OPERATIONAL AND DESIGN OPTIMIZATION METHODOLOGIES FOR FLEXIBILITY

VERSION 1.0

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EXECUTIVE SUMMARY

The report at hand is the deliverable D1.3. of Work Package 1 (WP1) of the Flexi-Sync project which summarizes the implementation of operational and design optimization methodologies for flexibility. The deliverable consolidates, withing the scope of WP1, the results from tasks T1.2 and T1.3 which are defined as follows:

> *Task 1.2 is "Operational flexibility enabled optimization". The characterization from Task 1.1 is used to develop optimization approaches that are widely usable and scalable. Different flexibility measures are included in the analysis (for example the thermal inertia of the buildings, the possibility to store heat in the network, as well as other storage solutions). The developed method will cover both optimization of operation and optimization-based control, the tasks is based on results from H2020 project Opti.*

> *Task 1.3 is "Design for operational flexibility", in it the principles and aspects that need to be consider on the design stage to enable operational flexibility are considered. There will be an interaction with WP2 and WP3 to safeguard the applicability in these contexts.*

The results obtained so far will be complemented by results from Work Packages 2 and 3, namely Tasks 2.2 and 3.3 in which the flexibility definition is applied at the simulation level of demonstrator areas and tested against the effect of weather conditions, respectively. Finally, a prototype solution will be implemented and tested in the real areas in Work Package 4.

CONTRIBUTION

Maryam Razi (LTU) developed and implemented the optimization algorithm and with the help of Khalid Atta (LTU), run the simulations on the dynamic model and obtained the preliminary results presented here. Maryam also wrote Sections 3 and 4 of this report, Khalid wrote Section 2 and Andre Yamashita (LTU) wrote Sections 1 and 5, based on the materials created by the group.

1 INTRODUCTION

In Flexi-sync we develop, test, and prepare a commercial solution for integration and optimization of flexibility in district heating and cooling systems. A successful implementation can increase the usage of renewable energy sources. The conceptualization and development of a prototype is not a trivial task, since we must meet the operating characteristics and demands of the consumer, distributor, and producer and at the same time, (i) provide a flexible and resilient solution and (ii) provide a (financial, environmental, societal) good solution.

Within the scope of Flexi-sync, flexibility is defined as the capacity of the proposed framework to accommodate conflicting requirements and calculate the best solution based on user-defined goals. Starting from this fundamental and abstract definition of flexibility, we searched the literature for its most common proxies in heating district optimization problems:

(i) capacity of the production side (Nuytten, Claessens, Paredis, van Bael and Six, 2013; Bachmaier, Narmsara, Eggers and Herkel, 2016),

(ii) available storage capacity on the consumer side (Finck, Li, Kramer and Zeiler, 2018; Stinner, Huchtemann and Müller, 2016; Kensby, Trüschel and Dalenbäck, 2015; Dominković, Gianniou, Münster, Heller and Rode, 2018),

(iii) demand response (Zhou, Zheng, Liu, Liu, Mei, Pan, Shi and Wu, 2019; Saurav, Choudhury, Chandan, Lingman and Linder, 2017; Clauß, Finck, Vogler-Finck and Beagon, 2017), (iv) thermal inertia of buildings (Li, Li, Zhang, Jiang, Chen and Li, 2020; de Coninck and Helsen, 2016) and

(iv) thermal comfort adaptation of the consumer (le Dréau and Heiselberg, 2016). Moreover, some authors try to define different dimensions of flexibility, for example time, power and energy (Stinner *et al.*, 2016) or size, time and costs (Finck *et al.*, 2018).

Further, flexibility can be defined as the degree to which a system can deviate from a baseline scenario and still be considered operational (Arroyo, Gowri, de Ridder and Helsen, 2017; de Coninck and Helsen, 2016) or to how well a model can represent a system (Arroyo, Spiessens and Helsen, 2020). These proxies are translated into constraints and are incorporated into the optimization problem to realize a flexible optimal solution (Morales-Valdés, Flores-Tlacuahuac, & Zavala, 2014).

In practice, flexibility is facilitated by technologies such as energy storage solutions, renewable energy sources, waste heat sources and process modelling, control and optimization. The interested reader is referred to Sun, Wang, Xiao and Gao (2013) for a review on peak loading shifting strategies and to Vandermeulen, van der

Heijde, and Helsen (2018) for a review on control strategies for district cooling and heating taking flexibility into account.

Once the concept of flexibility for heating and cooling districts is defined and translated into constrains, we are still left with defining an objective function for the optimization problem. We learned from the literature that different from flexibility, the expected goal of optimizing the integration of a heating and cooling district with renewable energy sources is to achieve peak shaving and valley filling (Powell, Kim, Cole, Kapoor, Mojica, Hedengren and Edgar, 2016) and to reduce energy consumption, which usually translates into reducing the operational cost of the integrated system (Li *et al.*, 2020; Zhou, *et al.*, 2019). Other authors use the concept of power shifting to implement a performance metric for the integration between thermal energy storage and energy generation. Saurav *et al.* (2017) calculates the ratio between stored energy variation to increase and to decrease the temperature of the storage by 2K, and Reynders, Diriken and Saelens (2017) calculate it as the rate of heat that can be transferred between storage and consumer.

In this report, we summarize the main results from Work Package 1: Flexibility characterization and operational flexibility, obtained between 05/2021 and 10/202.

1.1 Operational versus design optimization

In order to meet the scope of Work Package 1, it was necessary to understand the differences between operational and design characteristics of heating and cooling districts. Figures 1 and 2 illustrate the complexity of this task: on one hand, designing tasks have a time scale of years while on the other, operational tasks have a time scale of milliseconds to minutes.

As observed in Deliverable D1.1, renewable energy sources are intermittent and need therefore some kind of buffer to be incorporated. In this sense, flexibility from the district heating grid could be utilized to support the power grid through sector coupling points. The greater the fraction of renewable energy, the greater the need for either a large buffer (which is usually expensive) or a precise coordination strategy to mitigate the effects low availability of renewable energy. This is one aspect of flexibility that we explore in Flexi-sync and incorporate in our proposed solution.

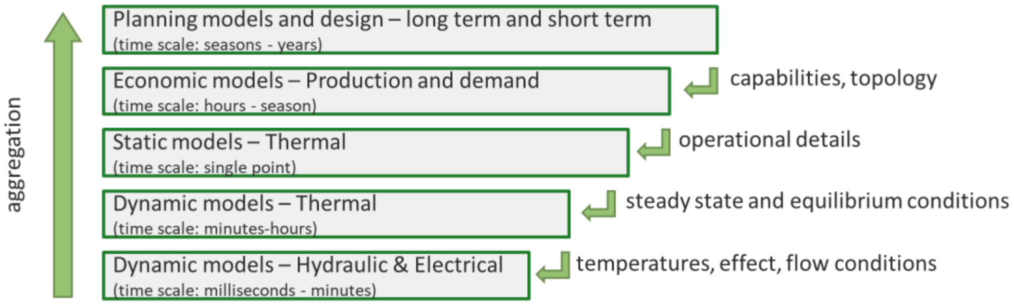

Figure 1: Hierarchical levels according to time scales and associated types of models used for representing the system, and for characterization and assessment of flexibility.

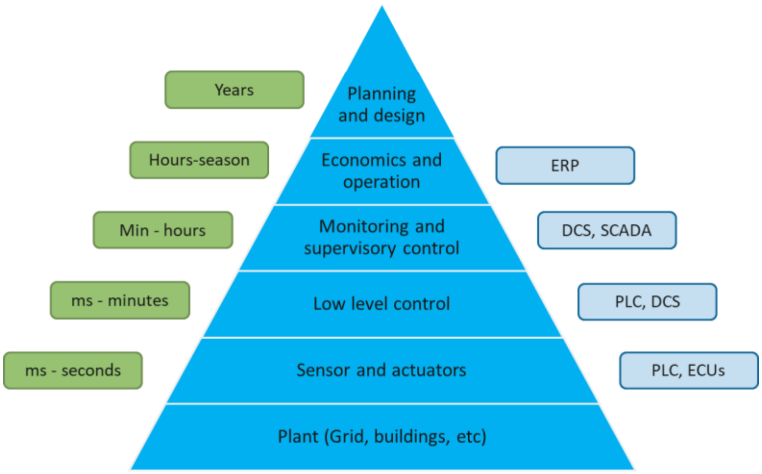

Figure 2: ISA-95 Automation pyramid with time scales and data sources for the association of modelling principles for flexibility.

Moreover, within the scope of Flexi-sync we must define a strategy to implement a flexibility transition from design to operation. In the former, flexibility is treated as the parameters and dimensions of the equipment in the system and can be illustrated as, for example, the number and size of water storage units. When we look at the operation scale, the flexibility that we once had at the design scale does not exist anymore, and becomes a part of the problem definition. On the other hand, as we are going to detail further in this report, it is not only possible but also beneficial to the overall objectives of integration of renewable energy and district heating and cooling systems, to define flexibility at the operation scale. This can be done, for example, by providing an acceptable temperature range in which the water storage units can operate and thus we can obtain an additional degree of freedom to the energy storage problem.

