Analysis of a district energy system containing centralized thermal storage

F.E.L. Batista[1,2*], J.I. Torrens[2], J.L.M Hensen[2], G.C. Graça[1]

(1) Dep. of Geographic engineering, Geophysics and Energy, Faculty of sciences, University of Lisbon, Portugal

(2) Dep. Building Physics and Services, Eindhoven University of Technology, The Netherlands

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ABSTRACT

This report review some of the most relevant aspects regarding thermal energy storage applied to district energy & district heating systems. A general overview of the available technologies, as well as the past, present and future lines of work are presented with the respective literature. A methodology to assess the benefits of integrating a centralized short-term storage unit in a district energy model is described and implemented in modelica.

1. INTRODUCTION

1.1. Sustainable development

Progressively, there is the awareness for the need for a more sustainable energy development. It is a fact that current trends in energy supply and use are unsustainable from the environmental and economic points of view, requiring decisive actions. In order to limit global temperature rise to 2ºC, International Energy Agency (IEA) prescribes a reduction in greenhouse gas emissions by 80 to 95% below 1990 levels by 2050. It sets out milestones which form a cost-effective pathway to this goal – reductions of the order of 40% by 2030 and 60% by 2040 [1].

Following this, many countries worldwide have been taking actions; however the complexity of creating and agreeing in good regulations is obvious, but also of great importance. Analysis of the visions of key EU member states to accomplish a low-carbon energy system by 2050 finds that the states are pursuing sometimes divergent strategies. On one hand, this can bring risks of energy policy fragmentation but can also imply new opportunities for cooperation [1].

In this context, the reduction of the use of fossil fuels in the built environment is an important step to meet the mentioned goals. Buildings are responsible for 36% of CO_2 emissions in the EU. In addition, approximately one third of global primary energy demand is attributable to the building sector, of which 75% is used for thermal purposes [2]. Therefore, the EU introduced the Energy Performance of Buildings Directive (EPBD) in 2003. The EPDB demands EU countries to reduce the energy use in new buildings, resulting in energy performance regulation for new residential buildings. Examples of this driving force are the EPC (energy performance coefficient) introduced by the Dutch government or the RCCTE (thermal performance characteristics of buildings regulation) used in Portugal. Nonetheless, the referred regulations focus only on energy use in the operational phase of buildings leaving out construction and demolition phase which also contribute to total energy use and emissions. In order to evaluate the sustainability of the whole building lifecycle, green building rating tools rating tools such as BREEAM or LEED are developed and can be used, allowing for example to assess the reuse of building materials [3].

In addition to the considerations on the building itself (demand), one can identify opportunities to achieve the prescribed goals on the building systems side (supply). One of the topics currently intensively discussed is the way to ensure space heating and cooling as well and hot water supply in the future. Among others, it is possible to find two main views; the first one where low energy or even plus energy buildings remove the need for heating and cooling, and a second stating that excess/waste energy from industry or power stations can be used in combination with renewable energy sources and other technologies such as large-scale solar thermal energy, geothermal energy or heat-pumps [4]. In such a scenario, district energy networks with increased flexibility become crucial.

Among other technologies, energy storage can support energy security and decarbonisation by providing valuable services in developed and developing energy systems, namely integrating electricity and heat systems or decoupling the energy supply and demand which confers an increased efficiency and flexibility. However energy storage will require additional attention before their potential can be fully realised [5]. The work presented in this report should be seen in this context. The research focus on district energy systems containing centralized thermal energy storage in combination with individual decentralized peak units; the concept will be discussed in the next chapters.

1.2. Thermal Energy Storage

Thermal energy storage systems that can be used in district heating/energy are broadly described in literature, [6,7]. The concept of thermal storage is to store energy by cooling, heating, melting or solidifying a material. It is called *sensible heat storage* when the material temperature rises or falls; *latent heat storage* if a phase change occurs and *thermochemical heat storage*, when the process is based on a reversible chemical reaction, which is energy demanding in one direction and energy yielding in the reverse way.

The storage methods in these categories can be differentiated into *centralized* and *decentralized storage*. While the first one is usually connected to all components in the district the second is normally applied in a smaller scale and associated only to a particular building or a specific part of the district network.

