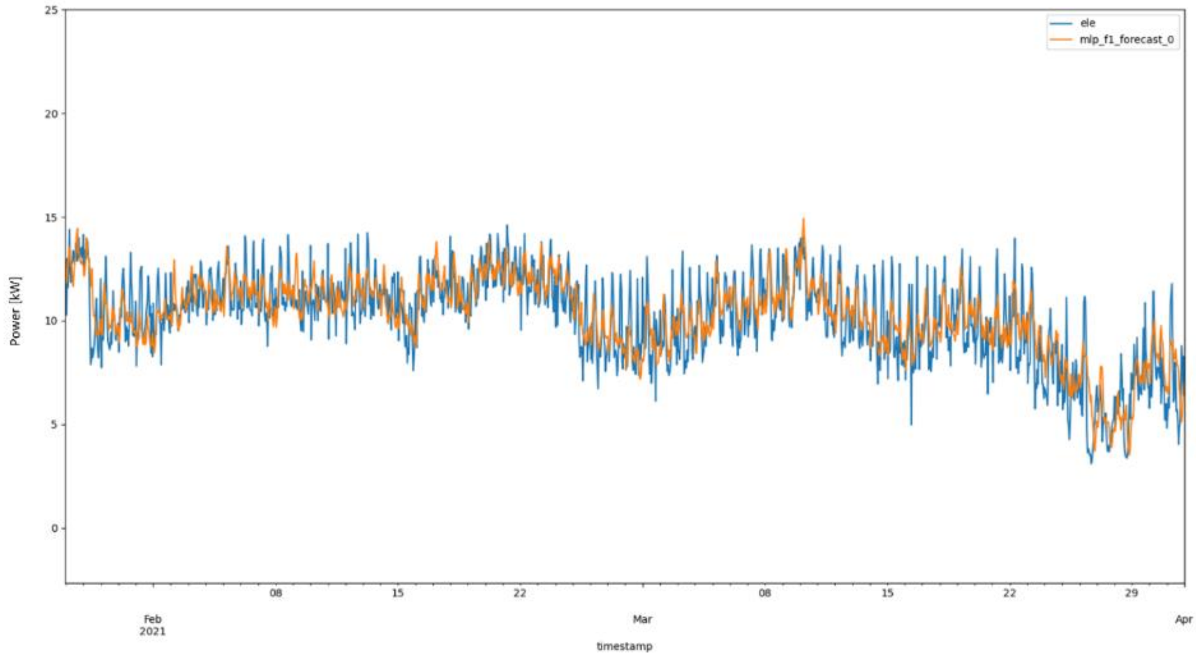


Figure 30: Electricity load forecast for 1-hour ahead. Forecast in orange and measured load in blue. Results are represented for a slice of the test period in February - March 2021.

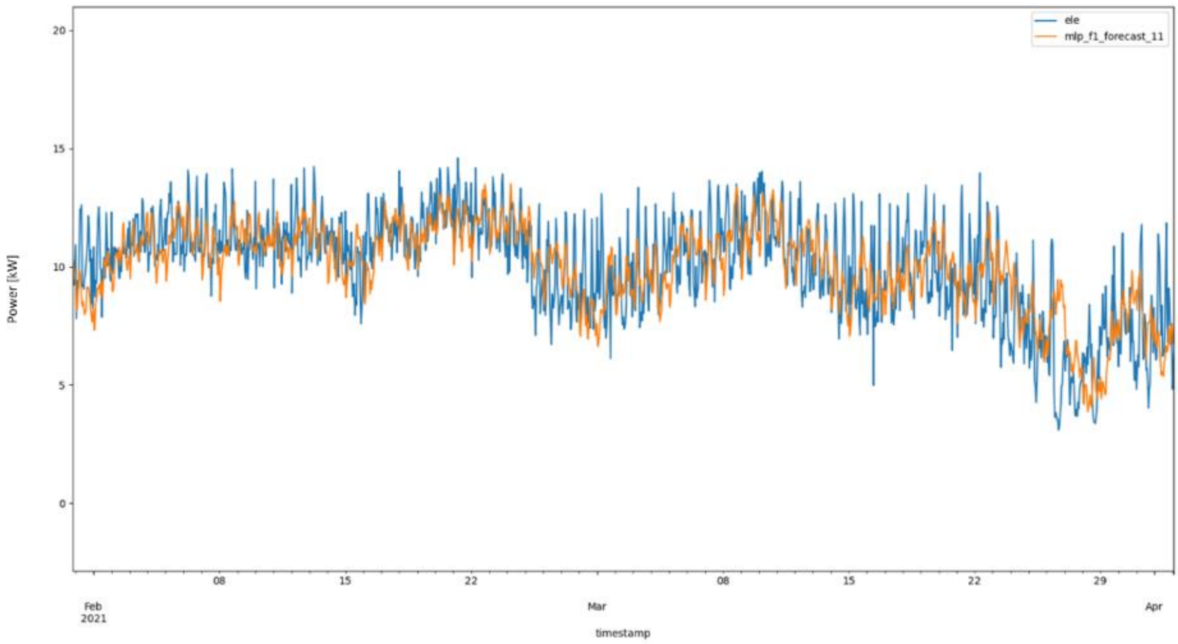


Figure 31: Electricity load forecast for 12-hour ahead. Forecast in orange and measured load in blue. Results are represented for a slice of the test period in February - March 2021.

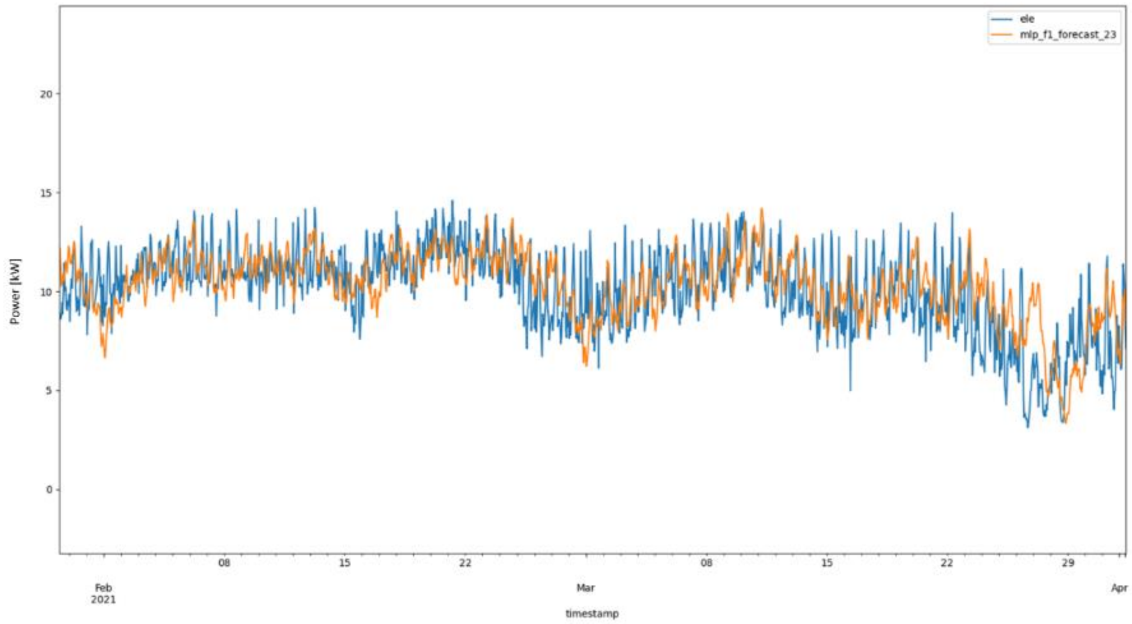


Figure 32: Electricity load forecast for 24-hour ahead. Forecast in orange and measured load in blue. Results are represented for a slice of the test period in February - March 2021.

4.2.2.2 Hybrid models for heating flexibility forecasting

The flexibility of the apartment buildings in Oulu PED area comes the thermal mass of the buildings, which is utilized as a passive energy storage. This allows temporal shifting of the heating load. Moreover, the buildings are equipped with multi-vector heat production system consisting of a heat pump and district heating connection. This allows balancing of energy across these two energy vectors. The flexibility model can be formally presented as follows:

$$(D_t, E_t, T_t) = f(T_{t-1}, O_t, c_t) \qquad (1)$$

$$\forall a_t \in \{0, 1\}$$

where D is the district heating energy used for space heating, E is the electricity used for heating, T is the average temperature inside the apartments, O is the forecast outdoor temperature and c is the control parameter. In the simples case it specifies whether heating is turned on or off.

The practical implementation of the flexibility model consist of space heating (includes DH and the heat pump), as well as, and indoor temperature model. Simple linear models are utilized for modelling heat demand that needs to be supplied by the heat pump and DH. The space heating model requires also that the priority, as well as, the maximum power output of the heat supplies is specified.

The indoor temperature model predicts the average room temperature during demand response events when heat is supplied into the building. The indoor temperature model is derived from Newton's law of cooling and the internal energy stored into the building. Equation 2 represents the mathematical formulation of the indoor temperature model.

$$T(t) = T_{env} + (T(0) - T_{env})e^{-t/\frac{C}{H}} \qquad (2)$$

The model represents the building as a simple lumped element model with single resistive and capacitive components. The resistive component is depicted by the heat loss coefficient, H, of the building. The capacitive component, C, is the thermal mass of the whole building.

Typical capacitance/area values for Finnish buildings, represented in Table 3 and Table 4 are used as initial value for the pilot buildings. These values are multiplied by the floor area of the building to obtain the total estimate for building's thermal mass. These values will be adjusted based on DR experiments executed during the two-year validation period.

Table 3: Typical thermal capacitance values per conditioned floor area for apartment buildings in Finland, including the furniture.

Structure type	Example structures	*C/A* [*Wh/(m^{2}K)*]
Light	Base floor is concrete, all other walls and floors are lightweight materials.	40
Medium	Walls are lightweight materials. Floors are concrete.	160
Heavy	Floors and walls are concrete.	220

Table 4: Typical thermal capacitance values per conditioned floor area for office buildings in Finland, including the furniture.

Structure type	Example structures	*C/A* [*Wh/(m^{2}K)*]
Light	Base floor is concrete, all other walls and floors are lightweight materials.	70
Medium	Walls are lightweight materials. Floors are concrete.	110
Heavy	Floors and walls are concrete.	160

We applied a simple method, called energy signature (ES) for estimating the heat loss coefficient, H, of the buildings in Oulu PED area. In ES method the indoor temperature of the building is assumed to be constant and linear model is fitted to mode the relationship between outdoor temperature and energy consumed both for space heating and heating of the domestic hot water. Building's heat loss coefficient is the gradient of the line. Naturally, the model is only fitted for the heating season and it is assumed that all energy consumption during the summertime (intermediate season) is caused by heating of the domestic hot water. Figure 33 illustrates the ES method and its parameters.

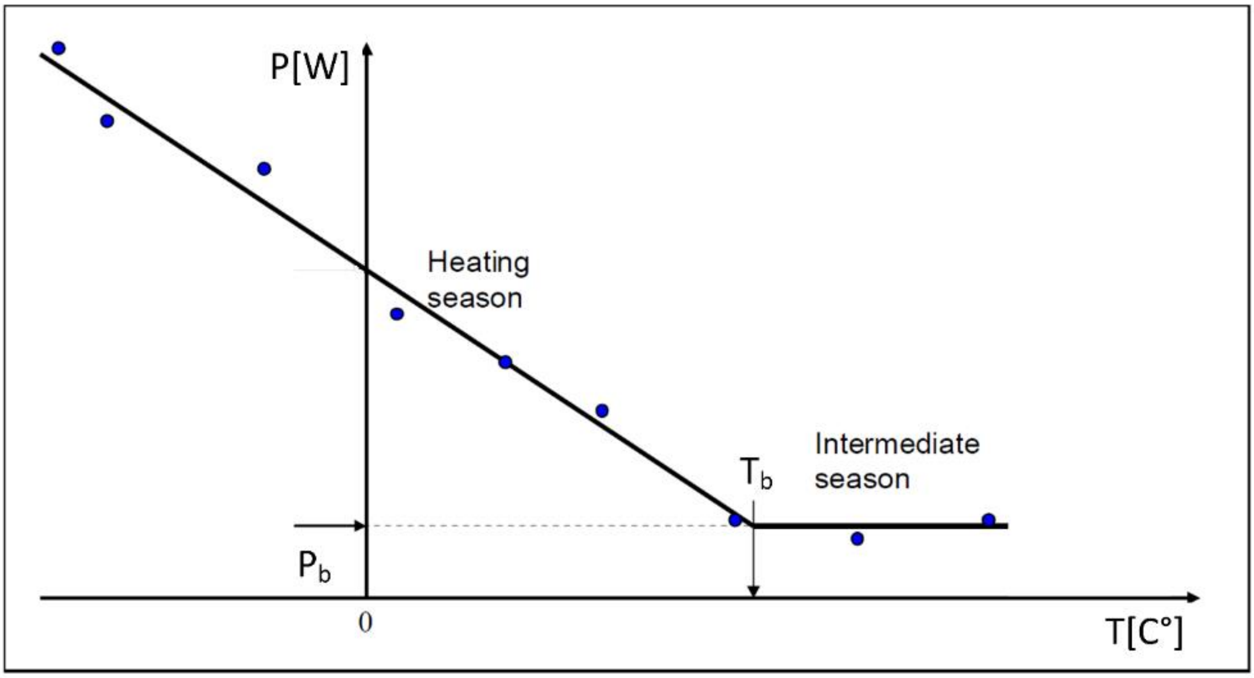


Figure 33: Illustration of the energy signature method.

P_b is the power used for domestic hot water (DHW). Tb refers to the temperature threshold between heating and intermediate seasons.