1.2 Organization of the report

The report is organized as follows. First, we formalize a systematic quantification of grid flexibility in Section 2. This definition serves as a theoretical basis to the optimization problem formulation and solution procedure detailed in Section 3. In Section 4 we describe the district heating system model of Luleå, Sweden, which was used as our testing bed. Finally, we present some conclusions in Section 5.

2 SYSTEMATIC QUANTIFICATION OF GRID FLEXIBILITY

The main objective is to find the parameters that will quantify the DH heat transportation network flexibility. These parameters are not unified between different components of the DH system and do not occur at the same flexibility level. Thus, the main parameters of the grid have to be converted into the required level of flexibility (refer to D1.2).

In this project, other work packages (for example WP2 that preforms the TIMES analysis) treat all the components in the grid as a potential energy storage system. Thus, it is required to quantify the different components in the system (including buildings, thermal energy storages, etc) and unify them at the same energy flexibility level. In the following subsections, we discuss and detail the calculation procedure of the parameters used to quantify grid flexibility.

2.1 Cycle efficiency (charge/discharge) [%]

The Cycle efficiency can be interpreted as the efficiency of the process of storing and extracting energy. It is related only to the Energy producers and the grid and it is not related to the consumers. This parameter highly depends on the type of the network and the type of the CHP plant/auxiliary boilers that is used in the process. It is dependent mainly on the efficiency of the generation units and the customer stations. Since the DH network is the end receiver of the energy, and from that point of view, the discharge efficiency is 100%. This is since the energy is stored within the destination transport media. The charge efficiency is also very high when we look from the energy perspective instead of the fuel point of view.

2.2 Yearly losses [%]

This parameter is dependent on the season of the year and the degree of isolation of the network. In general, it would be moderate, ranging around 10% to 15% (in Kiruna, Sweden it was around 12% during the year of 2010).

2.3 Auxiliary flow(s) (e.g., electricity consumption) [%]

Assume that the energy that will be added to the grid is $\mathrm{Q}\ \mathrm{MWh}$ and the amount of water in the grid is $V\ m^3$. The temperature of the grid ($\mathrm{T_s}\ °C$) will increase by $\Delta T\ °C$ following the equation:

$$Q \propto V * \Delta T \qquad (2\text{-}1)$$

Then we consider the consumer side equation: the energy consumption is $\mathrm{Q_c}\ \mathrm{MWh}$. The flow of water required by the user is $V_c \propto \frac{Q_c}{Ts}$. Then the new water demand will be:

$$V_c \propto \frac{Q_c}{T_s + \Delta T} \qquad (2\text{-}2)$$

The percentage of change in the flow will be $\frac{T_s}{T_s + \Delta T}$. Following the pumps curves, we can find the reduction of power. If we assume a linear relation between the pumped volume and the required power within the span they are varying within, then we can say that the reduction of power is:

$$\left(-\frac{T_s}{T_s + \Delta T}\right) * 100\% \quad (2\text{-}3)$$

Keep in mind that the calculation assumes that the consumer stations are efficient, and we assume a fixed return temperature.

Observe that this factor would have a negative impact on the water auxiliary flow. The reason behind it is that the energy stored in the grid makes the temperature of the water in the grid increase, which leads to less water being drawn by the customers at the same energy demand (consumed). Therefore, the pumping stations would pump less water.

2.4 Maximum inflow / maximum outflow [MW]

This parameter is dependent on the energy supply capacity, raise of temperature and the pumping flowrate. The calculation cannot be performed as easily as for the storage tanks. The main problem is the time delay in water transportation in the grid. A non-homogenous increase of the temperature in the grid might cause an oscillatory behavior that will lead to transient operation of the plant. Consider that the grid is required to store Q MWh and the amount of water available in the grid is $V\ m^3$. The temperature of the grid ($\mathrm{T_s}$ $°C$) will increase by ΔT. If the flow in the main pumping station is $\mathrm{q\ m^3/h}$ then the flow required for a homogenous operation should be:

$$Flow[MW] = \mathrm{q} * c * \Delta T \quad (2\text{-}4)$$

where c is the specific heat capacity of water in $\frac{MWh}{m^3 °C}$. On the other hand, it can be treated as the difference between the maximum power of the CHP plant minus the nominal power generation of the CHP.

2.5 Maximum capacity [MWh]

This parameter is more dependent on the water volume and the maximum possible temperature increase:

$$Maximum\ capacity\ [MWh] = V * c * \Delta T \quad (2\text{-}5)$$

2.6 Investment cost [kEUR/TJ]

The solution to utilize the grid as a heat storage has no investment cost and the flexibility can be utilized immediately.

3 OPTIMIZATION PROBLEM FOR OPERATIONAL FLEXIBILITY

In the definition of the optimization problem, we take into account the dimensions of flexibility and complexity. The former is implemented by relaxing constraints. The latter on the other hand, has to do with the fact that the optimization of a district heating and cooling system involves spatial and temporal distributions. The elements of the district (conventional and renewable energy-based energy generators, storage elements, buildings) are scattered over an area. The constraints and goals of each element must be considered. Moreover, the goals of the system are usually defined at the planning and design stage and must be adapted to the operation stage (time scale conversion from years to seconds).

In this Section we propose a new optimization problem based on the problem reported in Deliverable D1.2., but cast as a Mixed Integer Linear Programming (MILP) problem and solved using the Model Predictive Control (MPC) approach. In Subsection 3.1 we explain the proposed optimization problem. The constraints of the problem are described in Subsection 3.2 and finally the solution of the problem is presented in Subsection 3.3.

3.1 Optimization problem

In this section, the energy management optimization problem of a district heating and cooling system (DHCS) is stated. This system consists of energy generation, distribution, and consumption parts. In a DHCS, the thermal energy produced by generation units, including CHP units and boilers on the heating side and chillers on the cooling side, is carried by water medium in pipelines and pumped to primary heat exchangers. Then, it is delivered to consumers by secondary heat exchangers.

To state the problem, time is discretized with zero-order hold. For a chosen sampling interval Δt, discretization will give time instances $\tau = h\Delta t, h = 0, 1, \dots$. The optimization problem is formulated in a Model Predictive Control (MPC) framework with a prediction horizon N. The MPC is updated at every instant τ. The time instant along the prediction horizon of each update is represented by $t = \tau + k\Delta t, k = 0, 1, \dots, N-1$.

Because system dynamics impose constraints on the optimization problem, first, the DHCS model is given, and then the objective function is presented.

3.1.1 Pipeline model

The model of distribution part in the DHCS includes energy balance and mass flow continuity equations in pipes and nodes. According to the first law of thermodynamic, the energy flowing into one node is equal to the energy flowing out, Gu *et al.* (2017). Then,

$$\sum_{j\in S_{p,l}^{e,n}} Q_{p,j}^{out}(k+h|h) - \sum_{j\in S_{p,l}^{s,n}} Q_{p,j}^{in}(k+h|h) = 0. \tag{3-1}$$

The delay time of the temperature change at the outlet of every pipe is calculated as (Gu *et al.*, 2017, and Li *et al.*, 2020):

$$t_{delay,j}(k+h|h) = K_{delay}\frac{L_j}{v_j(k+h|h)}, \quad j \in S_{ps} \cup S_{pr}. \tag{3-2}$$

To convert the delay time to the length of time interval in hour, $t_{delay,j}(k+h|h)/(3600\,\Delta t)$ is rounded up to $k_{d,j}(k+h|h)$. By considering the delay time and energy loss in pipes, thermal power at the outlet of pipes can be formulated as:

$$Q_{p,j}^{out}\left(k+k_{d,j}(k+h|h)+h|h\right) = \left(1-\mu_{loss,j}L_j\right)Q_{p,j}^{in}(k+h|h), \quad j \in S_{ps} \cup S_{pr}. \tag{3-3}$$

Because of the wear protection for the pipes, the thermal power change is limited to:

$$\underline{\Delta Q}_p \le \Delta Q_{p,j}^{a}(k+h|h) \le \overline{\Delta Q}_p, \qquad a \in \{in, out\}, \quad j \in S_{ps} \cup S_{pr}. \tag{3-4}$$

To ensure stable operation of DHCS, the thermal power at the inlet and outlet of supply and return pipes on heating side of DHCS is bounded according to:

$$\underline{Q}_{ps,h} \le Q_{p,j}^{a}(k+h|h) \le \overline{Q}_{ps,h}, \qquad a \in \{in, out\}, \quad j \in S_{ps} \tag{3-5}$$

$$\underline{Q}_{pr,h} \le Q_{p,j}^{a}(k+h|h) \le \overline{Q}_{pr,h}, \qquad a \in \{in, out\}, \quad j \in S_{pr}. \tag{3-6}$$