In this overview, the methods are also grouped depending on the storage duration. Two types are distinguished; *short-term storage* when energy is retrieved on a daily to weekly basis and *long-term storage* if the energy is stored from season to season (Seasonal thermal energy storage) or even for a larger period. [6]

1.2.1. Sensible Thermal Storage applied to district energy

In sensible storage systems, energy is stored by changing the temperature of a storage medium. Being the most mature technology, it is also the most inexpensive and reliable with a significant number of projects implemented [7-13]. The amount of heat stored in the medium (Q) is proportional to the difference between the storage input and output temperatures, the mass of the storage medium and the medium's specific heat capacity:

$$Q = m \cdot c_p \cdot (T_f - T_i) \quad [J] \qquad (1.1)$$

Surveys conducted by several researchers have revealed that the storage medium is chosen based essentially on the required temperature level, storage duration and rate at which energy must be released and extracted [6,7]. As a result, the choice of the storage material is based on the following proprieties [14]:

- *Volumetric thermal capacity* ($\rho \cdot c_p$), which quantifies the ability of a given volume of material to store sensible thermal energy;
- *Thermal diffusivity* ($\lambda \cdot \rho^{-1} \cdot c_p^{-1}$), which measures the thermal inertia of a material; a bigger value means that the material will rapidly react to a temperature change;

As this technology is mainly used for low-grade heat, frequently used to store waste heat from power generation plants or combined with large-scale or domestic solar thermal energy applied in space heating/cooling and domestic hot water supply, the required temperatures range from 5 to 90 ºC. For this reason, water, rock-sort materials and ground/soil and other inexpensive materials became popular mediums [7].

In long-term sensible TES, aquifers, rock beds and large water tanks are used. The fact that the surroundings temperature amplitude decreases with depth led Underground Thermal Energy Storage (UTES) to be considered as a promising option for Seasonal storage. The idea of seasonal thermal energy storage (STES) is store energy seasonally in order to compensate and even make use of a seasonal variability on the supply and demand sides of the energy system. Table 1 [7] list a comparison of several commonly used seasonal sensible heat storage methods.

Table 1 - Comparison of sensible storage concepts (7).

	Water tank	Gravel-water	Borehole (BTES)	Aquifer (ATES)
Storage medium	Water	Gravel -water	Ground material	Ground material and water
Heat capacity [kWh/m³]	60-80	30-50	15-30	30-40

Over the past years, a number of studies have been carried out in many countries focusing on sensible thermal storage. The major part of the efforts aim to the resolution of specific TES issues (e.g. tank concepts) and new materials [7, 15, 16].

Regarding underground thermal storage, a major part of the work developed is related to the geological requirements and feasibility studies (techno-economic) embracing different strategies as well as documenting the achievements [1, 17, 18]. In addition, some international research programs have been carried out. As an example, Annex 12- IEA focused on HT UTES.

1.2.2. Latent Thermal Storage applied to district energy

Another method to store thermal energy is in latent form, using phase change materials (PCMs). This technology can offer higher energy density than sensible storage, however it stills in a yearly stage of development, especially in what concerns its implementation in district systems [7]. The energy is stored as heat of fusion, when the melting occurs, at a nearly constant temperature T_m (Figure 1). If the temperature decreases to the phase change temperature, the material changes back to solid phase and releases the stored energy. The amount of heat stored in PCMs is given by:

$$Q = m \cdot [\, c_{p\text{-solid}} \cdot (T_m - T_i) + a_m \cdot \Delta h + c_{p\text{-liquid}} \, (T_f - T_m)] \qquad [J] \qquad (1.2)$$

where T_i is initial temperature [°C], T_m is melting temperature [°C], T_f is final temperature [°C], m is mass of the PCM [kg], c_p is specific heat [$J \cdot kg^{-1} \cdot K^{-1}$], a_m is the melted fraction of the material and Δh is the enthalpy change at the phase change temperature [$J \cdot kg^{-1}$]. Materials used for storing energy in latent form (PCMs), should have a high heat of fusion or specific melting enthalpy and a phase change temperature within the operating temperature of the thermal system [19]. Figure 2 shows various PCMs and their phase change temperatures.