An important part of the ES method is sampling the data into reasonable resolution so that heating dynamics are averaged out. Daily resolution was used for fitting the linear model for the Oulu PED area buildings. Figure 34 illustrates the daily average DH power for Sivakka 1 building plotted against the outdoor temperature

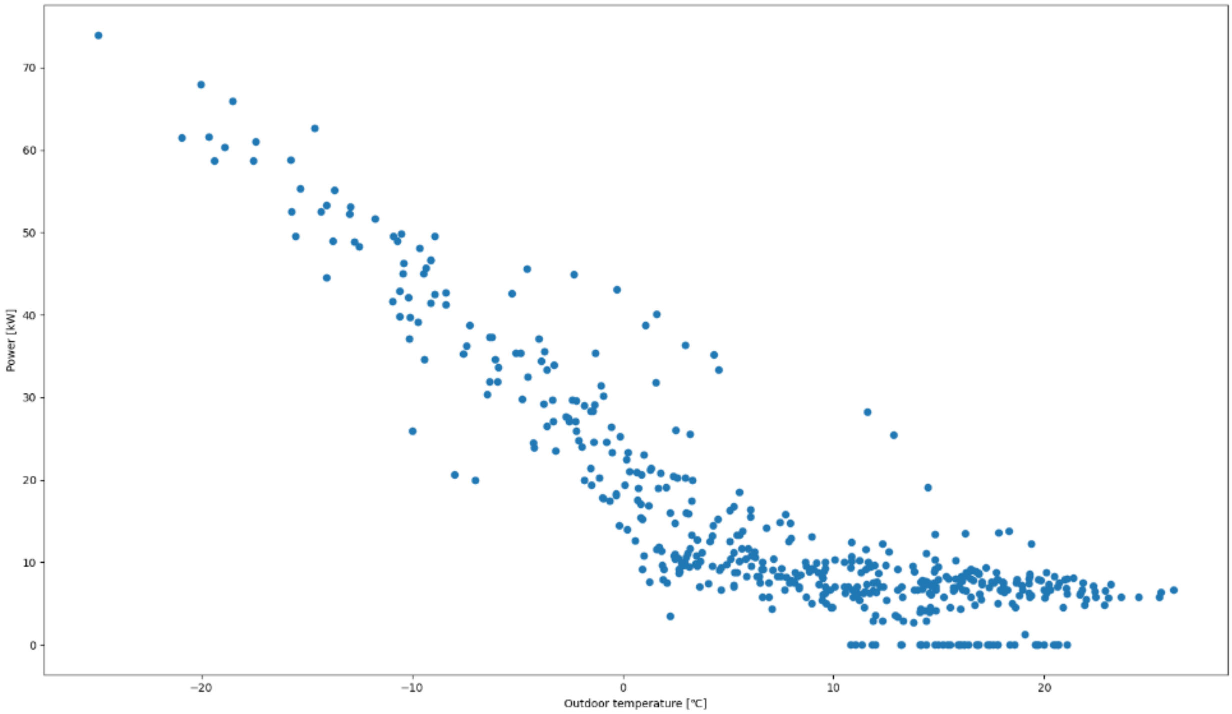


Figure 34: Daily average district heating power versus the outdoor temperature for Sivakka 1 building.

In this case, we estimated that no DH is required for space heating after 8.0 °C. After we remove data points at higher temperatures and apply the ES method (Figure 35), we get a line whose gradient is the heat loss coefficient of the building. For Sivakka 1, this parameter was estimated to be 1.976 kW/K. The H parameter is independent of the heat supply methods and can be thus estimated directly from the DH measurements using the ES method.

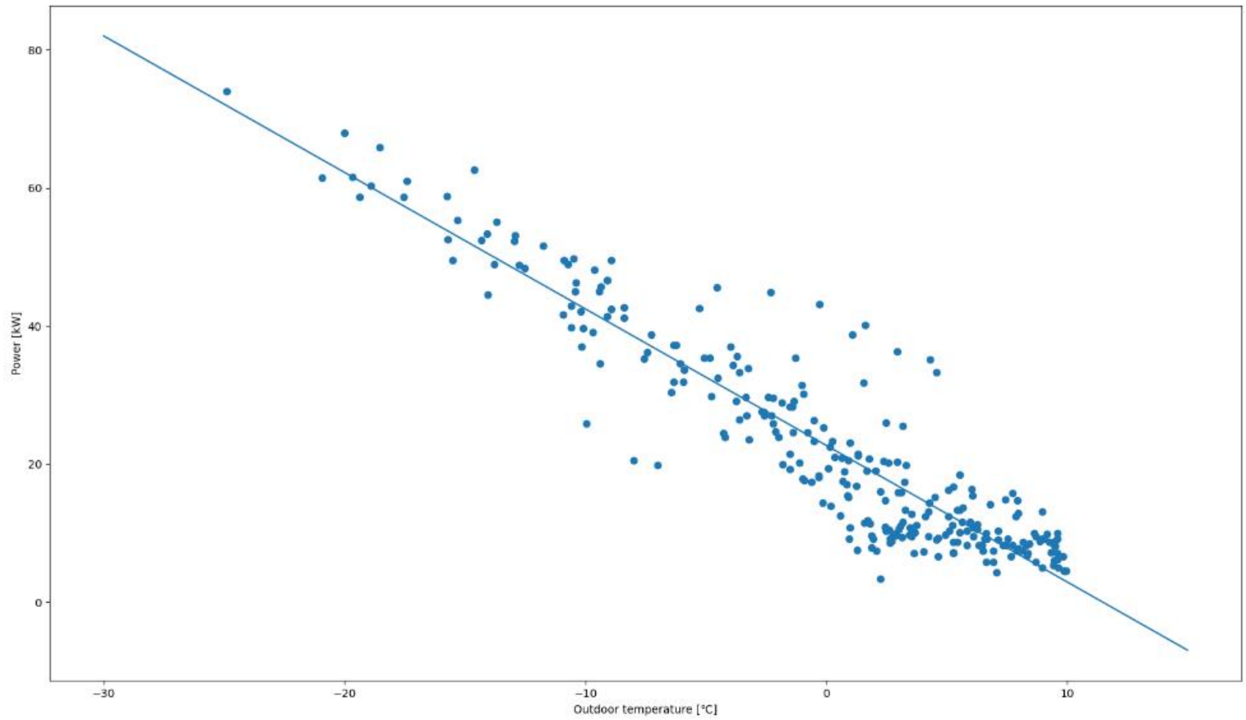


Figure 35: Energy signature method applied for the district heating measurements.

However, the fact that space heating and DHW is supplied also with a heat pump complicates the P_b parameter estimation needed to predict the total heat demand of the building. If measurements are available for the heat pump energy production the problem can be solved easily be adding together the DH and heat pump data. If there no separate measurements for the heat pump energy production are available, this problem can be solved as follows. First, estimate the temperature in which no space heating is required for the building (from electricity measurement data). Then correct the ES line fitted to the DH so that it gets value 0.0 kW at that temperature (original value is negative due to the heat pump). The new line represents the total energy demand of the building. For Sivakka building number 1, the outdoor temperature in which no space heating is required was identified to be 15.0 °C. Equation (3) specified the total heat demand of the building with respect to outdoor temperature.

$$P_{\text{heating}} = -1{,}976 \left[\frac{\text{kW}}{\text{C}^{\circ}}\right] * \text{T}_{\text{env}} + 29{,}6\ [\text{kW}] \quad (3)$$

5 Site-data Service

The Site-data Service is responsible for storing site-specific data, including energy and sensor measurements. Site-data Service consist of three components: Data Input Service, Data Output Service and a Database as presented in Figure 36.

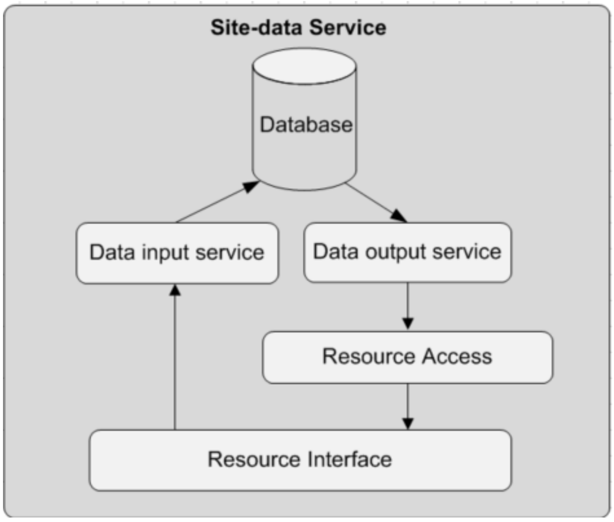


Figure 36. Site-data Service.

Data Input Service is responsible for ensuring that the format of incoming data is correct and there are no formal errors. If data is formally correct, the Data Input Service sends a new data packet into the Database. Data Output Service is responsible for ensuring that database queries are formally correct and that the query returns desired data from a database. Database Service is responsible for handling the database and its contents.

Each building do have similar Site-data Services, only content of the data varies between sites as shown in Figure 37.

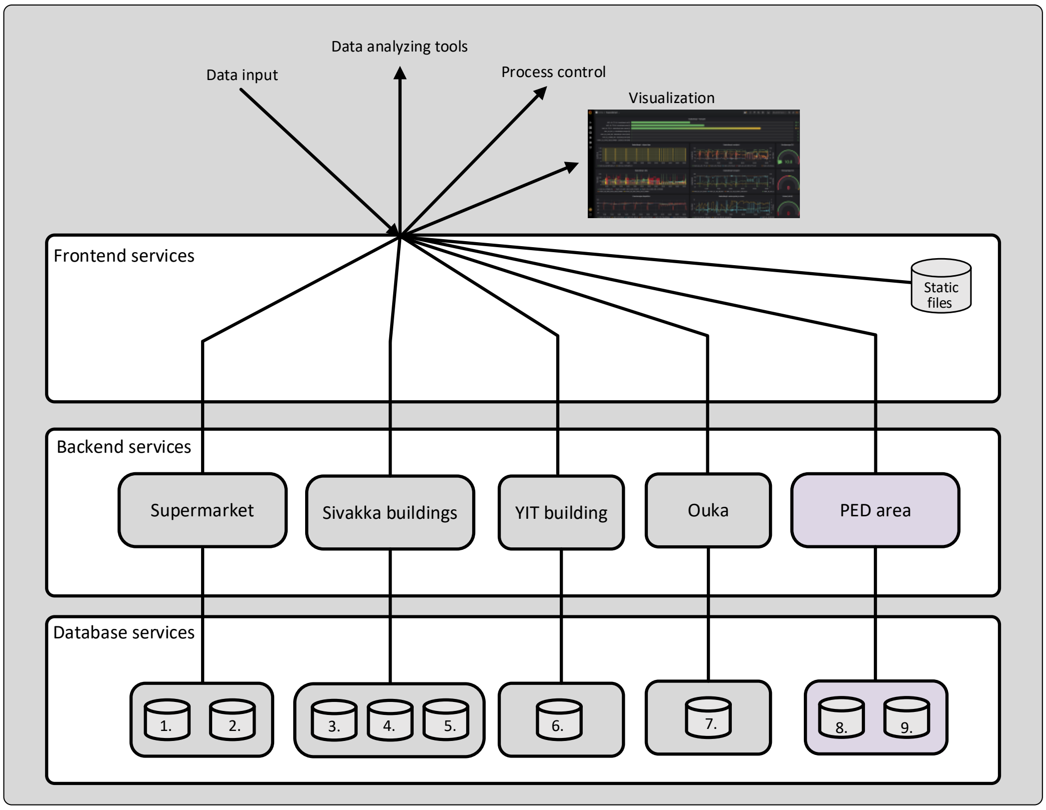


Figure 37. Data types by sites.

5.1.1 Supermarket

The supermarket database contains following data tables:

- Table 1: building automation and heating and cooling process data
- Table 2: energy data

5.1.2 Sivakka buildings

The Sivakka building database contains following data tables from all Sivakka's buildings:

- Table 3: heating system data
- Table 4: building automation data
- Table 5: apartments data (temperature, humidity, energy and water)

5.1.3 YIT building

- Table 6: heating system data

5.1.4 School building

- Table 7: heating system data

6 User interfaces

The user interface (Figure 38) is a web application accessed by the user through a web browser with an active internet connection. It is written with Responsive Web Design (RWD) approach. RWD enables one source code to be used in all devices, which simplifies software development.

Figure 38. Responsive Web Design approach.

The Home View (Figure 39) contains language selection, city-link at the center, surrounded by user login-link and links to solar page, grid page and environment page. City-link takes user to Positive Energy Districts -view, where different buildings can be accessed. Supermarket is the uppermost link titled “S-Arina”.

Figure 39. Main menu city-link takes to PED-view.

6.1 Supermarket monitoring interface

Supermarket monitoring interface (Figure 40 & Figure 41) contains 12 measuring targets, where power and energy consumption are measured and displayed with one-minute interval. Anonymous user can see only last 24 hours of measurement history, but logged-in user can select and view measurement history starting from 1 day (24 hours) up to 7 days.

Figure 40. Supermarket monitoring interface.

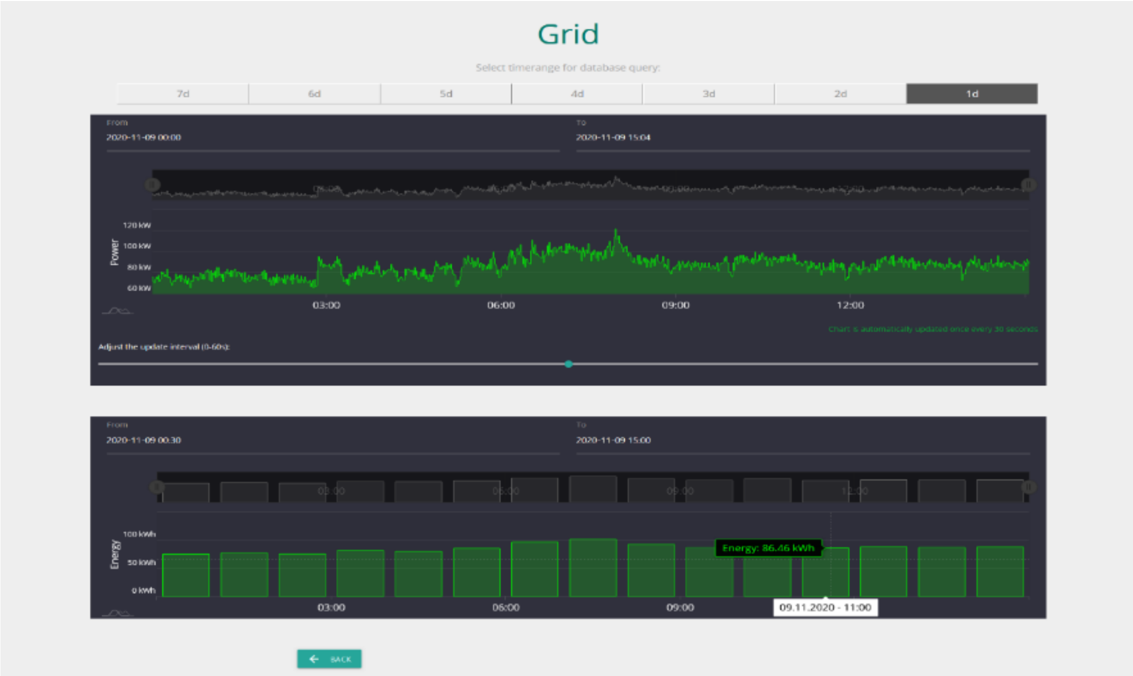


Figure 41. Supermarket grid power and energy during last 24 hours.