Similarly, the thermal power at the inlet and outlet of pipes on cooling side is bounded according to:

$$\underline{Q}_{ps,c} \le Q_{p,j}^{a}(k+h|h) \le \overline{Q}_{ps,c}, \qquad a \in \{in, out\}, \quad j \in S_{ps} \tag{3-7}$$

$$\underline{Q}_{pr,c} \le Q_{p,j}^{a}(k+h|h) \le \overline{Q}_{pr,c}, \qquad a \in \{in, out\}, \quad j \in S_{pr}. \tag{3-8}$$

According to the Kirchhoff laws, the balances of flow in nodes are expressed as (Gu *et al.*, 2017, and Zhou *et al.*, 2019):

$$\sum_{j\in S_{p,l}^{e,n}} m_{p,j}(k+h|h) - \sum_{j\in S_{p,l}^{s,n}} m_{p,j}(k+h|h) = 0. \tag{3-9}$$

The pressure loss in pipe j is formulated by

$$\Delta P_{p,j}(k+h|h) = \mu_{p,j} m_{p,j}^2(k+h|h), \qquad j \in S_{ps} \cup S_{pr}. \tag{3-10}$$

The total pressure loss in the pipes is equal to the pressure supplied by all pumps (Gu *et al.,* 2017):

$$\sum_{j\in S_{ps}\cup S_{pr}} \Delta P_{p,j}(k+h|h) = \sum_{i\in S_{pu}} P_{pu,i}(k+h|h). \tag{3-11}$$

The velocity of the medium in pipe j is proportional to its flow and inversely proportional to the diameter of the pipe and can be calculated as:

$$v_j(k+h|h) = \frac{m_{p,j}(k+h|h)}{\rho\pi(d_{p,j}/2)^2}, \qquad j \in S_{ps} \cup S_{pr}. \tag{3-12}$$

3.1.2 Heat exchanger model

The thermal power in a primary heat exchanger is formulated as:

$$\left(Q_{p,j_1}^{in}(k+h|h) - Q_{p,j_2}^{out}(k+h|h)\right) / \eta_{he,i} = Q_i(k+h|h), \; j_1 \in S_{ps,i}, \; j_2 \in S_{pr,i}. \tag{3-13}$$

The continuity of medium in the heat exchangers imposes (Gu *et al.*, 2017):

$$m_{p,j_1}(k+h|h) = m_{p,j_2}(k+h|h), \qquad j_1 \in S_{ps,i}, \; j_2 \in S_{pr,i}. \tag{3-14}$$

The thermal power in a secondary heat exchanger can be calculated as:

$$\left(Q_{p,j_1}^{out}(k+h|h) - Q_{p,j_2}^{in}(k+h|h)\right)\eta_{he,m} = \sum_{i=1}^{N_{zm}} Q_{R,i}(k+h|h), \quad j_1 \in S_{ps,m}, \; j_2 \in S_{pr,m} \tag{3-15}$$

Similarly, there are continuity constraints on the secondary heat exchangers too.

3.1.3 Buildings model

The thermal network model of the building zones includes thermal resistance (R) and thermal capacity (C), which have the capability to transmit and preserve thermal energy, respectively. Different architectures of RC model can be considered, and the building model is aggregated by several similar structural zone (Li *et al.,* (2020), Arroyo *et al.,* (2018), and Jiang *et al.* (2018)). The temperature change in a zone is expressed as:

$$C_{z,i}\Delta T_{z,i}(k+h|h) = f\left(T_a(k+h|h), T_w(k+h|h), Q_{R,i}(k+h|h), Q_{rad,i}(k+h|h)\right)\Delta t. \tag{3-16}$$

The comfort requirement of aggregated buildings should be fulfilled. Then, the indoor temperature of buildings should be kept within the limits set by considering the acceptable comfort:

$$\underline{T}_{z,i} \le T_{z,i}(k+h|h) \le \overline{T}_{z,i}. \tag{3-17}$$

Having a detailed model for the building enables us to assess the effect that extreme climate conditions have on the system and how operational flexibility is affected. Such extreme climate conditions can be reflected in terms of the ambient temperature, but also wind speeds, air humidity, and solar irradiation.

In the currently suggested building model approach the ambient temperature T_a is available as a factor in (3-16). Analysing different climatic scenario will result in different levels of thermal energy that can be stored in the building mass and will affect the flexibility offered to the grid operation. Performing simulation-based what-if analysis for the projected climatic scenario will provide the needed insights on how extreme climate will disturb the operation of the current DHC system.

3.1.4 Thermal energy storage (TES) model

In the DHCS, thermal energy storages can be used for some reasons, e.g., peak shaving, and cost optimization (Vandermeulen *et al.,* 2018). The thermal power of TES is calculated as follows:

$$\Delta Q_{s,i}(k+h|h) = \lambda_{s,i}\big(Q_{s,i}(k+h|h) - Q_{s0,i}\big) + \eta_{in,i}Q_{s,i}^{in}(k+h|h) - \frac{Q_{s,i}^{out}(k+h|h)}{\eta_{out,i}}. \tag{3-18}$$

The value calculated by (3-18) is constrained by the following inequalities:

$$\underline{Q}_{s,i} \le Q_{s,i}(k+h|h) \le \overline{Q}_{s,i} \tag{3-19}$$

$$0 \le Q_{s,i}^{in}(k+h|h) \le \overline{Q}_{s,i}^{in} \tag{3-20}$$

$$0 \le Q_{s,i}^{out}(k+h|h) \le \overline{Q}_{s,i}^{out} \tag{3-21}$$

$$Q_{s,i}^{in}(k+h|h)Q_{s,i}^{out}(k+h|h) = 0. \tag{3-22}$$

We consider that the initial value of TES thermal power at the beginning of the time horizon is:

$$Q_{s,i}(h|h) = Q_{0,i}(h). \tag{3-23}$$

3.1.5 Problem statement

The objective of the optimization problem is to minimize the thermal power production cost while taking account of the income from the electricity market.

$$\begin{aligned}\min_{Q_i,u_i} \sum_{k=0}^{N-1} \Bigg(& \sum_{i\in S_{hG}} \alpha_i Q_i(k+h|h) + \sum_{i\in S_{ec}} \beta_{c,i}(k+h)Q_i(k+h|h) \\ & - \sum_{i\in S_C} \frac{\beta(k+h)}{\phi_i} Q_i(k+h|h) \\ & + \sum_{i\in S_G} \Big(\gamma_{on,i}\big(u_i(k+h+1|h) - u_i(k+h|h)\big)u_i(k+h \\ & + 1|h) \\ & + \gamma_{off,i}\big(u_i(k+h|h) - u_i(k+h+1|h)\big)\big(1 \\ & - u_i(k+h+1|h)\big)\Big)\Bigg)\Delta t \\ & + \sum_{i\in S_G} \Big(\gamma_{on,i}\big(u_i(h|h) - u_i(h-1|h-1)\big)u_i(h|h) \\ & + \gamma_{off,i}\big(u_i(h-1|h-1) - u_i(h|h)\big)\big(1 - u_i(h|h)\big)\Big)\Delta t \end{aligned} \tag{3-24}$$

s.t.: (3-1) - (3-23)

$$u_i(k+h|h)\underline{Q}_i \le Q_i(k+h|h) \le u_i(k+h|h)\overline{Q}_i, \quad i \in S_G \tag{3-25}$$

$$Q_i(k+h|h) = Q_i^D(k+h|h) + \textstyle\sum_{j\in S_{hT}} \delta_{i,j} Q_{i,j}^s(k+h|h), \quad i \in S_{hG} \tag{3-26}$$

$$Q_i(k+h|h) = Q_i^D(k+h|h) + \textstyle\sum_{j\in S_{cT}} \delta_{i,j} Q_{i,j}^s(k+h|h), \quad i \in S_{ac} \cup S_{ec} \tag{3-27}$$

$$0 \le Q_i^D(k+h|h) \le u_i(k+h|h)\overline{Q}_i, \quad i \in S_G \tag{3-28}$$

$$0 \leq \sum_{j \in S_{hT}} \delta_{i,j} Q_{i,j}^{s}(k+h|h) \leq u_i(k+h|h)\overline{Q}_i, \quad i \in S_{hG} \tag{3-29}$$

$$0 \leq \sum_{j \in S_{cT}} \delta_{i,j} Q_{i,j}^{s}(k+h|h) \leq u_i(k+h|h)\overline{Q}_i, \quad i \in S_{ac} \cup S_{ec} \tag{3-30}$$

$$\sum_{i \in S_{hG}} Q_{i,j}^{s}(k+h|h) = Q_{s,j}^{in}(k+h|h) - Q_j^{rs}(k+h|h), \;\; j \in S_{hT} \tag{3-31}$$