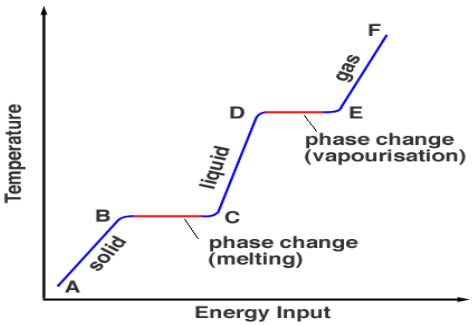


Figure 1 – Temperature as function of Energy stored in a PCM (B->C)

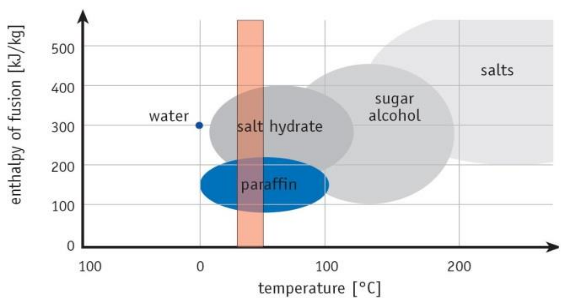


Figure 2 – Classes of materials than can be used as PCM and their typical range of phase change temperature and melting enthalpy.

Based on the literature collected one can conclude that appears to be potential for the integration of latent thermal storage in district networks; Nevertheless, at present most of the work conducted is based on small scale prototypes or in computational models [20]. Examples of this line of work are the five PCM-related projects conducted based on the Subtask C, IEA-SHC task 32. This task intends to compare storage options in terms of heat and cold storage, for a reference case (single family house) in four different climates. The first results are not as good as expected; there appeared to be no significant improvements of PCM stores compared to conventional water stores. According to the task participants, screening for better PCMs with higher heats of fusion, advancing the storage concepts to attain a higher PCM fraction and higher heat transfer rate should be addressed in the future [21-23]. By contrast, ice storage for cooling purposes is already a relatively mature technology (commercialization phase), implemented mainly in the US in several projects. Another field where LTS is already implemented in several projects is in agricultural greenhouses and a large amount of work documenting the progress can be found [24-29].

1.2.3. Thermochemical Storage applied to district energy

Thermochemical storage is seen as the most promising alternative to store thermal energy. With this technology it is possible to store energy at ambient temperature, for the desired duration, with negligible heat losses, making these systems suitable for long-term storage. In addition, it has the highest energy density when compared to the sensible and latent solutions.

The principle of thermochemical storage is based on the reversible reaction between two substances, with endothermic decomposition in one direction and exothermic synthesis on the opposite direction. No reaction occur as long as the two materials are stored separately allowing to store thermal energy until the two substances are mixed together.

Research in finding the most appropriate materials is still ongoing. There is the need to find stable, non-polluting and cost-effective materials, therefore the research focus mainly on material characterization and laboratory studies aiming to optimize the temperature level during the charging and discharging process [7]. Prototypes and projects have been developed, mainly related to long-term storage; examples of this are the *watergy,* the IEA-SCH task 32 D and the SWEAT (*Salt water energy accumulation and transformation)* projects [30-35].

1.3. Benefits of TES applied to district energy

Thermal Energy Storage can be used in a wide variety of applications, and a district energy system can benefit from its introduction in different ways.

To begin with, TES can increase system reliability; as for example it can be used to reduce the mismatch between energy production and consumption, particularly in energy system with high penetration of renewable energy. Another example of increased reliability is the fact that a thermal storage unit can be used as a backup unit or even integrated with other functions as for example, in applications where there are on-site water tanks, they can be used as fire protection units.

Moreover, TES is that it can increase the generation capacity. Demand for heating, cooling or power is rarely constant over time and the excess generation available during low-demand periods can be used to charge a TES in order to increase the effective generation capacity during high-demand periods. This process allows smaller production unit(s) to be installed, or to add capacity without purchasing additional units, resulting in a higher load factor for the unit(s).

In the same way, TES can be used to take advantage of off-peak electricity tariffs. In fact, there is a growing interest in the use of short-term (daily) TES for electrical load management in both new and existing buildings [5, 35]. TES technologies allow electricity consumption costs to be reduced by shifting electrical heating and cooling demands to periods when electricity prices are lower, for instance during night.

The above referred advantages are going to be discussed with further detail later in this report.