6.2 Sivakka1 monitoring interface

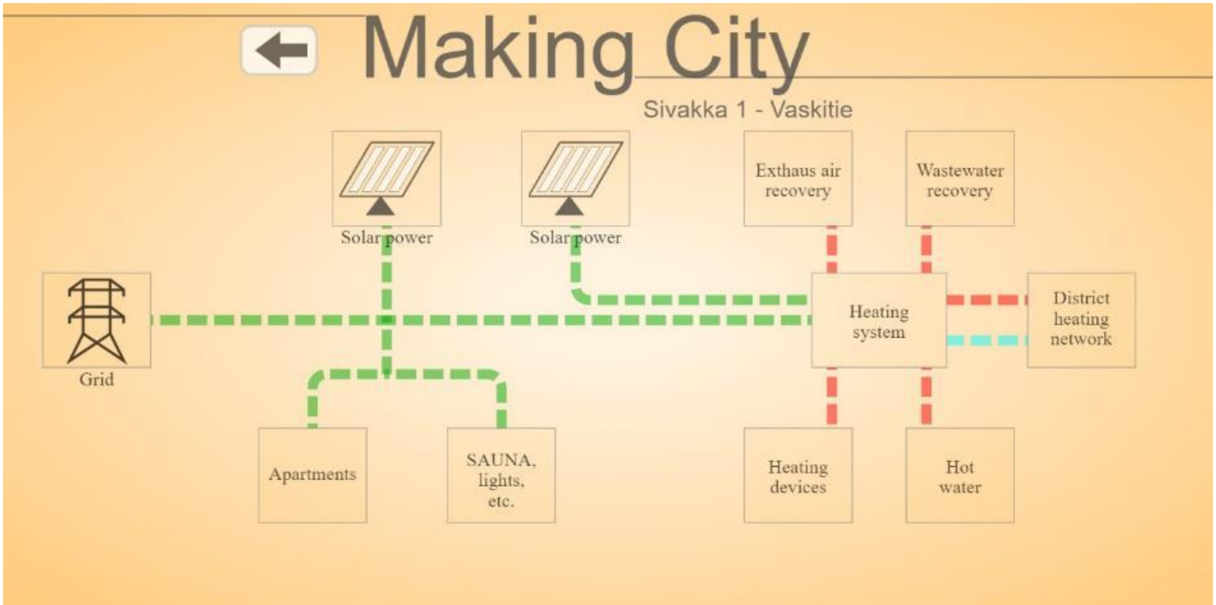


Figure 42. Sivakka 1 building monitoring interface.

6.3 YIT1 monitoring interface

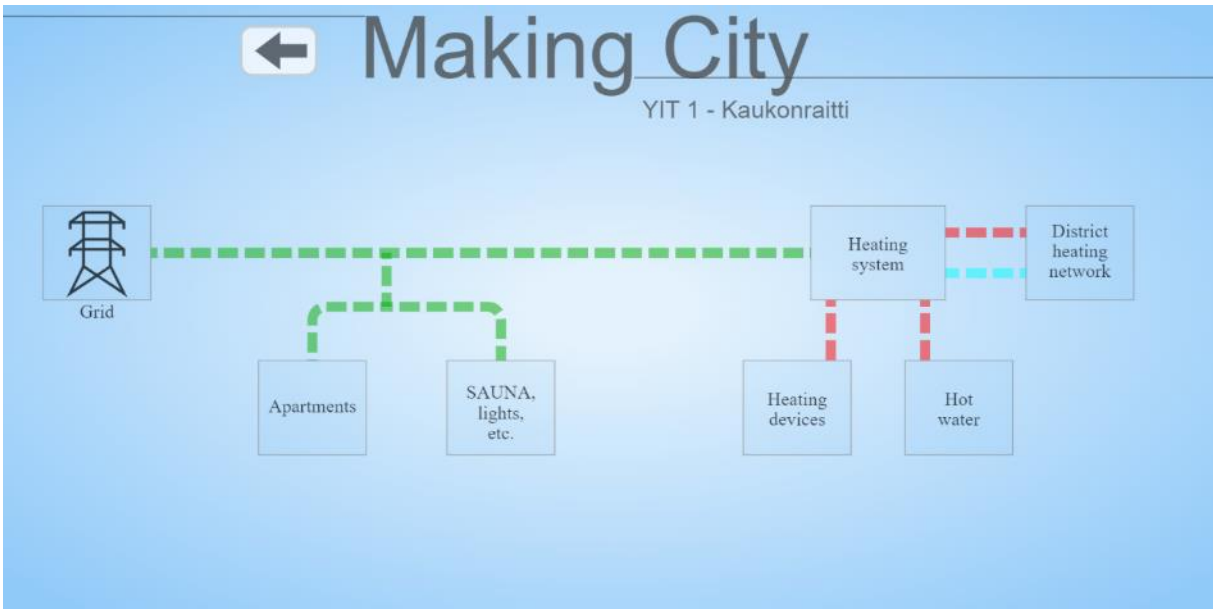


Figure 43. YIT 1 building monitoring interface.

6.4 Sivakka2 monitoring interface

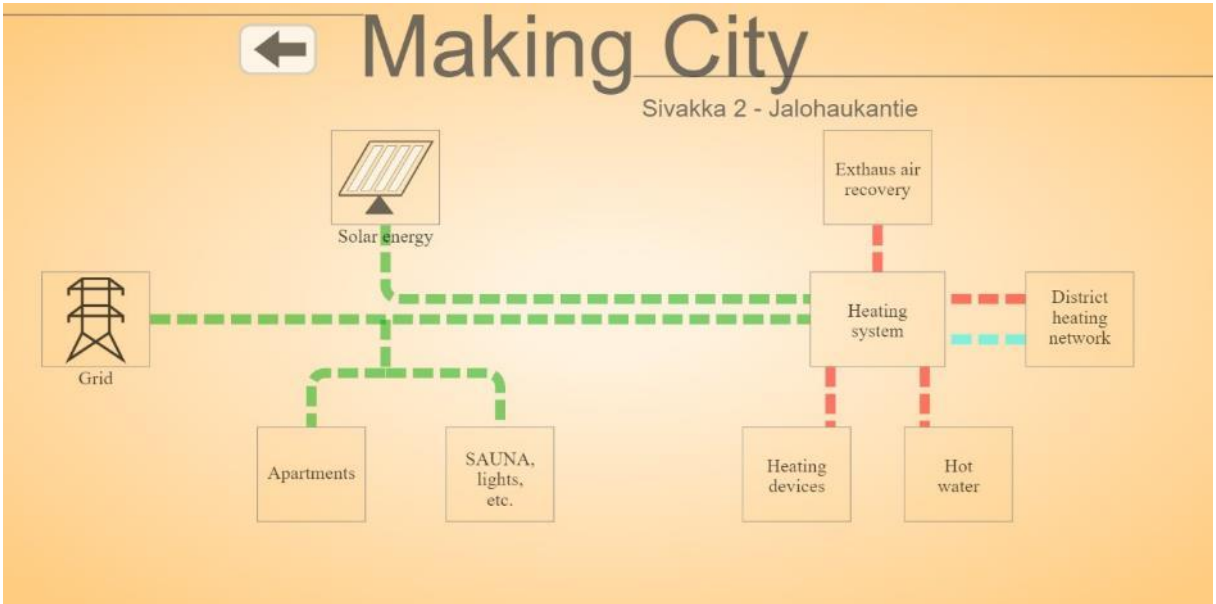


Figure 44. Sivakka 2 building monitoring interface.

6.5 Sivakka3 monitoring interface

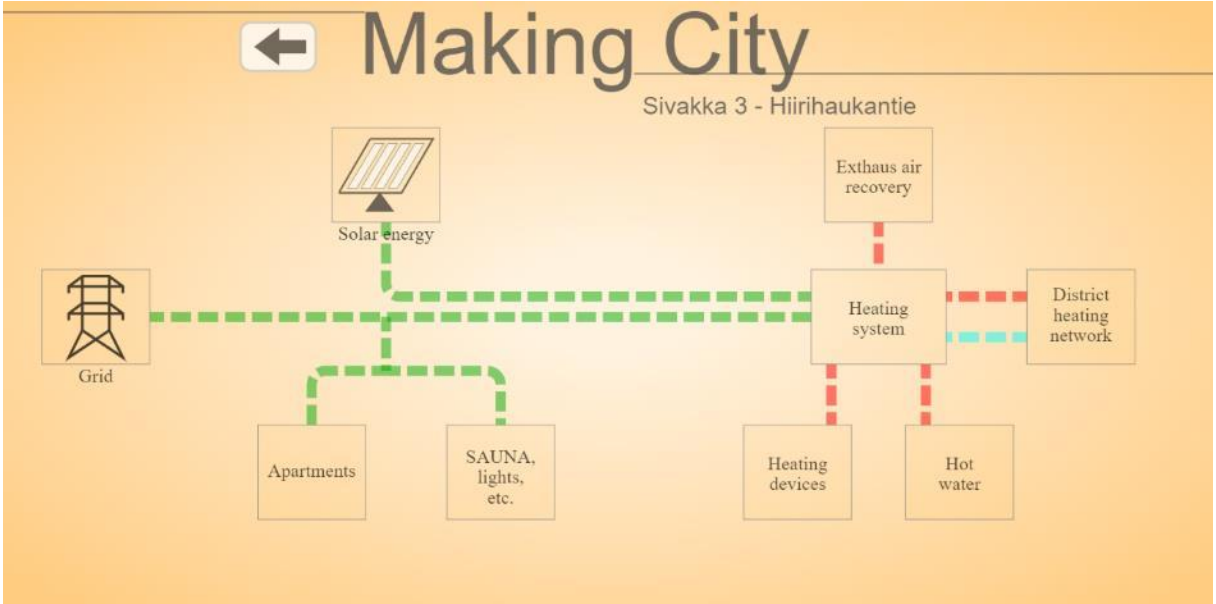


Figure 45. Sivakka 3 building monitoring interface.

6.6 School monitoring interface

Not ready yet.

6.7 User interface for system admins

The user interface has extended admin functionalities: a) Admins can list all Users and see (and modify) registration codes and read-key information. b) Admins can list all registration codes and generate new codes.

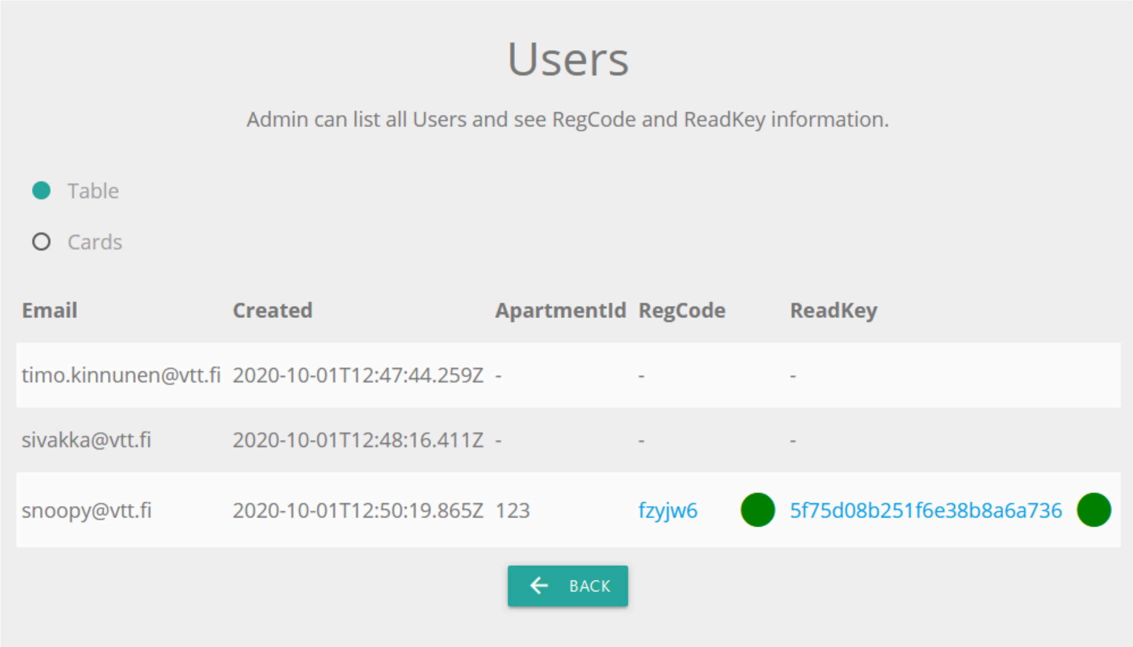


Figure 46. Admin can list and modify users' access to apartment data.

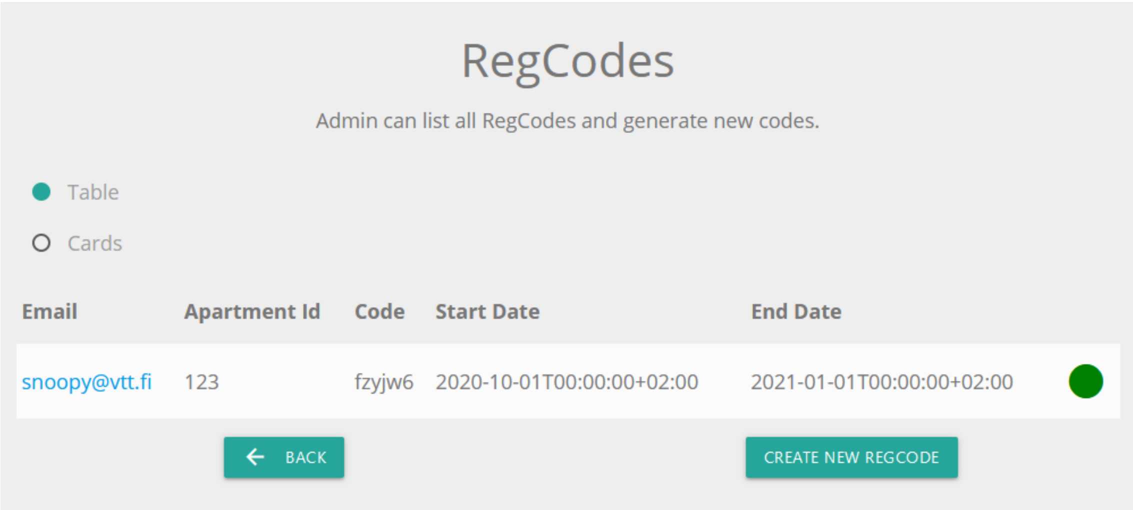


Figure 47. Admin can list all registration codes and create new ones.