$$\sum_{i \in S_{ac} \cup S_{ec}} Q_{i,j}^{s}(k+h|h) = Q_{s,j}^{in}(k+h|h), \;\; j \in S_{cT} \tag{3-32}$$

$$\begin{aligned} \sum_{i \in S_{hG}} Q_i(k+h|h) &= Q_{h,dem}(k+h|h) + Q_{h,loss}(k+h|h) \\ &+ \sum_{i \in S_{hT}} \Big(Q_{s,i}^{in}(k+h|h) - Q_i^{rs}(k+h|h) \\ &- Q_{s,i}^{out}(k+h|h) \Big) + \sum_{i \in S_{ac}} Q_i(k+h|h) \end{aligned} \tag{3-33}$$

$$\begin{aligned} \sum_{i \in S_{ac} \cup S_{ec}} Q_i(k+h|h) &= Q_{c,dem}(k+h|h) + Q_{c,loss}(k+h|h) \\ &+ \sum_{i \in S_{cT}} \Big(Q_{s,i}^{in}(k+h|h) - Q_{s,i}^{out}(k+h|h) \Big) \end{aligned} \tag{3-34}$$

$$\begin{aligned} \underline{\tau}_{on,i}\big(u_i(k+h|h) - u_i(k+1+h|h)\big)u_i(k+h|h) &\leq \left(\sum_{n=0}^{k} u_i(n+h|h)\Delta t \right) u_i(n+h|h) \\ &+ \left(\sum_{n=\tau_{1,i}}^{h-1} u_i(n|n)\Delta t \right) u_i(n|n), \quad i \in S_G \end{aligned} \tag{3-35}$$

$$\begin{aligned} \underline{\tau}_{off,i}\big(u_i(k+1+h|h) - u_i(k+h|h)\big)\big(1 - u_i(k+h|h)\big) &\leq \left(\sum_{n=0}^{k} \big(1 - u_i(n+h|h)\big)\Delta t \right) \big(1 - u_i(n+h|h)\big) \\ &+ \left(\sum_{n=\tau_{2,i}}^{h-1} \big(1 - u_i(n|n)\big)\Delta t \right) \big(1 - u_i(n|n)\big), \quad i \in S_G \end{aligned} \tag{3-36}$$

$$r_{u,i}\Delta t \leq P_i(k+1+h|h) - P_i(k+h|h) \leq r_{d,i}\Delta t, \quad i \in S_C \tag{3-37}$$

$$r_{u,i}\Delta t \leq P_i(h|h) - P_i(h-1|h-1) \leq r_{d,i}\Delta t, \qquad i \in S_C \tag{3-38}$$

where $P_i = Q_i/\phi_i,\; i \in S_C$, and $\underline{\tau}_{on,i}/\Delta t$ and $\underline{\tau}_{off,i}/\Delta t$ are rounded down to $\tau_{1,i}$ and $\tau_{2,i}$, respectively.

Remark: If the penalties for starting up and shutting down unit i are equal, i.e. $\gamma_{on,i} = \gamma_{off,i} = \gamma_i$, then the second and third terms in the objective function can be replaced with $\gamma_i\big(u_i(k+1+h|h) - u_i(k+h|h)\big)^2$.

Furthermore, the equality constraint (3-33) can be replaced with

$$\begin{aligned}
&Q_{h,dem}(k+h|h) + Q_{h,loss}(k+h|h) + \sum_{i\in S_{hT}} \left(Q_{s,i}^{in}(k+h|h) - Q_i^{rs}(k+h|h)\right) \\
&\quad - \sum_{i\in S_{hT}} \min\left(\hat{Q}_{s,i}^{out}(k+t|t), \overline{Q}_{s,i}^{out}\right) + \sum_{i\in S_{ac}} Q_i(k+h|h) \\
&\quad \le \sum_{i\in S_{hG}} Q_i(k+h|h) \\
&\quad \le Q_{h,dem}(k+h|h) + Q_{h,loss}(k+h|h) \\
&\quad + \sum_{i\in S_{hT}} \min\left(\hat{Q}_{s,i}^{in}(k+h|h), \overline{Q}_{s,i}^{in}\right) - \sum_{i\in S_{hT}} Q_{s,i}^{out}(k+h|h) \\
&\quad + \sum_{i\in S_{ac}} Q_i(k+h|h)
\end{aligned} \tag{3-39}$$

where $\hat{Q}_{s,i}^{out}$ is thermal power of TES i inserted in DHCS where $Q_{s,i}(k+h|h) = \underline{Q}_{s,i}$, i.e. TES is fully discharged and $\hat{Q}_{s,i}^{in}$ is power inserted in TES i where $Q_{s,i}(k+h|h) = \overline{Q}_{s,i}$, i.e. TES is fully charged. Similarly, constraint (3-34) can be replaced with

$$\begin{aligned}
&Q_{c,dem}(k+h|h) + Q_{c,loss}(k+h|h) + \sum_{i\in S_{cT}} Q_{s,i}^{in}(k+h|h) \\
&\quad - \sum_{i\in S_{cT}} \min\left(\hat{Q}_{s,i}^{out}(k+t|t), \overline{Q}_{s,i}^{out}\right) \le \sum_{i\in S_{ac}\cup S_{ec}} Q_i(k+h|h) \\
&\quad \le Q_{c,dem}(k+h|h) + Q_{c,loss}(k+h|h) \\
&\quad + \sum_{i\in S_{cT}} \min\left(\hat{Q}_{s,i}^{in}(k+h|h), \overline{Q}_{s,i}^{in}\right) - \sum_{i\in S_{cT}} Q_{s,i}^{out}(k+h|h)
\end{aligned} \tag{3-40}$$

In (3-17), the comfort bounds are relaxed to

$$\underline{T}_{z,i} - \epsilon_i(k+h|h) \le T_{z,i}(k+h|h) \le \overline{T}_{z,i} + \epsilon_i(k+h|h) \tag{3-41}$$

where $\epsilon_i(k) \ge 0$ can be random numbers, e.g., uniformly distributed random numbers.

If the optimization problem is not subject to the model of the buildings and their temperature, then the flexibility can be considered as

$$\underline{Q}_{R,i} \le Q_{R,i}(k+h|h) \le \overline{Q}_{R,i}. \tag{3-42}$$

3.1.6 Reformulating the optimization problem

The stated optimization problem for a DHCS is a mixed-integer nonlinear program. Because of some limitations of methods applied for solving these problems using

Matlab, e.g., the number of integer variables, the problem has been reformulated as a mixed-integer linear program.

In the objective function (3-24), the generation units turning on and off have been penalized using some nonlinear terms.

To reformulate them as some linear terms, for every unit i, integer variables, $S_{on,i}$ and $S_{off,i}$, are introduced and the following constraints are imposed on the problem as (Verrilli *et al.,* 2017)

$$S_{on,i}(h+k|h) \geq 0, \quad i \in S_G \tag{3-43}$$

$$S_{on,i}(h|h) \geq u_i(h|h) - u_i(h-1|h-1), \quad i \in S_G, \quad k=0 \tag{3-44}$$

$$S_{on,i}(k+h|h) \geq u_i(k+h|h) - u_i(k+h-1|h), \quad i \in S_G, \\ 0 < k \leq N-1 \tag{3-45}$$

$$S_{off,i}(k+h|h) \geq 0, \quad i \in S_G \tag{3-46}$$

$$S_{off,i}(h|h) \geq u_i(h-1|h-1) - u_i(h|h), \quad i \in S_G\,, \quad k=0 \tag{3-47}$$

$$S_{off,i}(k+h|h) \geq u_i(k+h-1|h) - u_i(k+h|h), \quad i \in S_G, \\ 0 < k \leq N-1. \tag{3-48}$$

Furthermore, by considering feasible operation regions of CHPs, the heat to power ratio of the CHP, ϕ_i in (3-24), is bounded, and the problem is subject to:

$$\underline{\phi}_i P_i\,(k+h|h) \leq Q_i\,(k+h|h) \leq \overline{\phi}_i P_i\,(k+h|h), \quad i \in S_C. \tag{3-49}$$

Then, (3-24) can be rewritten as

$$\min_{Q_i,u_i} \sum_{k=0}^{N-1} \Bigg(\sum_{i \in S_{hG}} \alpha_i Q_i(k+h|h) + \sum_{i \in S_{ec}} \beta_{c,i}(k+h) Q_i(k+h|h) \\ - \sum_{i \in S_C} \beta(k+h)\, P_i(k+h|h) + \sum_{i \in S_G} \gamma_{on,i}\, S_{on}(k+h|h) \\ + \sum_{i \in S_G} \gamma_{off,i}\, S_{off}(k+h|h) \Bigg) \Delta t. \tag{3-50}$$