1.4. Aim and Scope

In a district energy system, seasonal thermal energy storage (STES) can be used to meet some of the building thermal needs. These systems are often related to the supply of the basis load of the thermal demand, sometimes in combination with heat pumps and other production units. Due to weather or other external influences, still peak demand exists. The peak demand is normally supplied by a peak unit, such as an electric heater or a boiler for heating or a chiller for cooling. These configurations cannot deliver the demanded heat and cold very efficiently, because they are designed for the maximum possible demand, but do almost never run on this load, which leads to higher energy use and greenhouse emissions. In combination with partial load running of either the heat pump or the boiler, also the frequency of on/off switching operation of the system is not optimal for the energy use and emissions.

Thermal energy storage can be used to reduce partial load running, since TES allows using smaller production units with a higher load factor associated. In addition to this, TES can enable the shift of energy purchases to low cost periods, by producing and storing energy during low cost periods to be used during high-cost times, in cases where the thermal demand is supplied by electrical driven equipment, such as heat pumps.

This project intends to investigate the advantages of integrating short-term thermal energy storage in a district energy, supplied by a seasonal thermal energy system in combination with decentralized peak units. A comparison between two scenarios will be performed, in order to evaluate the possible energy and monetary savings prevenient from the energy shift operation. Scenario 1 represents a conventional district containing an Aquifer thermal Energy Storage in combination with heat pumps for the application of the base load. Each building has also a boiler to supply the peak load.

Scenario 2 contains the same elements of scenario 1, however a centralized short-term thermal storage unit is going to be added in order to allow to manage the electrical loads of the electrical components of the district, mainly caused by the heat pumps. In this scenario it is intended to shift the thermal production to low-peak hours, enabling a more constant operation under cheaper electricity prices. The comparison between the results of these two scenarios will allow quantifying the possible benefits of the integration of a centralized short-term storage unit in the district.

In addition, it is going to be tested if the supply problems that may arise from the introduction of new buildings in the district can be mitigated by the introduction of new short-term storage capacity. In other words, the number of the buildings linked to district energy is rarely inflexible; the objective is to understand what are the problems that may arise for the supply side, from increasing the number of buildings supplied by the seasonal storage, and if this problems can be solved by increasing the short-term storage capacity applying a modular approach to new construction in the district.

1.4.1. Research questions

The goals for this project led to the following research questions:

1. To what extend can short-term storage optimize the use of energy in a district energy system containing centralized seasonal storage in combination with individual boilers and heat pumps?

2. What problems can arise from the increase in the number of buildings coupled to the district? Can these problems be mitigated by adding new short-term storage capacity?

2. Methodology

The methodology for the evaluation of the district is presented in this section. Firstly the motivation for using integrated building performance simulation as well as the choice of using Modelica/Dymola is discussed. After this the case study and respective models are presented.

2.1. Building Performance Simulation

One of the key challenges on the process of modeling energy systems on a district scale is the complexity. In the past computational models, each part of the complete model of a district could only be designed separately, which did not allow having an optimal design for the entire system.

Moreover, the introduction of new technologies, such as intermittent renewable energy and the possibility of storage, increased the complexity to the analysis of these systems. With these more and more complex relations in buildings systems, a separate design would become even more outdated. In this context, there is a growing interest in integrated simulations, capable of embracing the different components and the complex interactions at the same time, in order to, for example in this case, allow reducing the system size, partial loads and assess an energy-shift scenario, improving energy use and costs.

Moving from a casual modeling philosophy towards object-oriented modeling, so that we have a more natural representation of the system, while enabling the possibility of reusing components, reducing also development time is vital. In addition, the integration of tools in a coherent work flow, increasing level of modularization permits modeling different disciplines such as electrical, thermodynamics or control systems. The referred characteristics are required when modeling energy systems on a district scale.

Modelica is an open-source high level object-oriented modeling language used to multi-domain physical and control systems. It contains the above referred characteristics necessary to model large-scale complex systems. It allows the reusability of models and components, using for example the Buildings Library developed by the Lawrence Berkley National Laboratory (LBNL) or the Modelica Standard Library (MSL). Both libraries are open source and for example MSL contains about 1280 model components and about 900 functions from many domains. These features make Modelica suitable for computational applications with increased complexity, such as the analysis of district energy systems [36].

2.2. Case study

The case study is based on IEA's Annex 60 which consists of a 24 buildings' neighborhood [37]. However, in order to simplify, it is assumed that if it is possible to prove benefits in a smaller group of buildings, then it would also be possible to have the same advantages in the whole district; in resemblance to what was done in literature addressing similar work. [38, 39]

Therefore, the case study consists of a group of 6 buildings of three different typologies – terraced, detached and semi-detached dwellings. These buildings are connected to an Aquifer Thermal Energy Storage (ATES) system, used to store thermal energy from season to season.