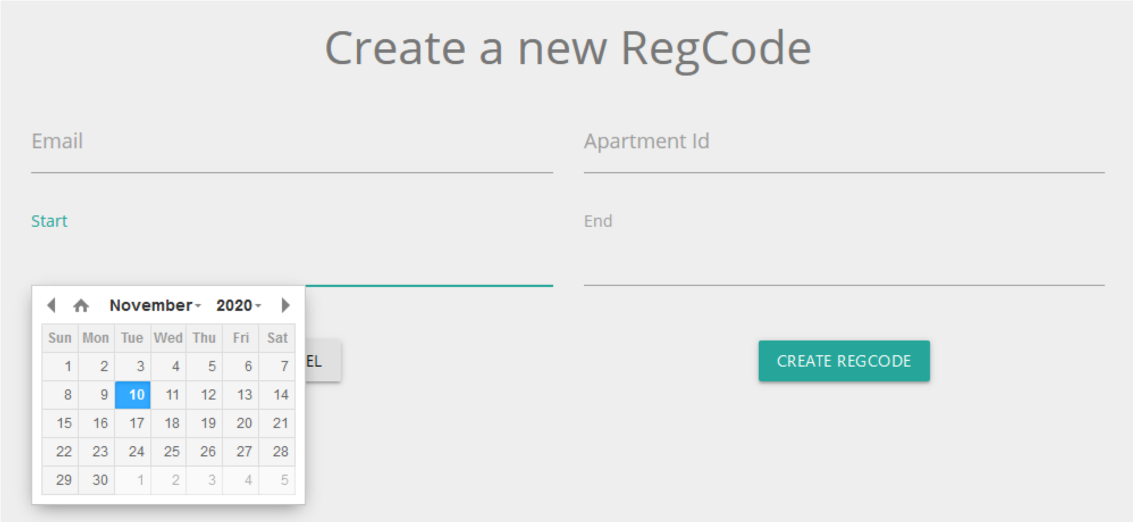


Figure 48. Admin creates a new registration code.

6.8 User interface for residents

The residents get access to their own apartment data through registering process:

1. Owner of the apartment (landlord) sends resident information (email address, start date and apartment address) to MAKING-CITY Admin.

2. Admin creates a new registration code for resident (Apartment ID is our internal ID, which is linked to actual apartment address and sensor data) including start and end dates. Dates represent timeframe when registration code is valid and can be used. Usually end date is not known beforehand so it can be set to one year or two years into the future. Admin can change dates anytime if needed.

3. Registration code is sent to resident.

4. Resident signs up from Signup form, by giving their email address, registration code and creating a new personal password. This is the step where the User is created.

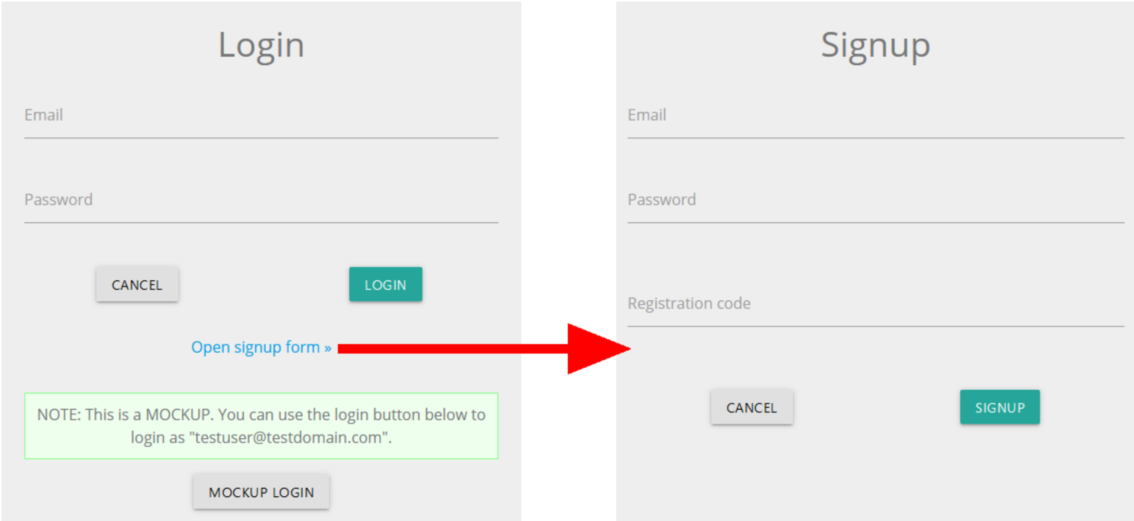


Figure 49. User Signup using registration code.

The signup process creates a new user with associated read-key User database. Each user has a unique read-key, which has same start and end dates as registration code. These "data-request-validation" - dates can be modified by the Admin and they are used to restrict access to apartment data in cases where for example user moves out from apartment and new resident moves in.

After Signup process, user can log into system and view his/her own properties, electricity consumption, water consumption and heating information. The values for electricity and water are total consumption for last 24 hours, but for heating we show the latest temperature and humidity.

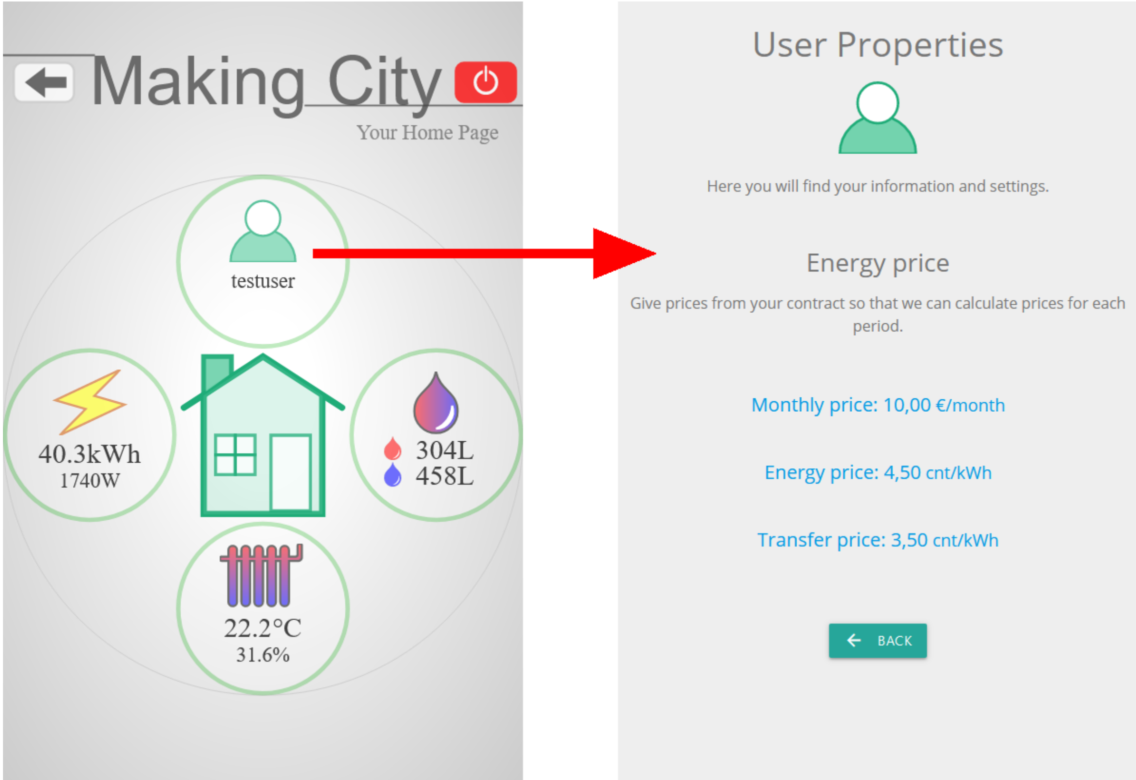


Figure 50. User Home Page and User Properties.

Currently we are using three different parameters to calculate energy price, user can modify each to reflect his/her own electricity contract.

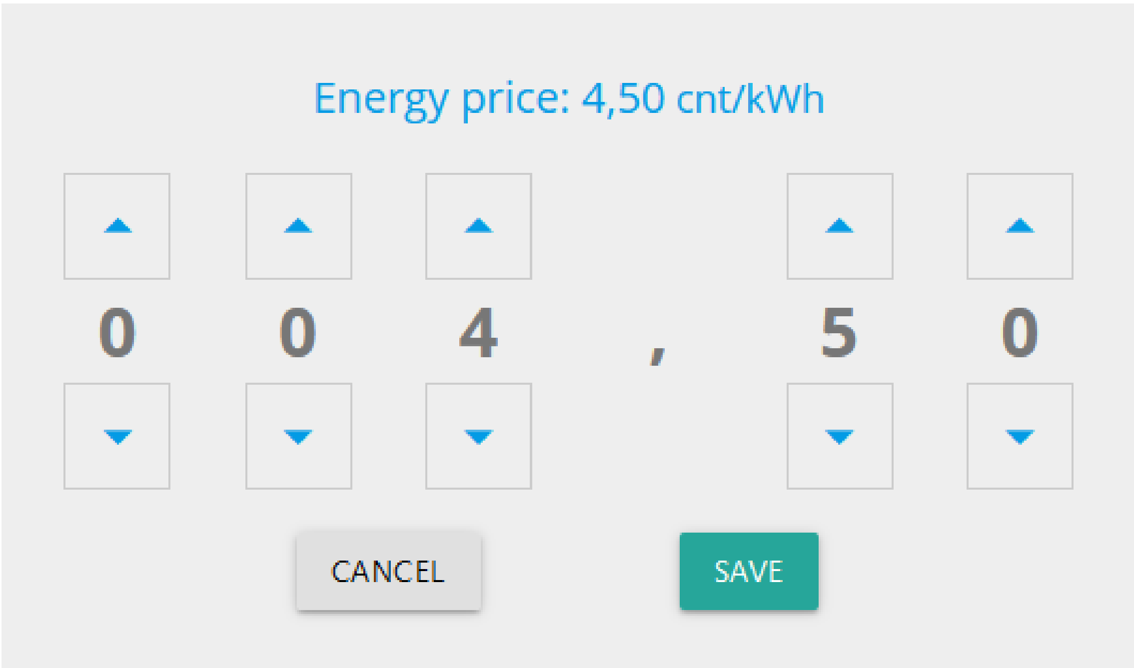


Figure 51. Edit prices to reflect your contract.

Using energy price information given by the user, electricity view sums up consumption and actual spending for three different periods: last 24 hours, last 7 days and last month.

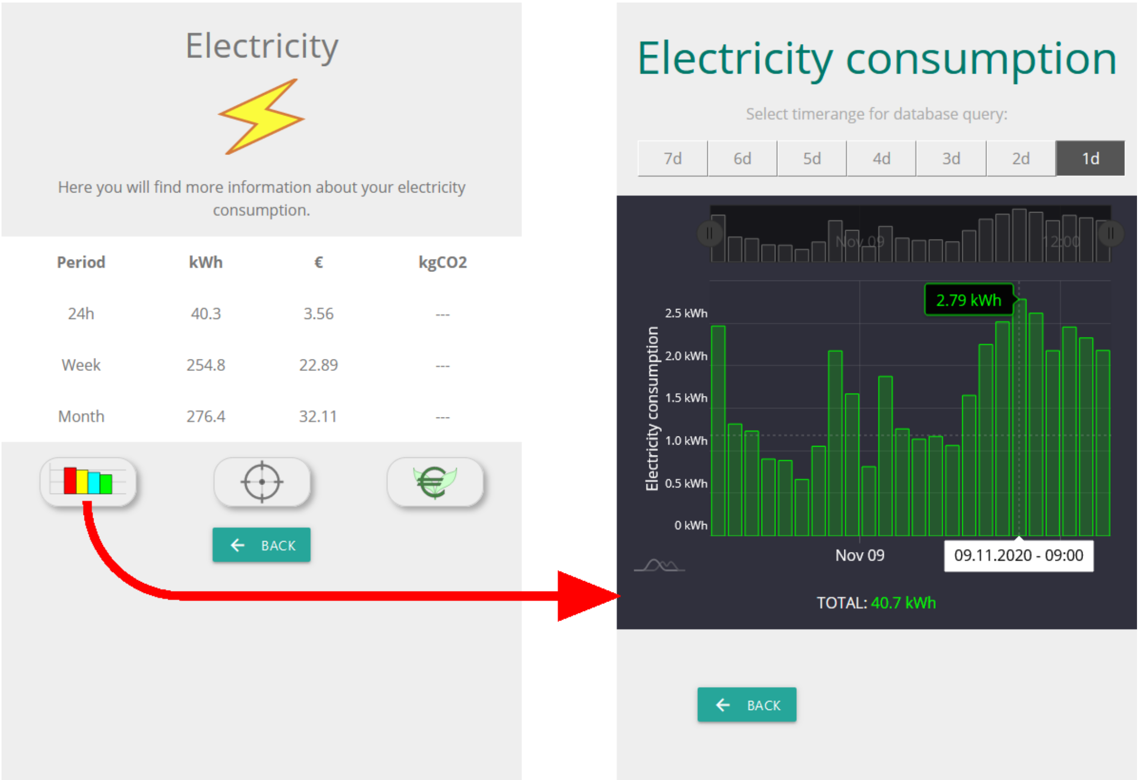


Figure 52. User electricity consumption.

Water consumption is reported separately for hot and cold water for three different periods: last 24 hours, last 7 days and last month. A more detailed line chart is also available, where user can select time range from 1 to 7 days.

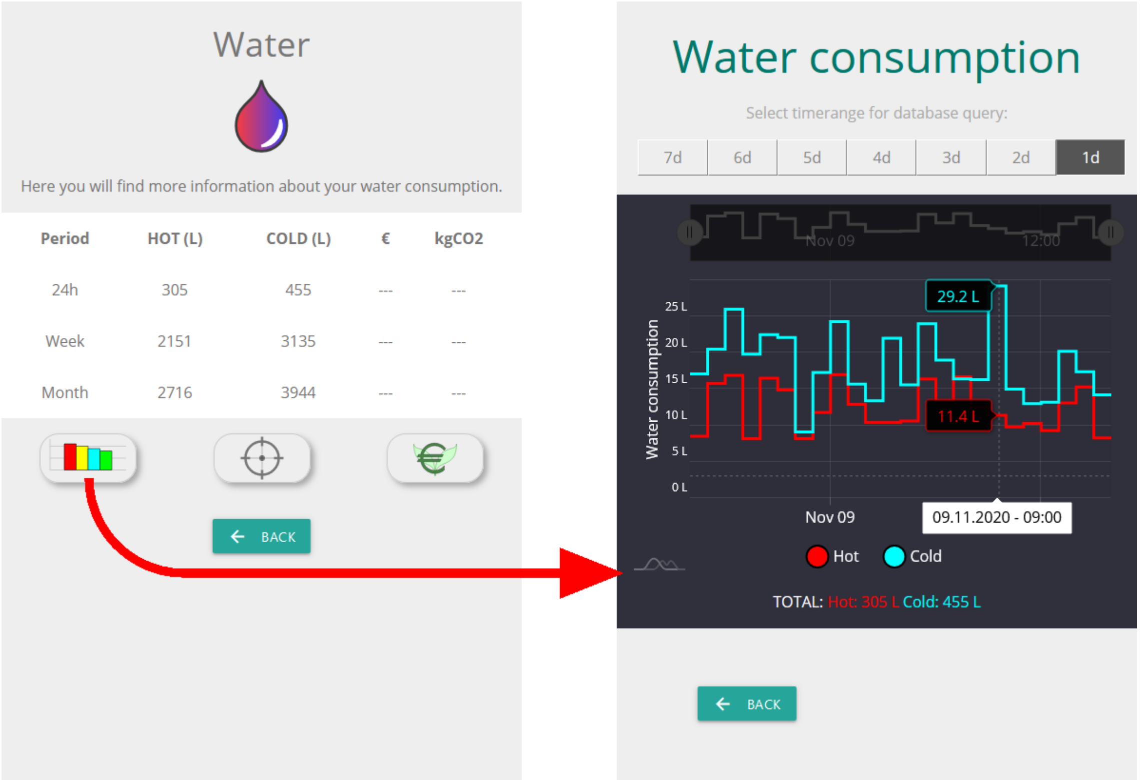


Figure 53. User water consumption.