The optimization problem includes nonlinear constraints (3-22), (3-35), and (3-36), which must be reformulated. In the TES model, to remove (3-22), we define an integer variable

$$u_{T,i}(k+h|h) = \begin{cases} 1 & \text{if TES } i \text{ discharges at } k \\ 0 & \text{otherwise} \end{cases} \tag{3-51}$$

and replace (3-20) and (3-21) with

$$0 \leq Q_{s,i}^{in}(k+h|h) \leq \big(1 - u_{T,i}(k+h|h)\big)\overline{Q}_{s,i}^{in} \tag{3-52}$$

$$0 \leq Q_{s,i}^{out}(k+h|h) \leq u_{T,i}(k+h|h)\overline{Q}_{s,i}^{out}. \tag{3-53}$$

To reformulate the nonlinear constraints (3-35) and (3-36), we define

$$\tau_{on,i}(h) = \begin{cases} 0 & h = 0 \\ \big(\tau_{on,i}(h-1) + \Delta t\big)u_i(h|h) & h \geq 1 \end{cases} \tag{3-54}$$

and

$$\tau_{off,i}(h) = \begin{cases} 0 & h = 0 \\ \big(\tau_{off,i}(h-1) + \Delta t\big)(1 - u_i(h|h)) & h \geq 1 \end{cases} \tag{3-55}$$

as the time intervals in which the unit i is continuously on and off, respectively. Then, we calculate

$$m_{1,i} = \max\left(0, \frac{\underline{\tau}_{on,i} - \tau_{on,i}(h-1)}{\Delta t}\right) \tag{3-56}$$

and

$$n_{1,i} = \max\left(0, \frac{\underline{\tau}_{off,i} - \tau_{off,i}(h-1)}{\Delta t}\right). \tag{3-57}$$

If $m_{1,i}\tau_{on,i}(h-1) \neq 0$, then (3-35) and (3-36) are replaced with

$$\sum_{j=0}^{min\,(m_i-1,N-1)} u_i(j+h|h) \geq m_i \tag{3-58}$$

$$\begin{aligned} u_i(k+h|h) - u_i(k+h-1|h) &\leq u_i(j+h|h), \\ & m_i + k_{on,i} - 1 \leq k \leq N-2, \quad k+1 \leq j \\ & \leq \min\,(k + k_{on,i} - 1, N-1) \end{aligned} \tag{3-59}$$

$$\begin{aligned} u_i(k+h|h) - u_i(k+h-1|h) &\geq u_i(j+h|h) - 1, \\ & m_i + 1 \leq k \leq N-2, \quad k+1 \leq j \\ & \leq \min\,(k + k_{off,i} - 1, N-1) \end{aligned} \tag{3-60}$$

where $m_{1,i}$, $\underline{\tau}_{on,i}/\Delta t$, and $\underline{\tau}_{off,i}/\Delta t$ are rounded up to m_i, $k_{on,i}$, and $k_{off,i}$ respectively.

If $m_{1,i} = 0$, i.e., $\tau_{on,i}(h-1) \geq \underline{\tau}_{on,i}$, then in addition to (3-59) and (3-60),

$$\begin{aligned} u_i(h|h) - u_i(h-1|h-1) &\geq u_i(j+h|h) - 1, \\ & 1 \leq j \leq \min\big(k_{off,i} - 1, N-1\big) \end{aligned} \tag{3-61}$$

is imposed on the problem.

Similarly, when $n_{1,i}\tau_{off,i}(h-1) \neq 0$, (3-35) and (3-36) are replaced with

$$\sum_{j=0}^{\min\,(n_i-1,N-1)} \big(1 - u_i(j+h|h)\big) \geq n_i \tag{3-62}$$

$$u_i(k+h|h) - u_i(k+h-1|h) \le u_i(j+h|h), \quad n_i + 1 \le k \le N-2, \quad k+1 \le j \le \min(k+k_{on,i}-1, N-1) \tag{3-63}$$

$$u_i(k+h|h) - u_i(k+h-1|h) \ge u_i(j+h|h) - 1, \quad n_i + k_{off,i} - 1 \le k \le N-2, \quad k+1 \le j \le \min(k+k_{off,i}-1, N-1) \tag{3-64}$$

where $n_{1,i}$ is rounded up to n_i.

If $n_{1,i} = 0$, i.e., $\tau_{off,i}(h-1) \ge \underline{\tau}_{off,i}$, then (3-63), (3-64), and the following constraint must be satisfied:

$$u_i(h|h) - u_i(h-1|h-1) \le u_i(j+h|h), \quad 1 \le j \le \min\left(k_{on,i} - 1, N-1\right). \tag{3-65}$$

Remark: To reformulate (3-35) and (3-36), some conditional constraints in the minimum number are imposed on the optimization problem.

When defining the conditional constraints it is impossible to simulate by some software, (3-59) and (3-60) for $1 \le k \le N-2$, (3-61), (3-65) and

$$\tau_{on,i}(h-1) \sum_{j=0}^{min\,(\max\,(0, m_i - 1), N-1)} u_i(j+h|h) \ge \tau_{on,i}(h-1) m_i \tag{3-66}$$

$$\tau_{off,i}(h-1) \sum_{j=0}^{\min\,(\max\,(0, n_i - 1), N-1)} \left(1 - u_i(j+h|h)\right) \ge \tau_{off,i}(h-1) n_i \tag{3-67}$$

replace (3-35) and (3-36).

In addition to the reformulation of the nonlinear constraints in the optimization problem, ramp up and ramp down limits on thermal power production of the units are considered as

$$r_{qu,i}\Delta t \le Q_i(k+1+h|h) - Q_i(k+h|h) \le r_{qd,i}\Delta t, \quad i \in S_G \tag{3-68}$$

$$r_{qu,i}\Delta t \le Q_i(h|h) - Q_i(h-1|h-1) \le r_{qd,i}\Delta t, \quad i \in S_G. \tag{3-69}$$

3.2 Implementing flexibility for operational optimisation

The design flexibility of a DHC system is determined during the planning and design stage and thus, is defined for a longer time scale than that of the optimization of operation. Moreover, the design and planning stage addresses future scenarios that might include the current DHC system or be a further development of it. Hence, the planning and design stage determines the boundary conditions of the operation and must be translated into the constraints and parameters of the optimization problem at the operation stage.

The design of the DHC defines the dimensions of the production units and thermal storages and the pipe characteristics of the distribution system. Further, the thermal characteristics of buildings, on the consumer side, are also defined at the design stage. All these characteristics and dimensioning values will contribute to define the constraints and parameters of the optimization problem. They not only enable a more flexible operation, but also impose fundamental limitations on the operation of a DHC system, limiting its performance.

As defined in Deliverable D1.1, we consider the following characteristics of flexibility: *Level of flexibility, Complexity of evaluation, Impact, Drawbacks, Requirements and Nature of flexibility*. These characteristics govern our decisions with respect to designing a flexible solution for the integration between district heating and cooling systems and renewable energy sources.

In the following paragraphs we present how the constraints and parameters in the problem formulation of the operation optimization are derived from planning and design flexibility.

3.2.1 Thermal power production units

We consider two types of thermal power production units: heating/cooling plant (simple, only supplies thermal energy) and CHP plant (more complex, determines how the supplied energy is used).

The resulting boundary conditions are characterized by the lower and upper bounds of the energy that can be produced by a production unit ($\underline{Q}_i$ and $\overline{Q}_i$ in (3-25) and (3-28), respectively). From a design perspective the upper bound is usually given, but from an operational perspective the lower bound is usually imposed as a minimum production level.

The CHP plants also have a ratio factor that determines the ratio between electricity and heat production, more commonly referred to as the alpha value. From a design perspective, there might be a constraint available for it, and this is considered in our simulations.

3.2.2 Distribution

Usually, the distribution is characterized by dimensioning numbers related to the dimensions and placement of the pipes. These numbers are needed to build the correct system model for the operational optimisation and might not be known from the planning phase directly but will be determined during the design phase of the system.

Note that the pipe dimensions impose a fundamental limitation on the material flow characteristics and will limit the achievable distribution performance.

According to the result on pipe wear described in D5.2, it is possible to impose constraints on the allowed fluctuations in the pipes. The wear protection factor is introduced as $\underline{\Delta Q}_p$ and $\overline{\Delta Q}_p$ in (3-4). However, if its effect is negligible, this constraint can be removed from the optimization problem.

3.2.3 Buildings

From a design and planning perspective, the thermal storage capacity of the building mass is offering flexibility. In addition, the thermal comfort range of the residents over time is also an important factor in terms of flexibility, but it is not design or planning related.

The thermal capacity $C_{z,i}$ of the comfort zone i in (3-16) needs to be determined from a design and planning perspective in the future scenarios. Observe that the term 'comfort zone' should not be confused with the thermal comfort range of a resident. A comfort zone, as defined in this report, is a space in the building where a certain desired temperature set point is defined. Depending on the degree of aggregation in the design and planning, this parameter needs to be adapted to the correct level of detail.