The stored thermal energy is used to supply each heat pump present at each dwelling. When heat is required (Winter), the ATES supplies hot-water (15ºC) serving as heat source for the heat pump. The return cold water (8ºC) is then stored in the ATES. During summer, the flow is reversed; the cold water stored during the heating season is used as cold source for the heat pump and hot water is produced and stored for the next season.

2.3. Scenarios

In order to assess the potential energy and monetary savings associated to the introduction of a centralized short-term storage unit in the system, two scenarios are going to be compared.

Scenario 1 – Base case

This scenario intends to represent the conventional case in which a centralized Aquifer thermal energy system is used in combination with individual heat pumps to supply the base load of the thermal load of the building. In other words, the STES and heat pump are capable of providing hot water at 50ºC or cold water at 5ºC. During peak demand periods an individual boiler is used, capable of heating water to a maximum of 75 ºC.

In this case, the heat and cold are delivered when there is a request by the demand, without having a specific period to produce thermal energy.

Scenario 2 – Added short-term storage

In this case, all the components of scenario 1 are also present. However, a centralized short-term storage is added to the district system. This way it is possible to test if by introducing the short-term storage, the heat pump could avoid some partial load operation and interruptions as well as evaluate if the installed power could be reduced.

Moreover, a dynamic energy pricing structure is introduced. The benefits from managing electrical loads, through a demand side management strategy (Figure 3), as well as the respective monetary savings, can this way be assessed.

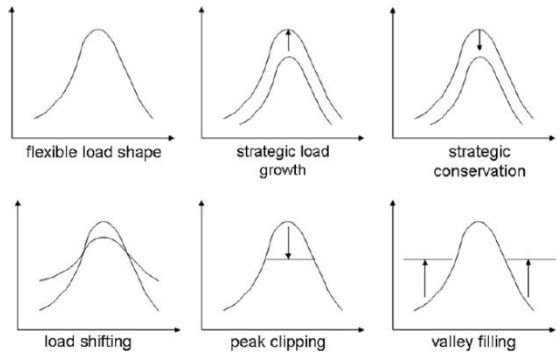


Figure 3 – Demand Side management categories [40]

Outputs

The comparison of the scenarios is done by analyzing the following data:

- Yearly Energy and Power profiles from the Seasonal storage, Heat pumps and water pumps;
- Annual peak history;
- Monthly/annual energy costs.

Scenario 3 – Increased number of buildings in the district

This scenario is divided in 2 phases:

- Phase 1: The number of buildings in the district is increased;
- Phase 2: The short-term storage capacity is increased.

Phase 1 allows assessing the problems for the supply side that may rise from the introduction of new buildings to the district energy system. In phase 2, an extra short-term storage unit is added, in order to see if it would solve the identified problems.

This analysis is done with the intention of evaluating the possibility of having a modular approach to new building connections in a district network, or in other words, for each group of buildings linked to the district we would have another short-term storage unit.

3. Implementation in Modelica

In this section are presented and described the general components of the district energy computational model, namely the *heat and cold consumers*, represented by 6 dwellings of different characteristics, the *decentralized production units* which contains the heat pump and boiler models, the *thermal storage* consisting on the ATES and the water tank model and finally the *distribution line.*

The models are created as a hierarchal structure. Firstly, the base models such as pumps, the heat pump, dwellings, boiler, and others are created separately. As modelica allows reusing the created models, these are then combined to gradually form the entire district as function of the scenario.

3.1. Heat and cold consumers

The building model (Figure 4), responsible for generating the heat and cold demand profiles is simplified as a completely mixed volume of air, a prescribed heat source for the internal heat gains, and a heat conductor for steady-state heat conduction to the outside. To increase the heat capacity of the building, such as due to heat stored in furniture and in building constructions, the heat capacity was increased by a factor. The convective heat transfer coefficient is lumped into the heat conductor model.