Heating measurement contains temperature and humidity for three different periods: last 24 hours, last 7 days and last month. A more detailed line chart is also available, where user can select time range from 1 to 7 days.

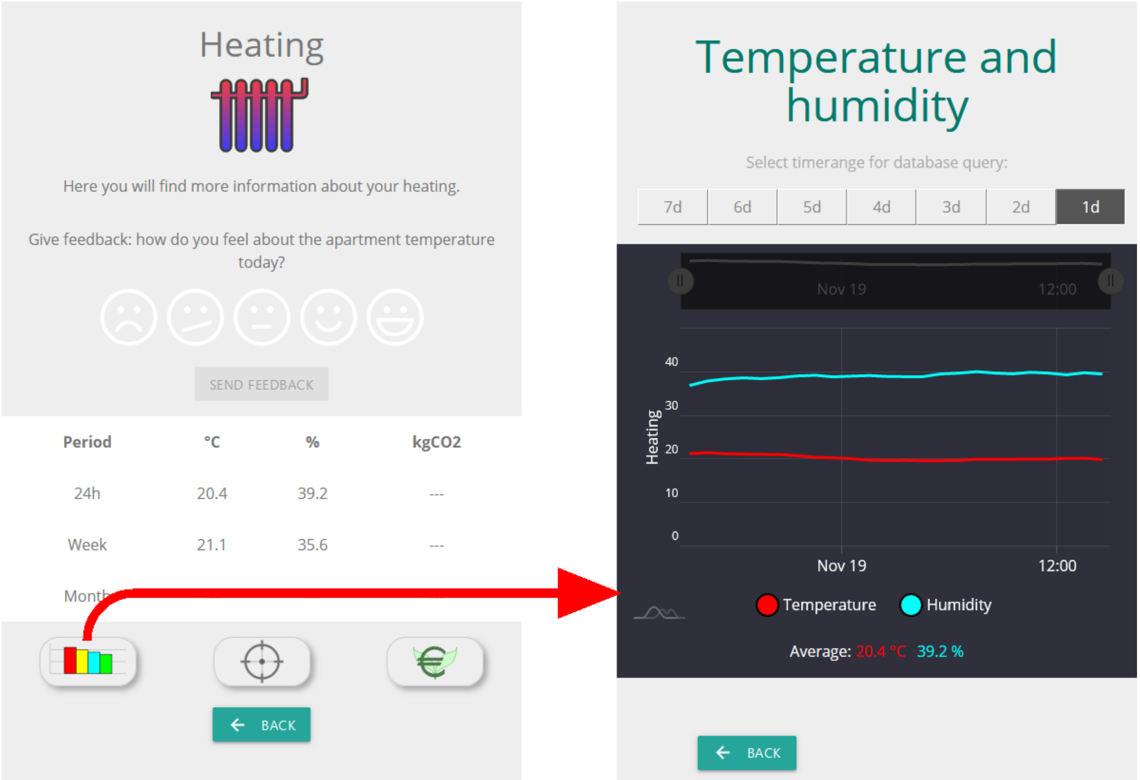


Figure 54. Apartment heating.

The resident can send feedback about apartment temperature anytime by clicking a five-level smiley and send-button. All feedbacks are stored into database with timestamp, so it is possible to show also a timeline chart about residents' satisfaction.

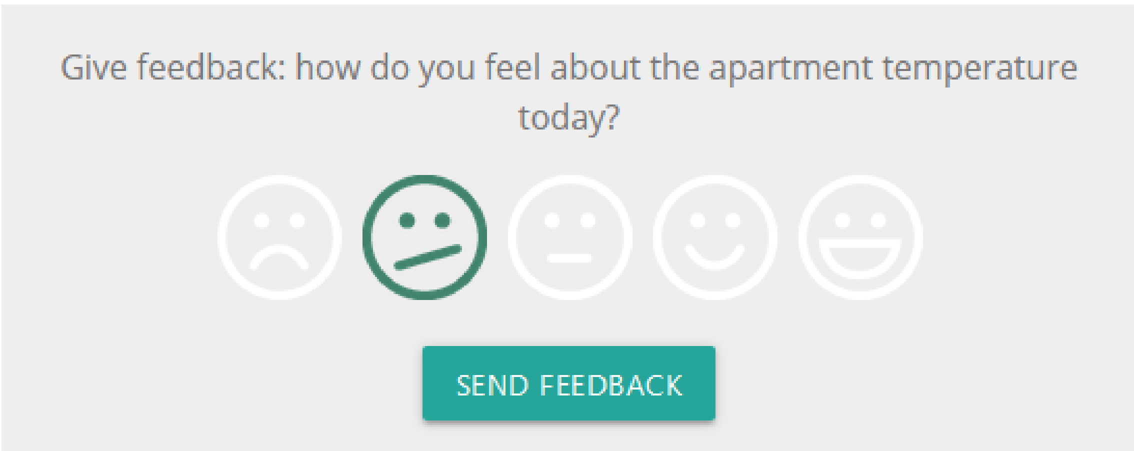


Figure 55. Apartment heating feedback.

7 Latent heat thermal energy storage in the local market

Encapsulated phase change materials (PCM) were ordered from Axiotherm GmbH which have a working temperature of 84 °C. This was coupled with a custom-ordered water tank that has metal plates inside dividing it into four sections with maintenance lids to increase the flow distance of the HTF. Theory and basic calculations are in delivery 2.3.

In order to try to optimize the energy production to DH-network in the market, thermal storage was installed in the technical room to provide energy storage for the DH-energy production downtimes. These downtimes can occur when the DH network requests momentarily higher temperatures than the market can provide. Such times can occur during the spring and autumn time when outside temperature decreases increasing the DH network required temperature for a short time. However, daily downtimes occur often due to recharge of domestic hot water tank (DHWT), which halts the production to DH network to ensure the heat for the DHWT. Preliminary tests were done with the installed TES without PCM capsules in the storage tank to give some idea regarding the function of sensible heat storage in the DH energy production system. The thermal storage tank was heated up to 98 °C until the heat has stabilized in all of the levels in the tank. Then energy was dissipated to DH-network with permission from the energy company to decrease the temperature of the water in the tank down to 40 °C. From the energy meters, the amount of energy stored and discharged could be seen. The temperature was also logged from numerous sensors in the tank.

A heating and cooling test was made with water in the tank (Figure 57) to have a baseline for the test coming with the encapsulated PCMs inserted in the tank. Calculations were done as 60 °C as the lowest point. Data is available down to 40 °C.

At the beginning of May 2021, the water tank was separated from the system manually with valves to ensure that hot water is not fed into the tank while its maintenance lids are open. The tank was emptied and opened. Using metal rods, the material capsules were stacked in the tank (Figure 56). The decision to use metal rods to keep the capsules in straight columns is related to the known poor heat conduction properties of the PCMs in the literature. This was to allow better even flow of water through the tank and thus increasing heat conduction properties.

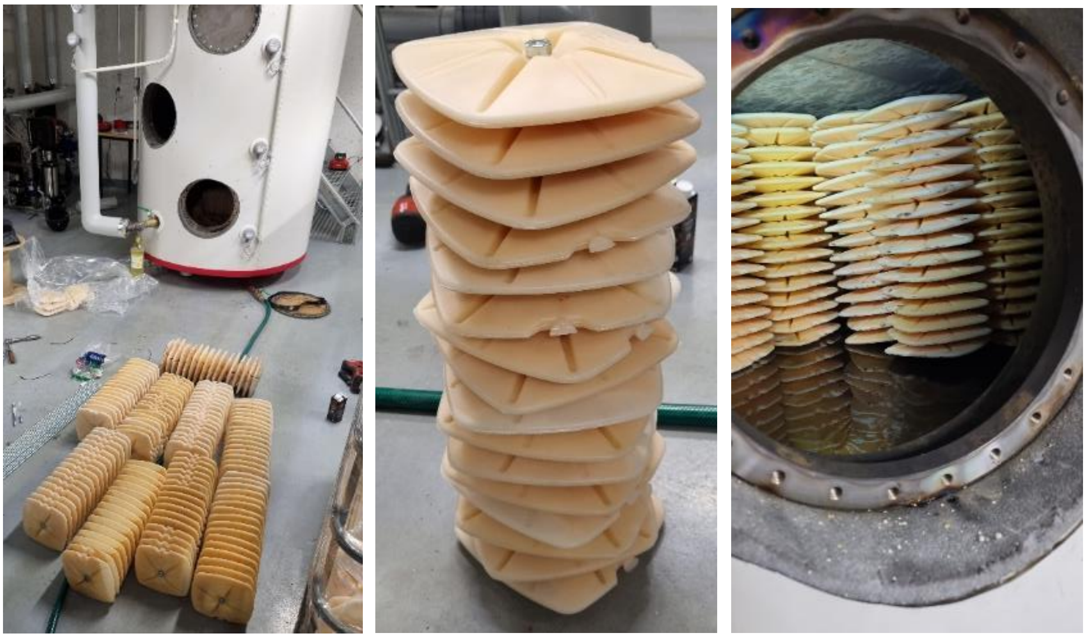


Figure 56. ATS84 encapsulated PCMs stacked and inserted into the tank in each four section

With a half-days work, PCMs were inserted, and lids were closed. As the tank was filled with water a normal operation could resume. Due to the encapsulation material being plastic, the company mentioned the maximum operating temperature for the capsules to be 100 °C. This needed to be considered while warming up the PCM-filled thermal storage tank since the temperature of the CO_2 line can be high as 115 °C occasionally.

With the PCMs inside the tank, a charging and cooling test from 40 °C to 99 °C was done. As with the water test, data was processed between 60 ° and 99 °C. The temperature curve of the LHTES charge and discharge test is presented in Figure 57. In both cases, when the temperature of the TES reached a certain point to be able to produce energy to the DH network the heat exchanger in the DH network was turned on (Figure 59). This was made to enable production to DH network and to keep the temperature of the TES below 100 °C since the manufacturer of the PCMs did not promise the capsules to withstand higher temperatures. This slowed down the charging process. The change in the charging curve of only water in Figure 57 is due to the start of DH energy production. This curve happens later with PCMs present most likely due to PCMs absorbing thermal energy thus slowing the increase of temperature of the water.

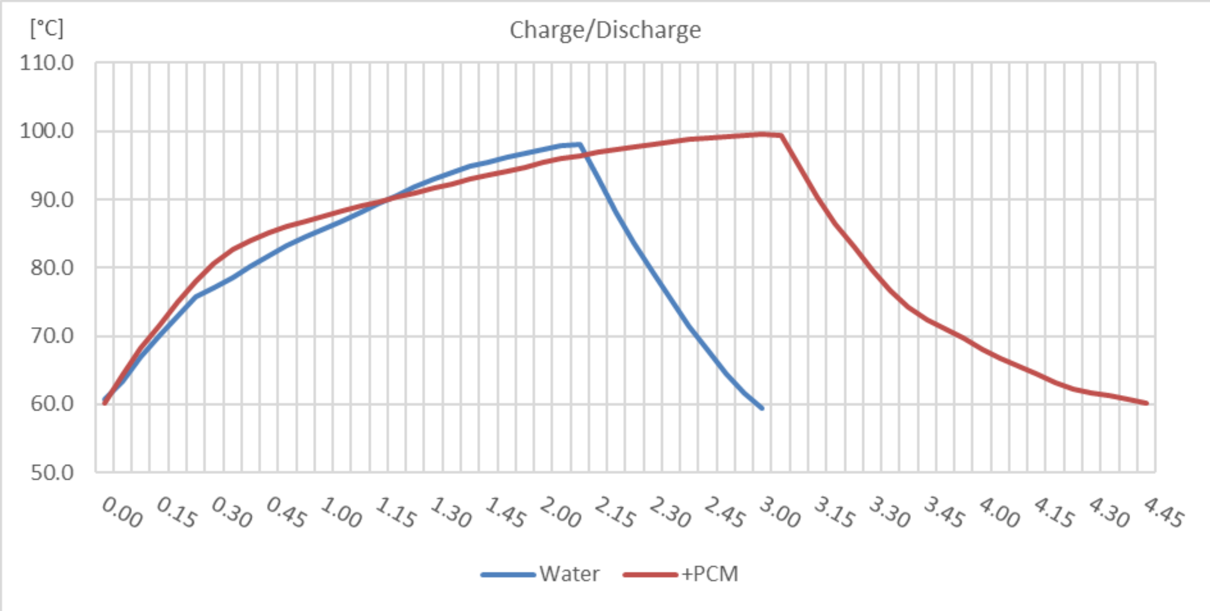


Figure 57. Measured temperatures of charging and discharging LHTES before inserting PCMs and after. Time on the x-axis as h.min.

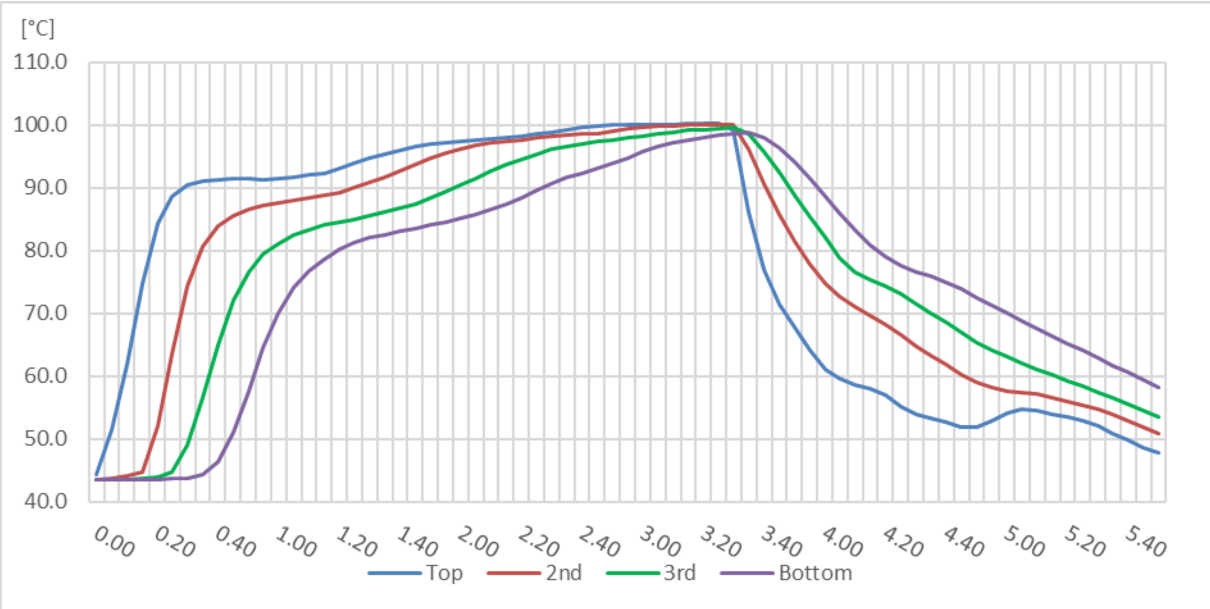


Figure 58. LHTES temperature measurements on every four sections. PCM capsules are in the tank. Time on the x-axis as h.min.