3.2.4 Thermal Energy Storages

A thermal energy storage can be charged and discharged, and the main limiting factor is the energy $\overline{Q}_s$ that can be stored, but there can also be a lower storage limit as well, denoted as $\underline{Q}_s$. The constraint is given in (3-19) and will be determined at the design and planning stage.

Further, there might be constraints on the ability to charge or discharge an energy storage within a certain timeframe which are determined at both operational and plant design stages. Such constraints directly affect the ability to make use of the available flexibility of TESs from an operational perspective. The constraints are considered during the design and planning stage and included in the optimization problem formulation as $\overline{Q}_{s,i}^{in}$ and $\overline{Q}_{s,i}^{out}$ in (3-20) and (3-21), respectively.

3.3 Solution to the Optimization problem

To solve the problem, an MPC can be employed. In MPC algorithms, at every time instant $\tau = h\Delta t$, an objective function is minimized, and the set of future control inputs at $t = \tau + k\Delta t, k = 0, 1, \dots, N - 1$ is calculated. Then, the first optimal value of the sequence is applied, and the horizon is displaced towards the future.

The DHCS optimal control presented in the previous section aims to minimize cost of energy production while considering the income from the electricity market. This problem is solved at every time instant, and the optimal on/off state of thermal energy generation units and optimal power produced by them are obtained.

4 TEST CASE FOR PRE-VALIDATION

We will now use a real-life city test case to evaluate the introduction of flexibility using a TES. Since the models for the Spanish demo site, ParcBit (Palma de Mallorca, Spain), were not ready at the time of conducting this work, DHS in Luleå, Sweden was used as an alternative city-scale case. The are relevant differences between the average temperature ranges encountered in Palma de Mallorca and Luleå, as show in Figure 3. From a heating perspective the Luleå case is more challenging due to the lower temperatures and the greater amplitude. Additionally, the Spanish demo site includes district cooling system too.

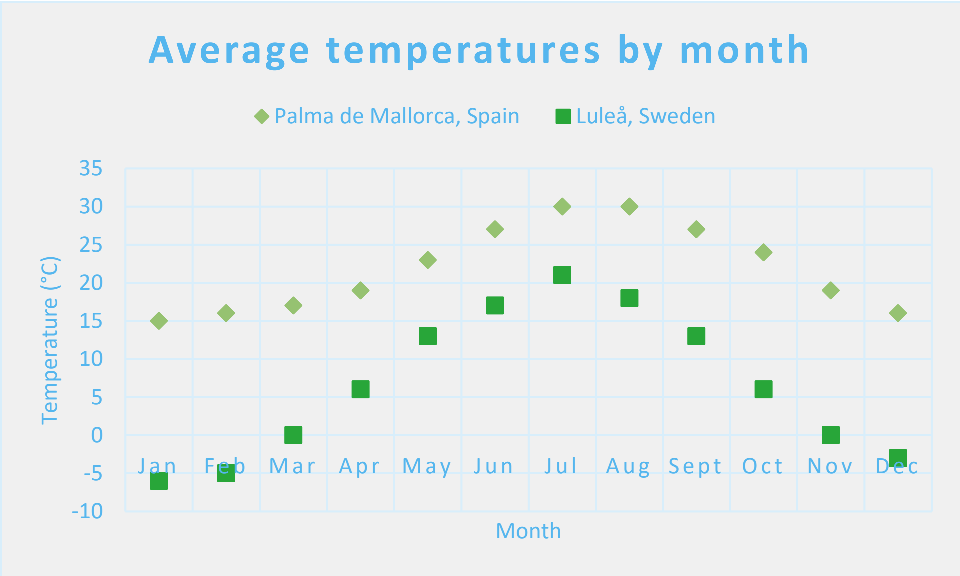

Figure 3: Average temperatures by month in Palma de Mallorca (Spain) and Luleå (Sweden). Data extracted from NOAA.

4.1 Luleå district

The DHS in Luleå has been studied and analysed in the EU H2020 project OPTi and will be used as a test case here, as a complete dynamic model of the DHS is available and implemented in a simulation environment. The simulator replicates all three main parts as a combination of physics-based models, machine learning models (black box), namely the generation, the distribution, and the consumer side (end users). Since the city is geographically quite large, several generation units are distributed over the city and connected to the same thermal grid. Figure 4 shows an overview of the thermal grid, with a distance of close to 20 km main generation unit and the farthest point of consumption.

The main generation unit uses a CHP plant that is located near the steel factory and utilizes the surplus gas from the blast furnace at the steel mill as its primary energy source. The power/heat generation ratio is determined based on the demand and the electricity price on the market. In addition to the CHP, four other heat generation units are geographically distributed over the city showed by HVC (HetVattenCentral or heating boiler plant) in Figure 4, and one close-by to the CHP plant. Every additional unit includes several heat only boilers. Moreover, a large heat storage tank has been considered as a TES.

The distribution network consists of a large network of double pipes (2 x 22376 pipes for supply and return) that deliver the heat energy to Luleå City. Pumping stations will ensure optimal flow in the network such that an optimal energy transfer to all the consumers in the city is guaranteed. Each heat generation unit is also complemented with a pumping station, for addition pressure increase. Further, three additional pumping stations aid to boost the energy transfer place at strategical points in the grid. The third part is the 9,533 end consumers, which are commercial buildings or residential buildings, everything from larger complexes down to one-family houses. Those consumers have variable and different loads as well as consumption profiles.

The model representing the behaviour of the TES considers a tank with two layers, hot at the top and cold at the bottom. The model considers a loss of energy to the outside weather and a transfer of energy between the two layers and could be extended to a multi-layer model. In order not to slow down simulations too much, this simplistic case is used for the test case.

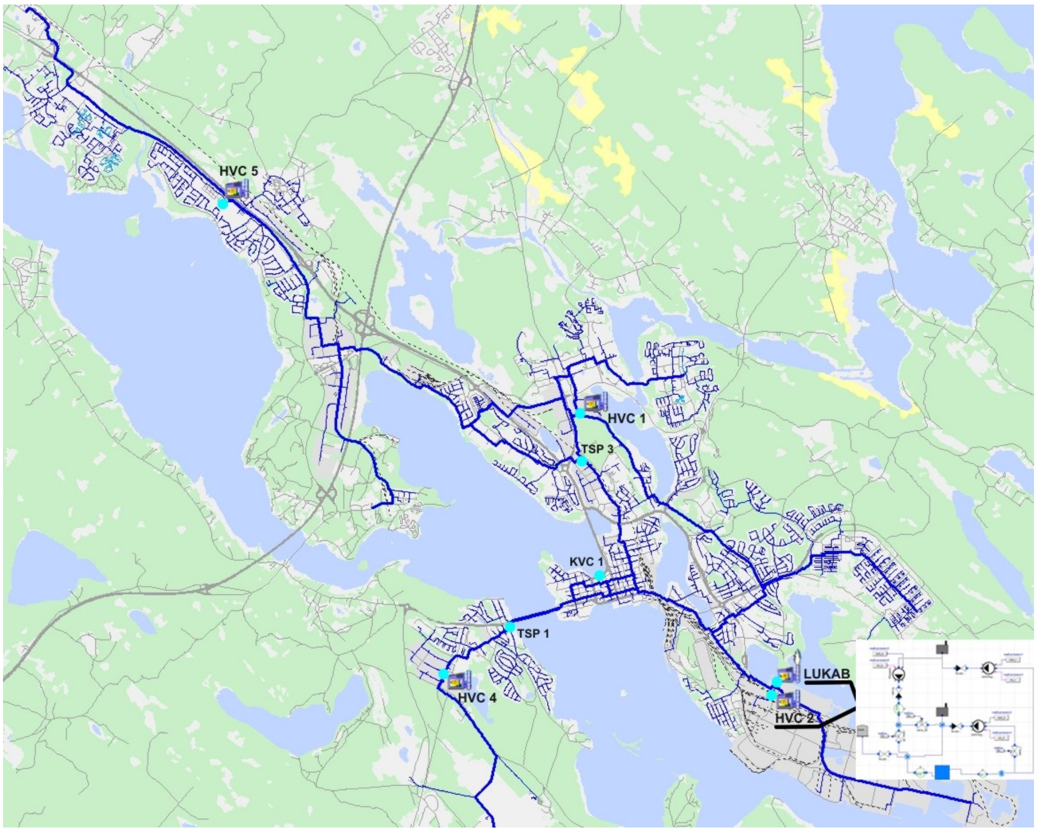

Figure 4: Luleå DH system sketch. Abbreviations for components in the picture: auxiliary boilers (HVC), CHP (LUKAB), pumping stations (TSP)

4.2 Simulation

The scenario for the test case is the simulation of the optimization problem and usage of the storage tank on some cold winter days when the outdoor temperature falls rapidly. Figure 5 shows the outdoor temperature.