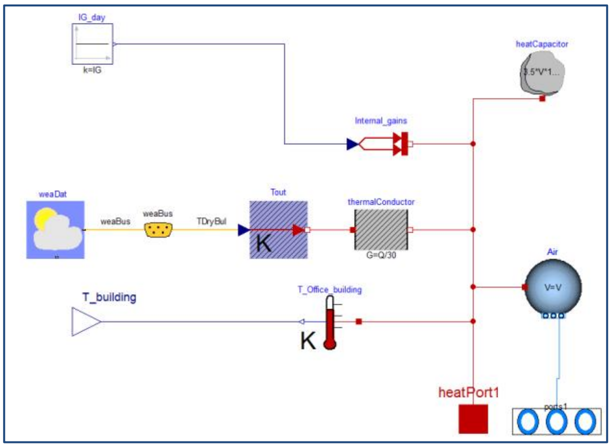


Figure 4 - Building model.

A temperature sensor is placed in this model and is used to measure the indoor temperature, required to regulate the operation of the production units, which are described in the next chapter

3.2. Production units

3.2.1. Heating

In order to supply heat for space heating purposes, the model of a radiator (EN 442-2) from the Buildings library was used. The amount of hot water that flows into the radiator is controlled by the distribution pump and a thermostatic valve. The flow is imposed by the distribution pump which is controlled by a PID controller using a differential pressure control.

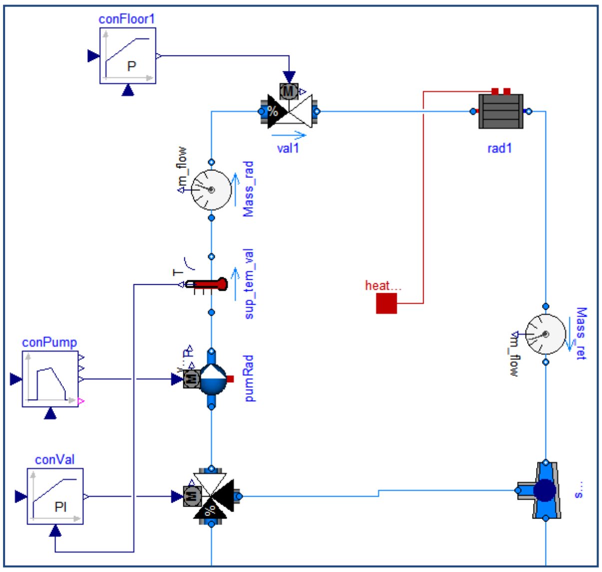


Figure 5 - Radiator loop model.

Using a modified heat pump model from IDEAS library and the boiler model from the Buildings library, the water temperature is raised to the required level. A block from the buildings library is used to compute the ideal supply and return temperatures of the heating system (Figure 6). This is done by inputting the outside temperature, as well as the temperature set-point for the building.

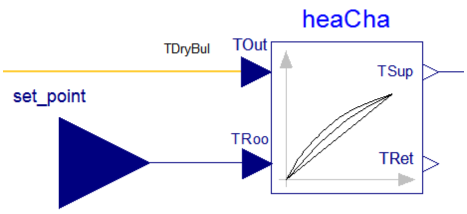


Figure 6 – *HeaCha* - Block used to compute the ideal supply and return temperatures for the heating system.

The temperature level computed by this block is then used to implement the controls for the heat pump and boiler.

<u>Heat pump</u>

The heat pump model is based on the interpolation in performance tables for the Viessmann vitocall 300-G heat pump. These tables were already encoded in the *heatSource* base class from IDEAS library. Based on this base class, the required power and environmental heat losses as well as the electricity consumption are computed, as the heat pump tries to reach the specified set point.

The control is made by a PID controller that receives the temperature set point computed by the block "*heaCha*" as input and compares it with the actual flowing temperature measured with a temperature sensor. However, since the heat pump is responsible only for the base load, the defined set-point was limited at 50ºC.

Boiler

The boiler block is controlled by inputting the partial load ratio at each instant. The control is done using expression 1.1; by measuring the upstream and downstream temperatures, as well as, the water mass flow is possible to calculate the required power at each instant, to guarantee the computed supply temperature. The calculated instant power is then limited between 0 and 1, and inputted as the partial load factor. The blocks responsible for this operation are presented in figure 7.