Figure 58 is more detailed temperature measurements from every four compartments in the LHTES with encapsulated PCMs present. PCMs absorbing energy can be seen from the change in temperature curves after 85 °C is passed. The DH network heat exchanger starts to function when the temperature of the top compartment is around 99.5 °C meaning that its being in function is not the cause of change in temperature curve. Energies measured from the charging and discharging are presented in Table 5 at results.

To see the functioning of the thermal storage, tests were done with the system operating as intended, where the flow of hot water was fed through the PCM thermal storage tank, while the temperature is set to a certain range unaffected by the outdoor temperature. This was necessary since outdoor temperature decreased occasionally below 0 °C during the nights and increased to 8 °C during the day meaning that DH-networks required heat quality varied meaning that static tests were impossible. These tests caused cooler water to be fed into the DH network however, the energy quantity is low meaning that it does not affect the overall temperature of the DH network and Oulun Energia Company was aware of these tests.

DH temperatures for the tests were 70, 75, and 80 °C, and flow was directed through the tank and in other tests tank was bypassed to compare the effectiveness of the storage.

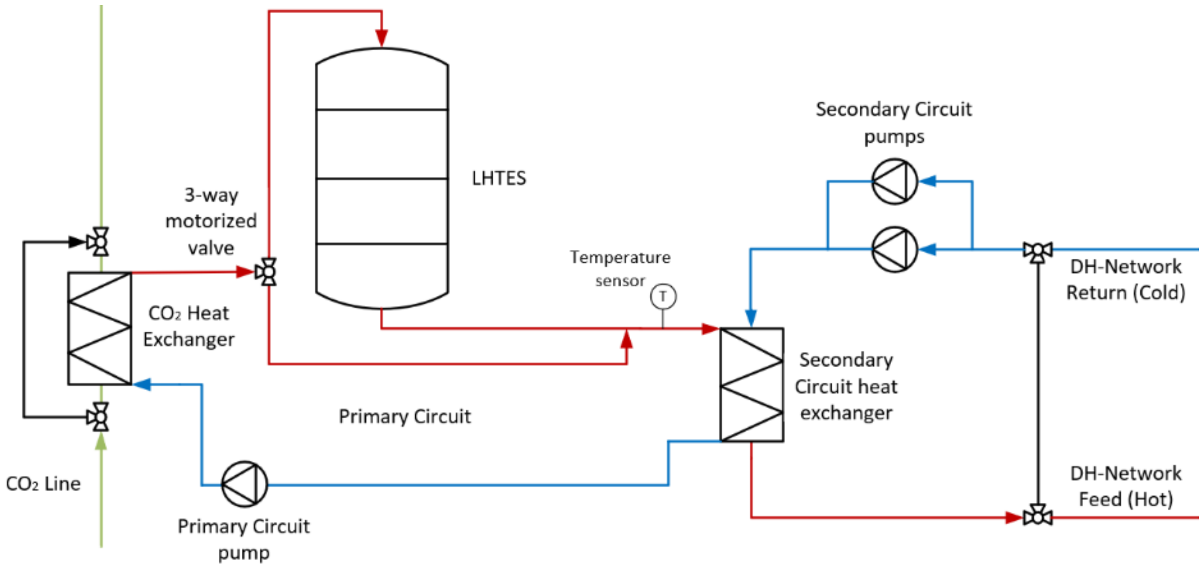


Figure 59. LHTES system diagram from the market machine room, green line: CO_2 line from compressors, red line: hot water line, blue line: cold water line.

7.1 Tests with LHTES

Tests were done throughout the month and measured aspects of the system were the temperature of the LHTES tank and energy measurements from the CO_2 heat exchanger, secondary circuit, and DH-network circuit. To compare the effectiveness of the LHTES, the daily production of the energy into the DH network with standard temperature levels is measured and compared to daily operation where LHTES is bypassed. During the preliminary tests, it was concluded that the existence of a thermal storage tank in the circuit reduces the temperature of the FHT in the final heat exchanger in the DH network. For this reason, when LHTES is in use the required temperature from the CO_2 line is increased by 5 degrees. It is important that when looking into the effectiveness of the DH energy production the electricity consumption of the refrigeration machine is also taken into account as well as the amount of energy taken from the CO_2 line.

To ensure the production of the energy to the DH network, a 3-way valve was installed that can be used to direct the flow of water either to the thermal storage tank or bypass it directly to the DH heat exchanger. By comparing daily energy production while bypassing LHTES and using it, we can see how beneficial it is to have a thermal storage tank in this system.

DH-network's required temperature was fixed to a certain temperature to simulate the summer season conditions when DHs required temperature is at 70 °C. Additionally, to see the effect on energy production, the requested temperature by DH-network is also tried at 75 and 80 °C temperatures. During the first tests, the LHTES was bypassed meaning that it was not in use. With these same temperature levels, the bypass valve before the tank was turned so that the HTF is rerouted through LHTES, which also meant that heat taken from the CO_2 line would be 5 °C higher to counter the possible heat losses due to the storage tank.

Lastly, tests were done utilizing the 3-way valve for mixing before the LHTES, which can be seen in the system diagram (Figure 59). Since PCMs cannot be used to their full extent due to the higher temperature level in the system. When energy is taken from the LHTES, the top compartment in the tank gets cooled down to 65 – 70 °C meaning that PCMs start to release the stored energy. The second compartment also cools down, but the effect is lessened. At the bottom of the tank, the temperature is around 80 – 85 °C. If the tank would be conventional SHTES the cold-water pulse would come out of the tank after a certain time, but due to PCMs present the water pulse gets mitigated by the release of energy from the capsules. The idea of using the motorized 3-way valve is to try to dimmish the cold-water pulses from the usage of the TES by using the PCMs energy in the tank. Valve is controlled by the temperature sensor before the DH network heat exchanger. Temperature is set to be high enough for the DH network requirement. After the use of LHTES during the domestic hot water tank (DHWT) recharge, part of the flow goes through the LHTES while the other part bypasses the LHTES to provide high-temperature fluid to the DH network heat exchanger. Flow to LHTES is needed to recharge the energy reserves while PCMs are heating the water from the "cold pulse" from the DHWT charging time. To see the effect of the PCMs it was tried to increase the time of the charging of DHWT by increasing the set temperature from 60 °C to 65 °C. Idea was to get LHTES down to cooler temperatures to see if PCMs increase the produced energy to the DH network.

7.2 Results

Firstly, preliminary results from the charging and discharging test are presented in Table 5. The most important aspects are the energy content of the TES and charged energy amount to the DH network. To achieve full discharge, these energy quantities must be close to each other.

Table 5 Stored energy contents from calculating the energy content and reading measurements from energy meters. Calculations with different temperature differences of 40 and 50 °C.

ΔT 40 °C	Stored energy [kWh]	Discharged energy [kWh]	Energy differences
TES with Water [kWh]	86.6	82.8	4 %
TES with PCM [kWh]	114.9	102.6	11 %

ΔT 50 °C	Stored energy [kWh]	Discharged energy [kWh]	Energy differences
TES with Water [kWh]	111.6	107.7	3 %
TES with PCM [kWh]	133.5	127.2	5 %

When looking at the 40 °C temperature difference in charge and discharge with the water test, the difference with energies is about 4 % while a tank filled with PCM has an energy difference of 11 %. When data is examined on 50 °C temperature difference it can be seen that energy differences between stored and discharged quantities are close to each other.

After multiple days of testing the results were compiled to Table 6 and visualized in Figure 60. Data for the measurements were taken in a daily range so data can be compared. DH-network's requested temperature was fixed to set the value to give consistent data for each measured temperature level. Temperatures were 70, 75, and 80 °C, and these temperatures were chosen to simulate the spring, summer, and autumn times when DH-networks temperature is between 70 to 80 °C and input of excess heat from refrigeration machine is possible. Total consumed energy is the total that refrigeration machine consumes electricity. Meaning that cold appliances' needs are met and markets heating needs are satisfied with this electricity amount.

Table 6 Comparisons of daily energies produced to DH-network and how much was taken from the CO_2 line. Total consumed energy is measured energy of refrigeration machine.

LHTES bypassed	70 °C	75 °C	80 °C
CO_2 heat exchanger [kWh]	1590.8	1594.1	1416.0
Produced energy to DH [kWh]	1450.4	1448.4	1223.2
Total Consumed electricity [kWh]	1158.4	1158.0	1158.0

LHTES in use	70 °C	75 °C	80 °C
CO_2 heat exchanger [kWh]	1668.8	1587.9	1370.5
Produced energy to DH [kWh]	1499.8	1403.0	1211.2
Total Consumed electricity [kWh]	1200.8	1202.1	1160.8

Table 7 Using the 3-way valve to control temperature before DH network heat exchanger. DHWT is set to a higher set point temperature from 60 °C to 65 °C to see If LHTES is more effective.

Domestic hot water tank temp 65 °C	DH set 70 °C
CO_2 heat exchanger [kWh]	1605.5
Produced energy to DH [kWh]	1444.9
Total Consumed electricity [kWh]	1282.9

Domestic hot water tank temp 60 °C	DH set 70 °C
CO_2 heat exchanger [kWh]	1695.1
Produced energy to DH [kWh]	1494.7
Total Consumed electricity [kWh]	1287.7

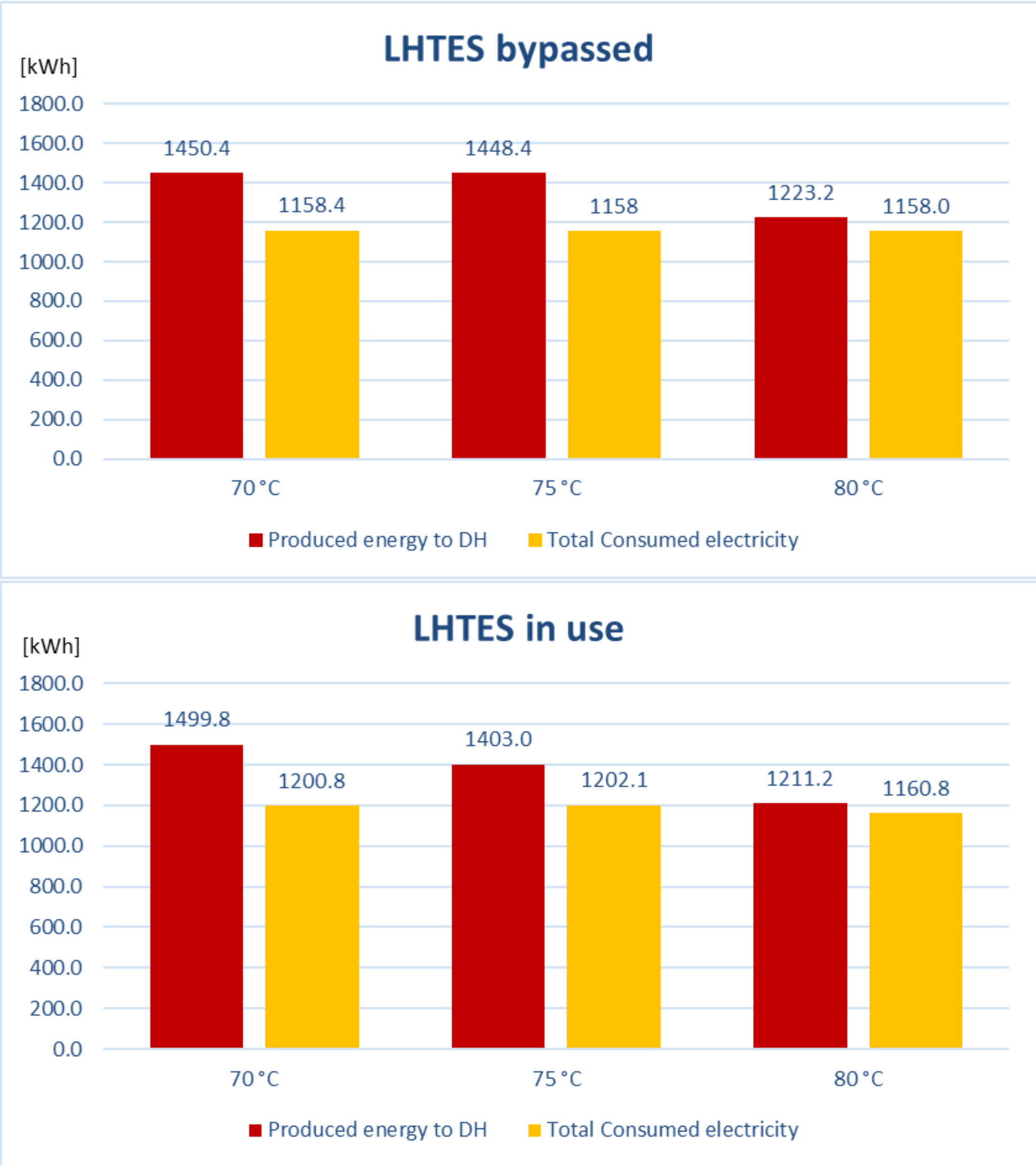


Figure 60. Produced energy to DH-network with and without LHTES. Total consumed energy for the refrigeration machine.

7.3 Discussion

In preliminary charging and discharging tests it can be seen (Table 5) that most of the stored energy is released from the TES in both cases. Small discrepancies with stored energy and released energy amounts can be thought to be from some measurement error from the energy meters but are mostly from heat losses of the system. When looking at data with a 40 °C temperature difference, energy discharged from the TES or produced to the DH network is lower than the stored energy amount. This most likely means that there is still energy left in the LHTES in the encapsulated PCMs. When data examination is extended to a 50 °C temperature difference, the stored energy amount is closer to produced energy amount to the DH network meaning that PCMs have released most of their energy.

This could be interpreted that due to known poor heat conduction of the PCM, a larger temperature difference of HTF is needed to fully utilize the energy stored in the PCM.