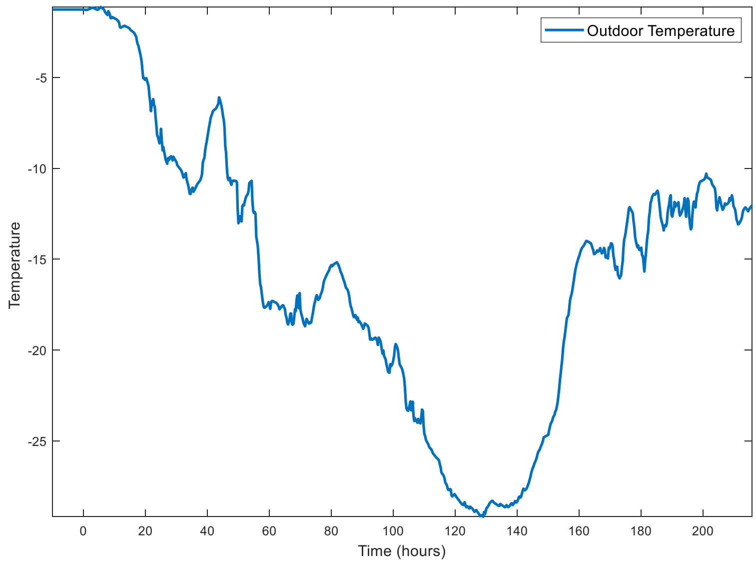

Figure 5: Outdoor Temperature during cold days at Luleå city

Because the flow rate of the medium in the pipes is not constant, according to (3-2) and (3-12), the transmission time delay on DHS is variable. Measuring the flow in a large number of pipelines at every instant is impossible, and for DHS in Luleå, it is only measured in some pipes near the generation units. Moreover, estimating flow in all pipes using a model is not realistic. Then, at every time instance, an average time delay is calculated as:

$$\int_{t-t_{ds}}^{t} m_v(\tau)d\tau = V/2 \tag{4-1}$$

$$\int_{t}^{t+t_{dr}} m_v(\tau)d\tau = V/2 \tag{4-2}$$

where t_{ds} is the average time delay in the supply pipelines, t_{dr} is the average delay time in the return pipelines, m_v is the volume flow in the grid, and V is the total volume of the medium in the DHS.

The future delay is estimated as the mean value of the samples of flows in the last instant (Saarinen, 2008).

Some controllers control the pressure of the medium supplied by pumps in DHS in Luleå. Therefore, the optimization problem is not subject to (3-1)-(3-15), and the average time delay is considered in providing the total demanded thermal power, $Q_{h,dem}$, in (3-33). Furthermore, the model of the buildings is not considered in the simulation.

The sample time, Δt, is 1h, the prediction horizon, N, is 8, and the penalties for starting up/shutting down generation units, $\gamma_{on,i}/\gamma_{off,i}$, $i = 1, \dots, 5$, are chosen arbitrarily at 80 EUR/h. When there are two or more generation units with the same production cost in the optimization problem, this parameter helps to reduce the on/off switching events. In general, the unit with the lowest production cost should have the smallest penalty for turning on and the biggest penalty for turning off.

Simulation is done for five cases, including four cases with the optimizer and a TES and one without them. In Case 1, it is assumed that the TES initial level is the mean of the lower and the upper storage limits, and the average delay time is calculated at every time instant using (4-1) and (4-2). There is no constraint on the final thermal power of the TES along the horizon.

The effects of the initial power of the TES, the heat to power ratio of the CHP, and the average time delay on the production cost are assessed in cases 2-4, respectively.

The optimization problem is solved in Matlab, and the optimal thermal power produced by the units is obtained and fed to the simulator.

The optimal power and the optimal on/off state of the generation units in Case 1 are depicted in Figure 6 and Figure 7, respectively. The thermal power inserted in TES, the power of TES inserted in the DHS, and the electrical power are shown in Figure 8. The heat power of every unit is normalized on a percentage basis, considering its maximum power as 100%. The TES power in, its power out, and the electrical power of CHP are also normalized by considering their maximum values as 100%.

As can be seen in Figure 7, the CHP is on during the simulation, then HVC4 and HVC1 start sequentially when the demanded thermal power is high. HVC5 and HVC2 are off for this simulation. Observe that the production cost for HVC4 is smaller than for HVC1, which in turn is smaller than HVC2 and HVC5.