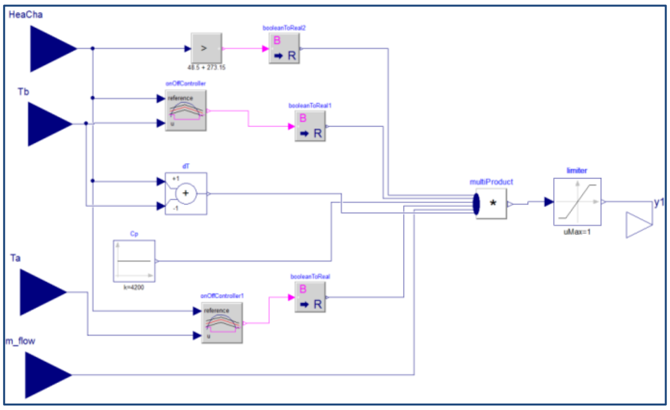


Figure 7 - Boiler temperature control

As an example, the next figure shows the temperature of the water flowing for the radiator, for four typical winter days. It is possible to observe that the temperature follows the set point calculated by the *HeaCha* block.

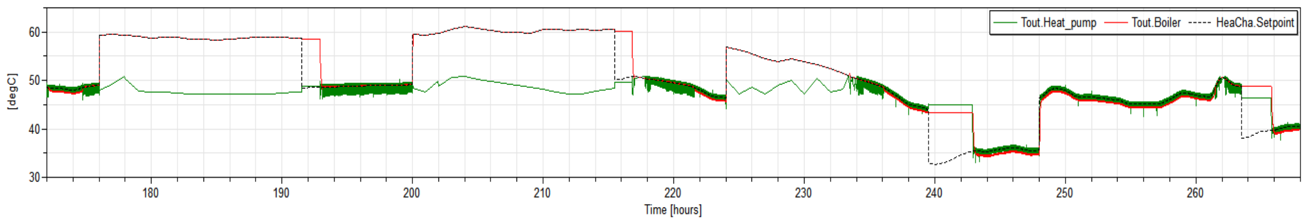


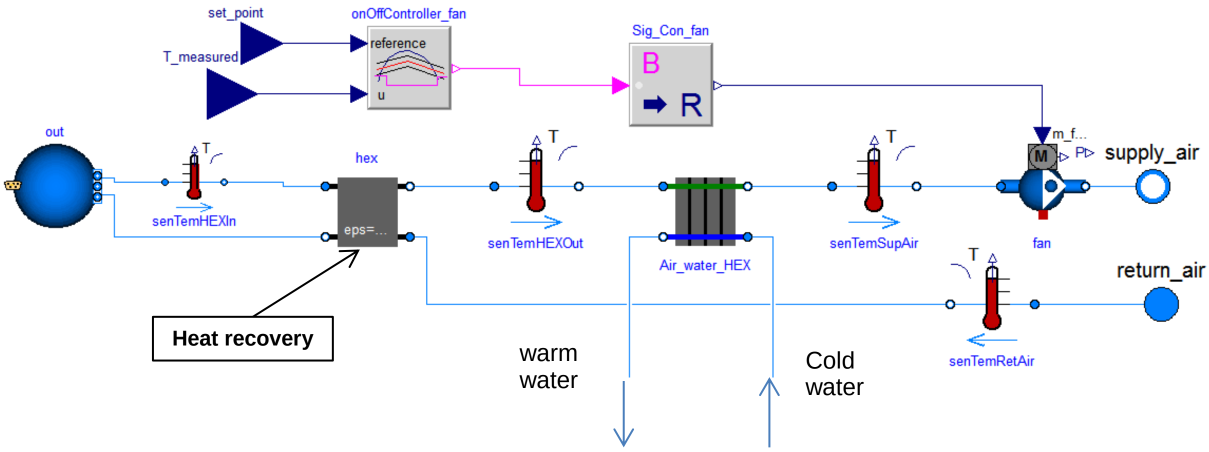
Figure 8 - Temperature of the radiator supply water, for four winter typical days.

3.2.2. Cooling

The cooling model consists of a closed loop fresh air supply with heat recover, an air-water heat exchanger and a fan. The fan is controlled by an ON/OFF switch, and it is operated with a constant air mass flow. To model ambient outside air conditions, it was used the instance "*out*" which is directly connected to the weather data. The block "*Air_water_HEX*" is responsible for cooling the air from the outside, maintaining the supply air at constant temperature (18ºC).

The air is cooled in the air/water heat exchanger using the fresh water stored in the ATES. In order to keep the adequate temperatures, the water loop is ruled by a pump controlled by a differential pressure control in combination with valves and a bypass, using a PID controller.