From later DH energy production tests, daily energy production amounts to DH-network are not significantly improved with LHTES compared to a bypassed system without it. Market's best production periods are thought to be summertime when DH networks temperature is at its lowest and most cooling is needed for the cold appliances meaning that refrigeration machine is running with higher capacity. For this reason, inspecting the production to 70 °C DH temperature level is most meaningful. Without TES in the system, the DH energy production is halted multiple times a day to ensure a hot domestic hot water supply (

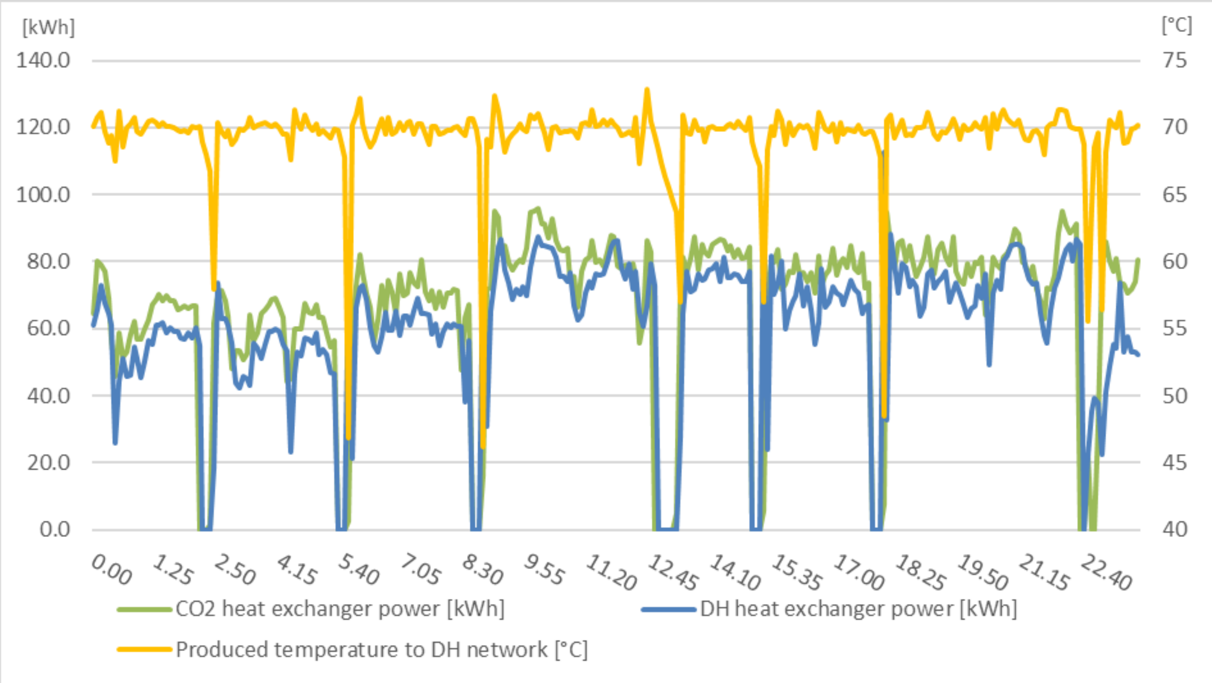


Figure 61). Data is taken from the measurements in the market's system.

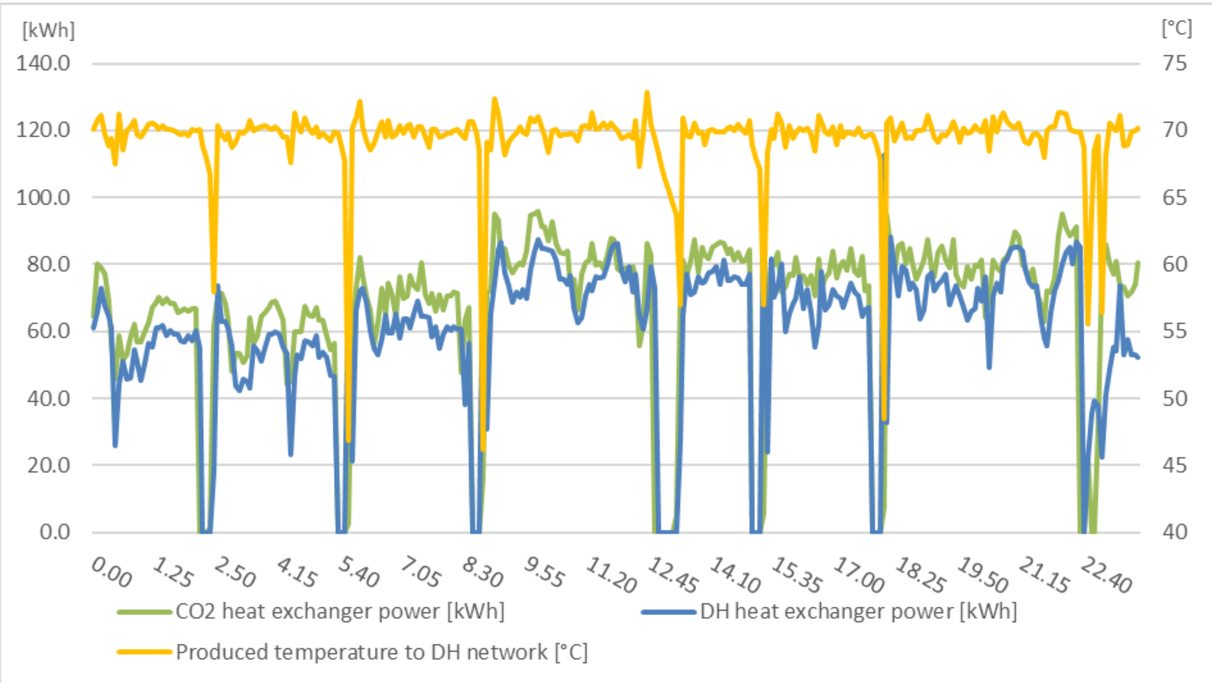


Figure 61. Power from the CO_2 line and power to DH network while LHTES is bypassed. DH network demand set to 70 °C. Time in h.min in the x-axis.

During the short time of 10 - 20 min, the domestic hot water tank is warmed up to a set temperature of 60 °C. This occurs multiple times a day in which the DH production halts. These recharge moments can be seen in

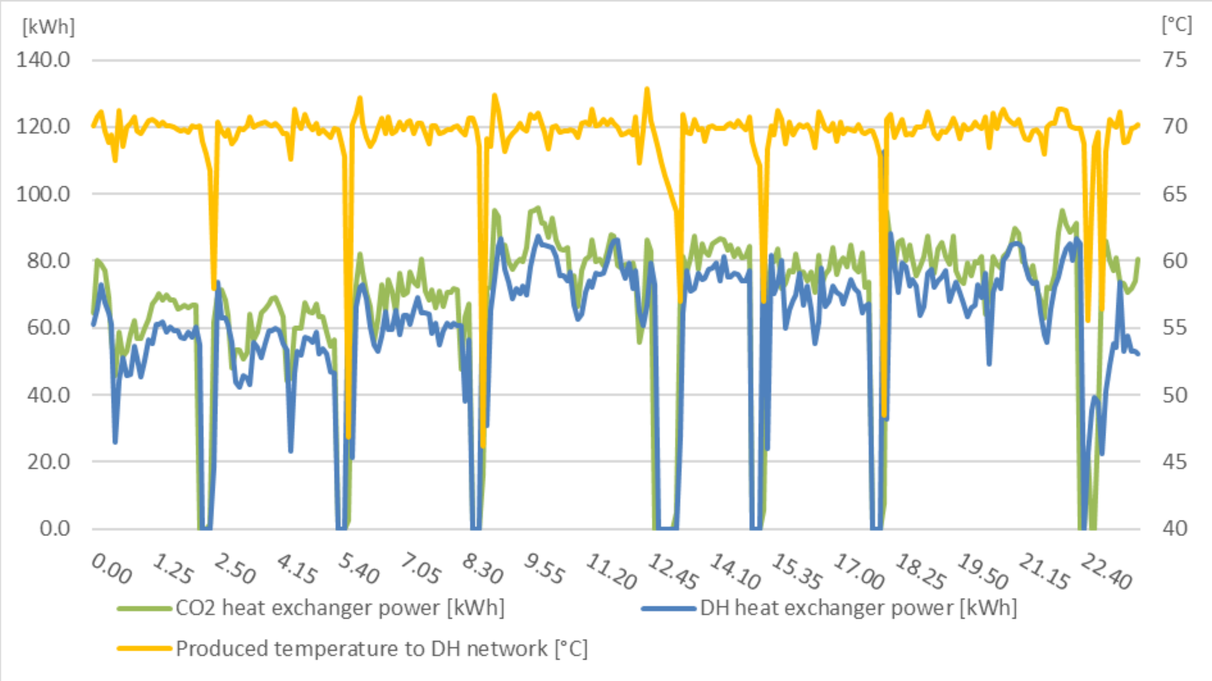


Figure 61 when DH heat exchanger and CO_2 heat exchanger energy decreases to zero.

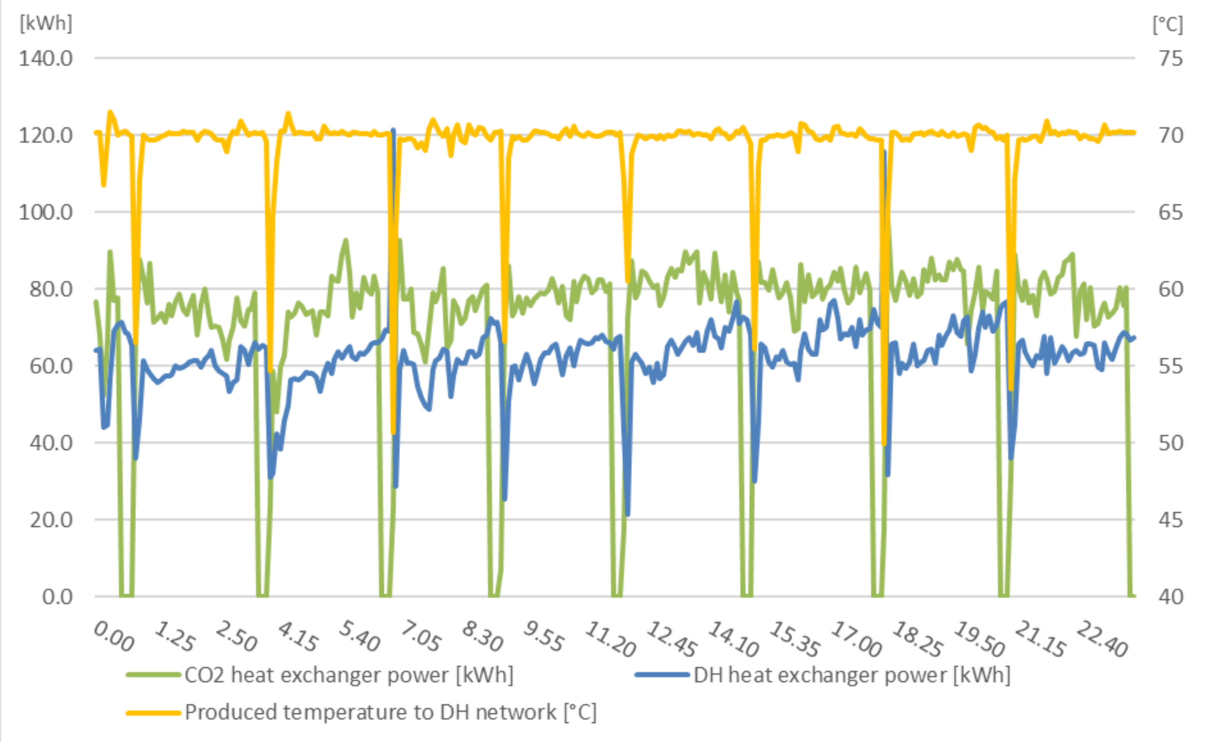


Figure 63 shows the DH heat exchanger energy while LHTES is in use. Similar domestic hot water recharge moments can be seen from the graph but during those times, the energy is taken from the LHTES providing a more stable production throughout the day. However, due to the nature of TES, it must be recharged (Figure 62) after it releases energy meaning that during the recharging period, the production of energy to the DH network will be lower. Due to this aspect of TES, the overall energy production amount with LHTES is barely higher than the system without TES. Spikes in the graphs are from starting up the energy production causing a disturbance in the energy meters.

As seen in Figure 62 the energy production to the DH network drops after a short production time from the TES. The main explanation for this fast drop in energy output is the wrong functioning temperature level of PCMs. When the material was chosen it was thought that a little over 90 °C water temperature is the maximum that can be taken from the CO_2, meaning that temperature would not have been enough for the higher temperature material from the catalog which was 89 °C. After the use of materials and thermal storage, it was noted that temperature can sometimes climb up to 105 °C meaning that it would have been possible and more beneficial to use the 89 °C temperature ATS89 material.

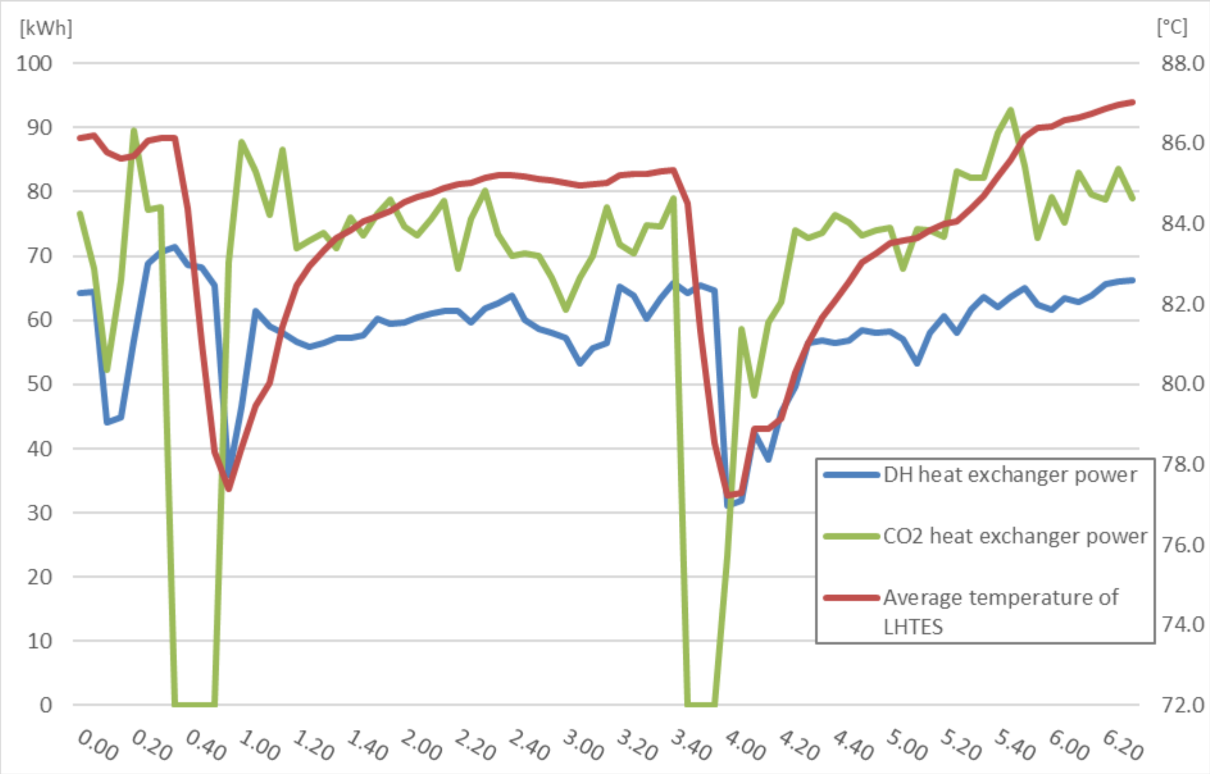


Figure 62. LHTES average temperature between domestic hot water tank charges. Time in h.min in the x-axis.

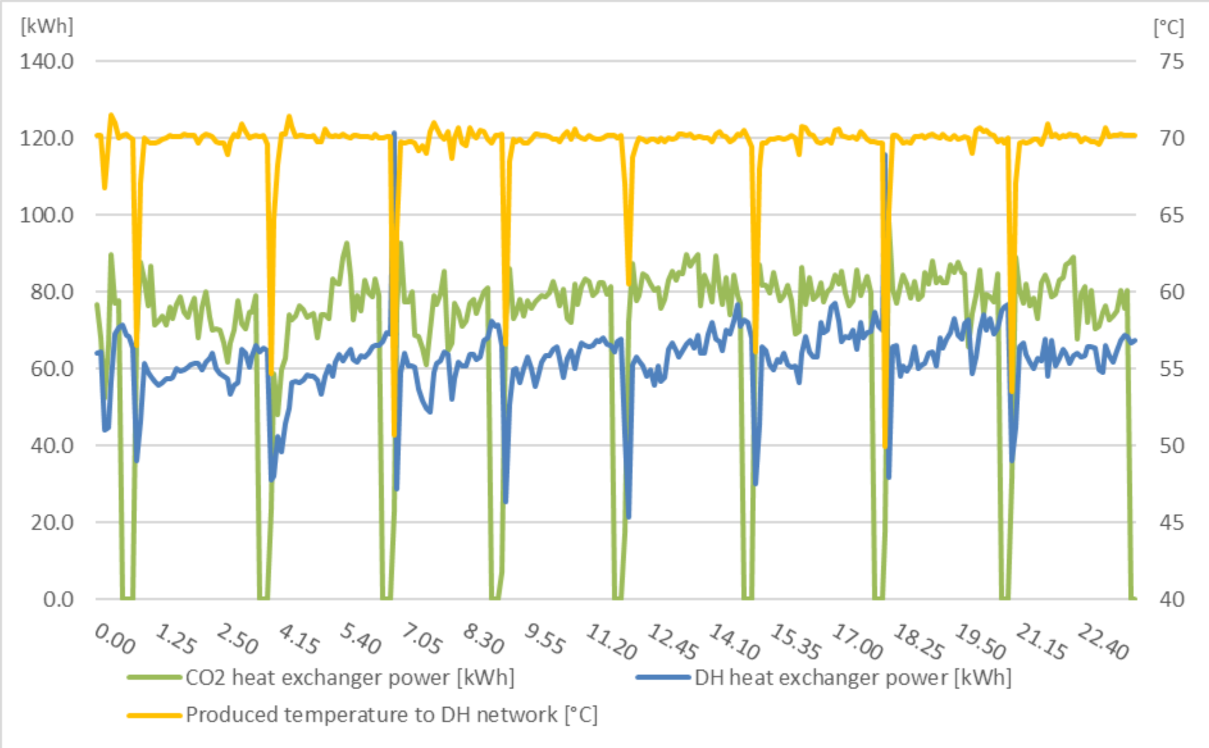


Figure 63. CO2 line heat exchanger power and DH heat exchanger power while LHTES is in use. DH network demand set to 70 °C. Time in h.min in the x-axis.

When cold water is fed into the TES for the recharge time of the domestic hot water tank, the same cold water comes out of TES with delay meaning it will have a negative impact on outgoing temperature from the TES. However, due to PCM capsules releasing their heat in the tank the impact of the "cold pulse" is lessened. This effect can be seen in

Figure 64 when temperature measurements are line in order and highlighted. Cooler water is mixed as water flows through the tank aided with the encapsulated PCMs.

			Domestic hot water tank charge													
Sensors	0:00	0:05	0:10	0:15	0:20	0:25	0:30	0:35	0:40	0:45	0:50	0:55	1:00	1:05	1:10	
TE7	86.6	86.4	80.5	72	68.3	70.2	85.2	89	88.9	88.5	88.4	87.9	87.4	86.9	86.4	TOP
TE15	86.9	86.6	80.7	72.7	68.4	69.9	85.2	89.1	89.1	88.7	88.6	88.1	87.6	87.1	86.6	
TE19	86.5	86.5	76.1	69.6	65.3	66.8	69.4	71	83.2	86.7	87	86.8	86.6	86.4	86	
TE11	86.5	86.3	76.3	68.9	65.6	66.9	69.5	71.1	83.9	88.4	88.3	87.8	87.4	86.8	86.4	
TE8	86.7	86.5	85.4	82	79.7	78.7	78.4	78	78.5	80.9	85.4	85.8	85.9	86.2	85.8	2ND
TE16	86.9	86.8	86.3	83.3	80.2	79.1	78.8	78.5	78.4	81.2	85.4	86.2	86.9	86.8	86.4	
TE20	86.2	86.3	83.7	79.1	76.2	75.6	75.6	75.6	76	78.4	80.5	83.5	84.4	85	85.2	
TE12	86.1	86.2	83.2	78.7	75.8	75.4	75.4	75.5	76.1	78.1	79.5	82.2	83.4	84.1	84.3	
TE9	86.1	86.2	86.1	85.2	83.3	82.1	81.3	80.9	80.6	80.7	81	81.3	82.5	83.3	83.9	3RD
TE17	86	86.1	85.5	84.1	82.5	81.1	80.2	79.7	79.4	79.7	80.1	81	82.2	83.2	83.9	
TE21	85.4	85.4	85.3	83.6	81.8	80.9	79.9	79.4	79.1	79.4	79.9	80.5	81.1	81.8	82.4	
TE13	85.4	85.4	85.3	83.9	82.2	81.3	80.5	79.9	79.6	79.9	80.3	80.8	81.3	81.8	82.4	
TE10	85.5	85.5	85.6	85.3	84.7	84.1	83.5	82.7	82.1	81.7	81.5	81.5	81.6	81.7	82.1	BASE
TE18	85.4	85.4	85.4	85.1	84.5	83.9	83.4	82.7	82.1	81.7	81.5	81.5	81.6	81.7	82	
TE22	84.6	84.6	84.7	84.3	83.4	82.9	82	81.2	80.7	80.5	80.5	80.7	81	81.3	81.6	
TE14	84.5	84.6	84.6	84.4	83.4	82.8	81.9	81.1	80.6	80.4	80.5	80.7	81.1	81.3	81.6	

Figure 64. Temperature [°C] measurements from the LHTES from top to bottom when domestic hot water tank is charged. DH network temperature set to 70 °C. On the left side are the temperature sensors in each section. Time in h.min in x-axis at top.

The red color represents the warmer water and fades to green as it gets colder. When the CO_2 heat exchanger is bypassed to charge the domestic hot water tank, cold water starts to flow in the top part of the tank which is seen in

Figure 64 presented by green color and temperature readings. Time goes on in 5 min steps and the water flows down to lower sections of the tank warming up due to warm water present and due to PCMs releasing latent energy in them. This can be thought to be an advantage of this system since most likely without the presence of PCMs the cooler water would eventually come out of the tank disrupting the DH energy production. Separating the tank into sections, unfortunately, prevents water from mixing naturally, which might prevent these "cold-water pulses", but it is unknown if stacked encapsulated PCMS would cause the same hindrance to the temperature ranges in the tank.

Finally, to maximize the use of PCMs to diminish the cold-water pulse in the tank after the charge of DHWT a motorized 3-way valve was used. The valve was used to regulate the water temperature before the DH network heat exchanger to make sure that the temperature was high enough for the need of the DH network. A temperature sensor before the DH network heat exchanger (Figure 59) was used to control the valve's performance. As seen in the results Table 7 the daily production to DH network is not much higher than using the LHTES without bypass. This was to be expected since the amount of energy taken from the CO_2 line was kept the same. When DHWT recharge temperature set point was increased to 65 from 60 °C the energy production to DH network was reduced when compared to both scenarios where LHTES was in use without control valve and with control valve and DHWT temperature set to 60 °C. This can be thought to mean that LHTES energy output is already on the limit when DHWT recharge periods are short. Increasing the charge time of DHWT only reduces the produced energy amount to the DH network. When looking at the electricity consumption by the refrigeration machine it can be seen increased compared to previous results. This is due to the uneven electricity consumption habits of the machine. The electricity consumption increases and decreases due to a large number of variables of the system and market. For this reason, the electricity consumption is not compared between results but is included.

To get a view of the efficiencies of the different setups that were presented it is important to look at the quality of the produced heat into the DH network. Figure 65 presents a day measurement from all tests where energy taken from the CO_2 line and energy to DH network are present. Additionally, the temperature of the outgoing DH flow is present, which indicates the produced quality.

Figure 65. Graphs depicting energies and produced temperature quality. Time is presented on the x-axis as h.min. Setting domestic hot water tank (DHWT) charge temperature to 65 °C reduces daily charging times but makes them longer.

When LHTES is bypassed, the produced quality into the DH network is variating more and with LHTES in use, the temperature variation decreases slightly. Spikes in the production are present in all scenarios due to DH networks circulation pumps turning off when energy from the CO_2 line is drawn. This could be fixed by changes to the automation system. In Figure 65, where DHWT is set to 65 °C. more energy is drawn from the LHTES which can be seen as longer recuperation time from energy produced to DH network.

7.3.1 Errors and uncertainties in the study

The main purpose of this project was to experiment with new technology ideas and implement them to provide guiding instructions for future projects on how such systems should be designed and what should be taken into account. As the project proceeded, some errors were made due to uncertainties in the system. The most notable being the functioning temperature of the PCM being low for the actual working temperature of the system. Another large uncertainty factor comes from the complexity of the system meaning that results that are being presented would be difficult to reproduce even with the same system they were done. Due to the complexity, many factors can change the results such as outside ambient temperature and refrigeration need coming from the number of customers in the store. Table 8 and Table 9 have a list of possible errors that can be quantified or are unquantifiable. Measurement errors from energy sensors and temperature sensors have not been looked up. Measured energy has been cross-referenced to ensure the accuracy of the system which was proven to be true.

Table 8. Quantifiable errors

PCM functioning temperature	Due to uncertainty of the working temperature of the system, the material was chosen to be ATS84. A higher temperature level would have been ATS89 which could have been enough as later was seen.
Energy sensor readings	Energy readings are taken from meters that energy companies use which has higher measurement interval but is accurate in longer measurement periods.
Temperature sensors	Slight measurement errors

Table 9. Unquantifiable errors

Outdoor temperature affecting refrigeration machine output	Outdoor temperature affects directly the heating need of the market.
Customer amount affecting the need of cooling the cold cabinets and indoor heating	Customers opening outdoors increases the need for heating and opening cold cabinets increases the need for cooling.
The complexity of the system	Many variables make repeatable testing impossible. Observing data for long periods is needed.
The fixed set point of DH network temperature	Due to the colder climate DH network demands higher temperature water than presented at tests. This is due to low outdoor temperatures which increases the network temperature requirement higher. The energy company has been permitted to feed lower temperature water into the network due to its temporality and relatively low volume.

7.4 LHTES conclusion

After testing of the LHTES in the local supermarket used to produce energy to the district heating network it can be said that using a 2 m^3 TES does not have a substantial effect on daily energy production amount. As it was seen in tests where LHTES was bypassed and it was in use, the produced energy was not remarkably higher with LHTES in use than it is bypassed. In Table 6 it is seen that when LHTES is in use for the production of energy for a required temperature of 70 °C, the daily production is only about 50 kWh more than bypassed LHTES. Also, it could be noted that refrigeration machine consumes 50 kWh more electricity when LHTES was in use, but this is incomparable since refrigeration machines' daily electricity consumption varies greatly due to multiple variables such as outside weather and the number of customers. One of the biggest issues is the too low functioning temperature of the PCMs since at the start it was unknown how high-water temperature from the CO_2 can be drawn. Since a majority of the time, the temperature of the LHTES is above 84 °C with exception of the charging times of DHWT. If the material would be of higher temperature it would have had more possibilities to release energy to the system. This would also require used energy to be stored again into the storage since it acts as a buffer and a delay in the system meaning that it only contributes if the production pauses are long enough, and TES has a large enough energy capacity. This means that stored energy that is taken from the LHTES must be returned to the energy storage thus reducing the produced energy to the DH network while LHTES charges. Lastly, due to the encapsulation of the PCM being plastic and manufacturer recommended temperature not to exceed 100 °C. This limits the maximum temperature of the LHTES meaning that some of the possible capacity is lost. A better encapsulation material is necessary on higher temperature systems such as this one.

Even though LHTES did not provide significant DH production benefits when looking at the quality of the produced heat, there can be seen improvements. Quality of heat, in this case, is defined by continuous, stable required temperature production to the network. In original views of the project, the market would have supplied a local small DH network and in such case, a TES would have been a must in the system to provide a steady flow of heat. Though produced energy is lower when LHTES is in use its production is more stable and continuous which is more important when networks size is smaller. The use of a 3-way motorized valve seemed to improve produced energy quality but not the amount of energy produced daily. Now, LHTES is only used when the domestic hot water tank is reheated to 60 °C which prevents energy taken from the CO_2 line to the DH network. Another possible use for the TES is to produce energy for the DH network when the market is possibly used for peak-load shifting in the future. During a peak-shifting, the use of refrigeration machines might be decreased to reduce electricity consumption meaning that temperature in the CO_2 line will decrease and DH energy might get halted. Energy can be taken from the LHTES during these times.

Costs of PCMs coupled with the small gain of produced energy make it an uncertain investment, but with a better selection of material for the functioning temperature and if the quality of produced heat is more important it might be feasible. A 3-way valve is recommended for the system to control the bypass of the LHTES to ensure the produced energy is out of the system. Using a cascading LHTES would possibly also be an option with 84 °C and 89 °C PCMs. In the future, tests are continued with normal SHTES filled with water to see how PCMs exactly affected the energy production.

Conclusions

This deliverable documented the building-level energy management system (BEMS) for forecasting, controlling and communicating building energy consumption and flexibilities for buildings in the Kaukovainio PED. BEMS is broken into five functional components that are detailed in their own sections.

Tests were done for the latent heat thermal energy storage in the market of Kaukovainio which are detailed in this deliverable. It was noted that having a LHTES in the system did not increase daily production of DH energy, but it made the production more continuous and with more stable temperature. Having a TES is essential in smaller system which would have more dependence on the production of local heat.

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