The water loop pump is turned on if there is the need for fresh air. The fresh air flow is ON if the measured indoor temperature exceeds the temperature set point plus 1ºC.



3.3. Distribution

The distribution network is modeled as a two way, supply and return, buried piping system. There are two separated networks, one for the transport of the warm fluid and another for the cold fluid. It takes into account friction and thermal losses.

The pipe characteristics are based on catalogue data from a manufacturer, and the model is implemented using the pipe model from the buildings library. To increase accuracy, the thermal losses are calculated as function of the soil temperature, computed using the kusuda function, for a constant depth of 1 meter.

3.4. Thermal energy storage

The seasonal thermal energy storage model is modeled as a simple volume of water in contact with ground. The heat conduction to the ground is implemented using a heat conductor. In order to simulate the ground temperature the kusuda function is once again used for a depth of 50 m.

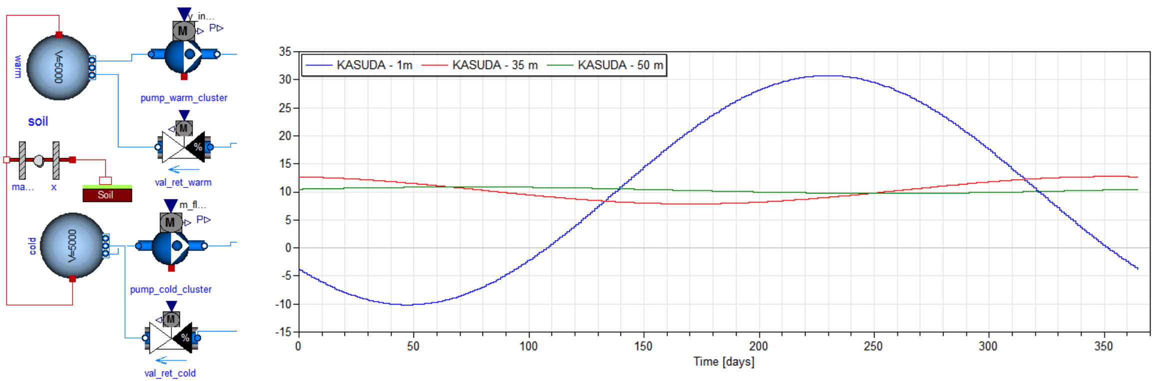


Figure 10 - (left): ATES model; (right) - Temperature of the soil as function of the depth, using the Kusuda Function.

The temperature of the water flowing for the warm and cold clusters is controlled by a valve using a PID controller. Moreover, the mass flow is controlled by a PID controller with a differential pressure control.

In scenarios 2 and 3 the short-term storage unit is implemented using the water tank storage model from buildings library.

4. Conclusions and Future Work

To begin with, this report review some of the most relevant aspects regarding thermal energy storage applied to district energy & district heating systems. A general overview of the available technologies, as well as the past, present and future lines of work were presented with the respective literature.

In what concerns the implementation in modelica with aim to achieve the goals initially defined for this project I believe some aspects have failed. Firstly, and most importantly the level of detail that was defined for the different components of the district proved to be higher than the required and feasible. This led to a major problem; unsustainable simulation time.

Modelica allows building and testing base models individually. Therefore, in order to estimate the simulation time of a top hierarchy model, only individual simulations were performed and the time was sumed. However, the simple fact that the models are combined made the simulation time to increase substantially more than what was expected. For this reason, and in the future it would be better to gradually create and test the base models combined in order to better estimate the simulation time subjacent to the entire model hierarchically above. In addition, it was possible to observe that it is not good from the point of view of stability, to have models from different libraries combined.

Nonetheless, Modelica/Dymola proved to be beneficial for increasing the modeling capabilities related to the assessment of topics concerning a district scale. Its feature of object-oriented modeling language, and the possibility of using and reusing libraries from different disciplines, can really save time to developers and enable a better understanding of different complex aspects thanks to its natural representation of systems.

As this project stills ongoing, future work will focus on reducing the level of detail of the most time consuming elements, such as the heat pump from the IDEAS library. Furthermore, the amount and resolution of PID controllers could also help to reduce the simulation time associated to the model. In addition, the methodology and base models used for the assessment of potential energy and economic savings resulting from the introduction of a short-term storage should be refined. As an example, instead of generating all the data with modelica, external software could be used and the generated values could be inputted.

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