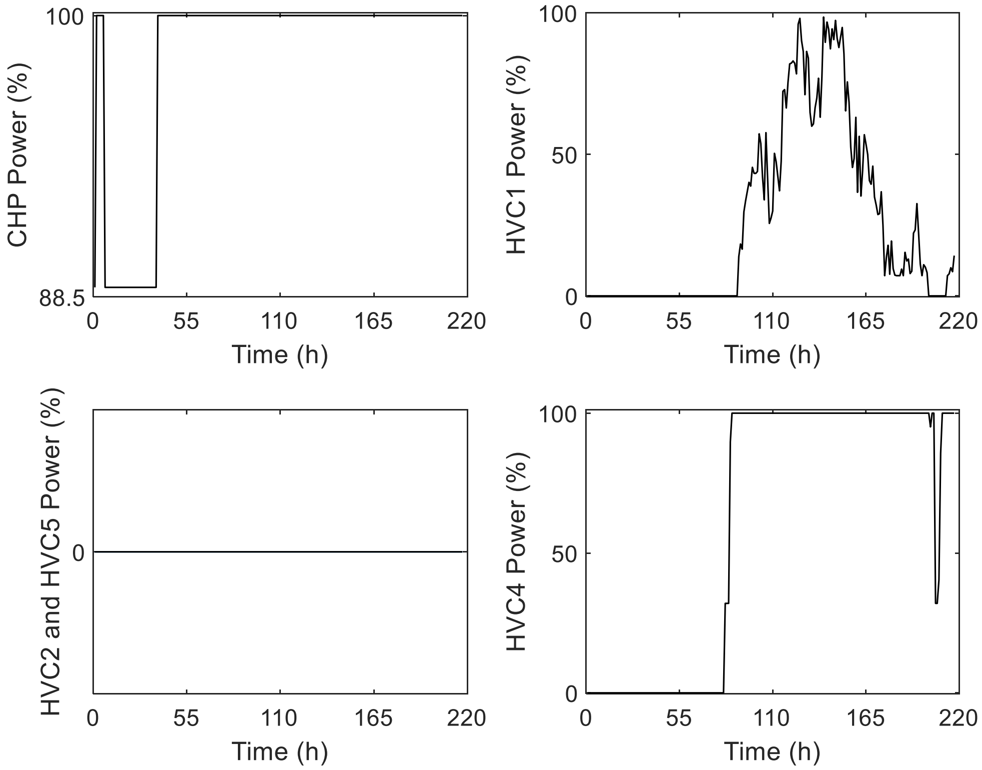

Figure 6: Optimal power produced by the units in Case 1

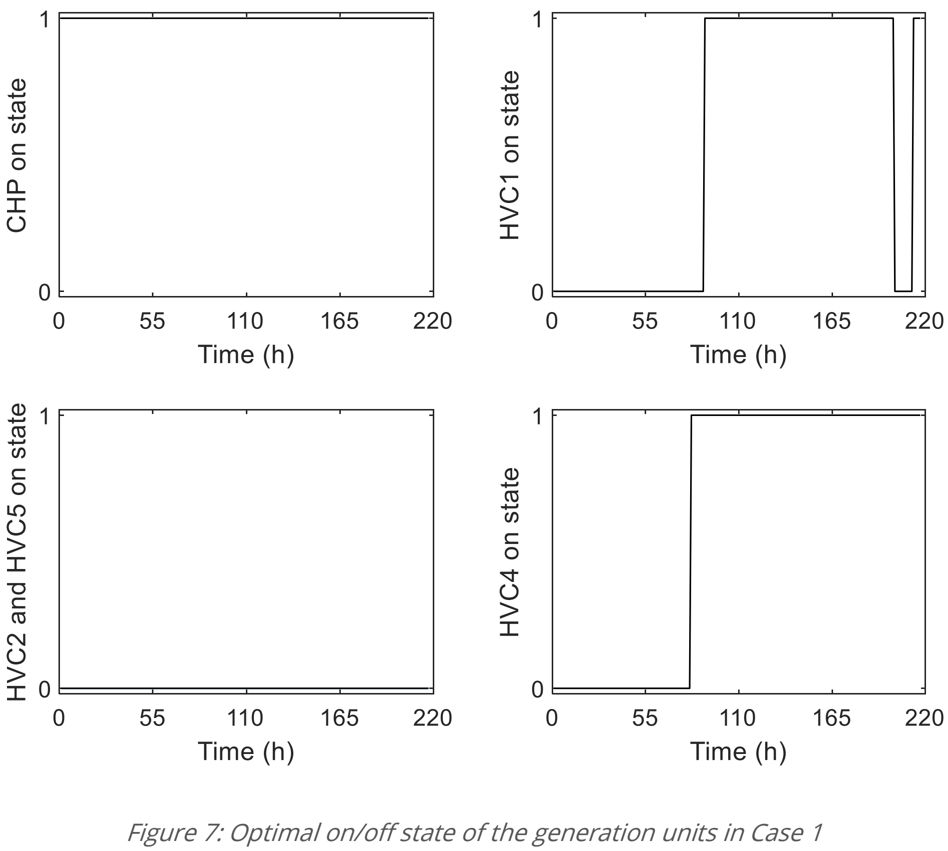

Figure 7: Optimal on/off state of the generation units in Case 1

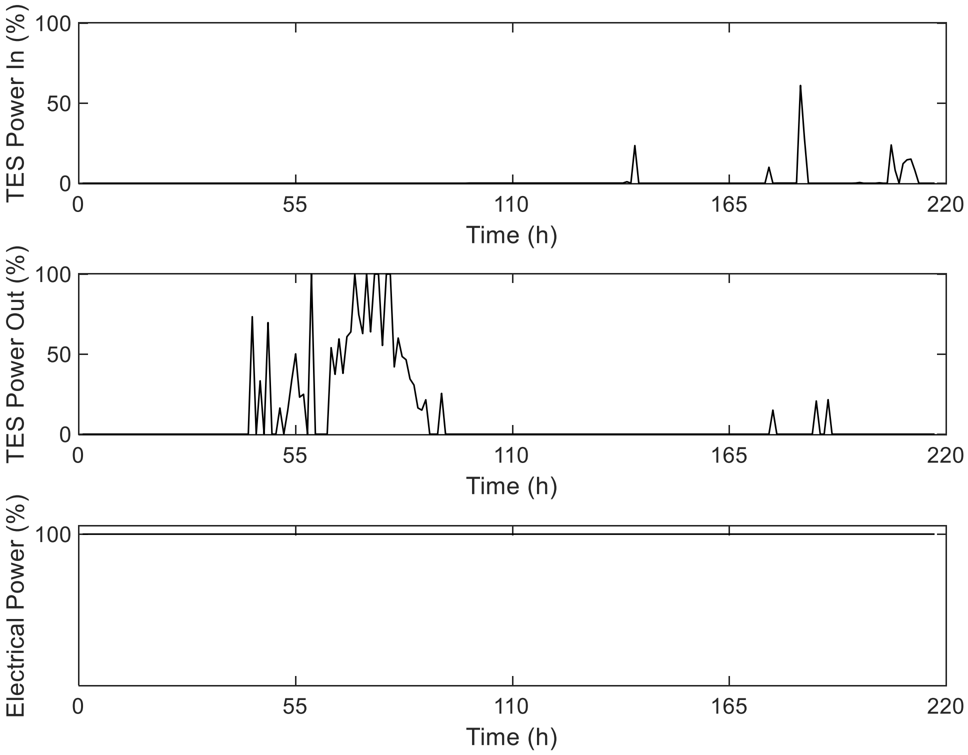

Figure 8: The thermal power inserted in TES, the power of TES inserted in the DHS, and the electrical power in Case 1

The production cost is affected by the TES specification and its initial capacity level. To show the impact of the initial power of the TES on the cost, the simulation is done for Case 2, in which the TES initial level is increased by 63% compared to Case 1 to reach near its maximum value. The average production costs are compared in Table 1. In order not to disclose any confidential information, we normalize the values obtained for Production Cost and Electricity Income on a percentage basis, considering Case 1 as 100%. In Case 2, the cost reduces in comparison to Case 1.

Moreover, the heat to power ratio of the CHP has effects on the production cost. In Case 3, its minimum value is decreased by 18.75%. The cost increases compared to Case 1.

In Case 4, the average time delay is not considered (Eqs. (4-1) and (4-2)). The average cost does not change considerably.

Simulation results are compared with the current operation of heat production in Luleå (without the optimizer and the TES) in Case 5. The data on electricity production and, therefore, the income from the electricity market is not available for this case.

The results in Table 1 show that the maximum cost reduction using the optimizer and the TES is about 22.2% in comparison to the current case (Case 5).

Table 1: Comparison of the average costs and the average electricity income.

Case	Production Cost (%)	Electricity Income (%)
1	100	100
2	83.35	100
3	100.49	100
4	100.17	100
5	107.15	-

5 CONCLUSIONS

As a result of Work Package 1, we formulated an optimization problem to deal with the integration of TES in DHCS. Moreover, we embedded the concept of flexibility, from both the design and operation perspectives, as constraints of the optimization problem. The resulting nonlinear mixed-integer problem was reformulated as a linear mixed-integer problem and was solved using a MPC approach, in which we used a model to predict the future behaviour of the system and calculated the optimal inputs at the present that minimize the forecasted thermal power production cost.

Additionally, we defined indicators to quantify the advantages of flexible operation. This task was not straightforward because we not only need to choose indicators that are representative, but also make sure that they are calculated at the same level of flexibility. Such parameters will facilitate comparisons between different case scenarios and will help support the recognition of the benefits due to the flexible optimization of DHCS.

The optimization procedure was applied to the Luleå district dynamic model from the OPTi project. In the simulations, the optimization algorithm calculates and supplies the optimal thermal energy production rates of the units in the DHCS in the Luleå dynamic model. We analysed a scenario of around 9 winter days in which the outdoor temperature falls rapidly. We compare the possible financial savings obtained by the proposed optimization algorithm with TES and a base scenario without any optimization. The simulation results show that the production cost reduces by 22.2% maximally using the optimizer and the TES in comparison to the current operation of heat production in Luleå.

We believe that although the Optimizer still needs fine tuning, the preliminary results demonstrate that it is possible to exploit the integration of TES in DHCS, along with the increased operational flexibility, in order to decrease costs and increase the share of renewable energy.

ABBREVIATIONS

Abbreviation	Explanation
CHP	Combined heat and power
DH	District heating
DHC	District heating and cooling
DHCS	District heating and cooling system
DHS	District heating system
DR	Demand response
MPC	Model predictive control
RC	Thermal resistance and thermal capacitance
TES	Thermal energy storage

NOMENCLATURE

Symbol	Unit	Description
$\underline{a}$ / $\overline{a}$	unit of a	minimum/maximum values of each parameter a
$C_{z,i}$	kJ/°C	thermal capacity of zone i
$d_{p,j}$	m	diameter of pipe j
h	h	time instant
K_{delay}	-	thermal delay coefficient of the pipelines
L_j	m	length of pipe j
$m_{p,j}$	kg/s	mass flow rate in pipe j
N	-	prediction horizon
N_{zm}	-	the number of buildings in substation m
P_i	kW	electricity power produced by CHP unit i
$P_{pu,i}$	Pa	pressure supplied by pump i
$\Delta P_{p,j}$	Pa	pressure loss in pipe j
$Q_{c,dem}$/$Q_{h,dem}$	kW	total demanded thermal power on cooling/heating side of DHCS
$Q_{c,loss}$	kW	total thermal power loss on cooling side of DHCS
$Q_{h,loss}$	kW	total heat loss including heat loss on heating side of DHCS and in absorption chillers
Q_i	kW	thermal power produced by energy generation unit i
Q_i^D	kW	thermal power inserted in DHCS by unit i
$Q_{i,j}^s$	kW	thermal power inserted in TES j by unit i
Q_j^{rs}	kW	heat inserted in TES j by other heat sources, e.g. data centers
$Q_{p,j}^{in}$ / $Q_{p,j}^{out}$	kW	thermal power at the inlet/ outlet of pipe j
$Q_{R,i}$	kW	thermal power required by aggregated buildings i
$Q_{rad,i}$	kW	solar irradiation for aggregated buildings i
$Q_{s0,i}$	kW	thermal power of TES $\boldsymbol{i}$ at which its loss is zero
$Q_{s,i}$	kW	thermal power of TES $\boldsymbol{i}$
$Q_{s,i}^{in}$	kW	thermal power inserted in TES $\boldsymbol{i}$
$Q_{s,i}^{out}$	kW	thermal power of TES $\boldsymbol{i}$ inserted in the DHCS
$r_{u,i}$ / $r_{d,i}$	kW/h	ramp up / down rate of electrical power of the CHP unit i
$r_{qu,i}$ / $r_{qd,i}$	kW/h	ramp up / down rate of thermal power of unit i
S_{ac}	-	set of absorption chillers
S_C	-	set of CHPs
S_{cT}	-	set of cold storages
S_{ec}	-	set of electric chillers
S_G	-	set of thermal energy generation units
S_{hG}	-	set of heat generation units including CHPs and boilers
S_{hT}	-	set of heat storages

Symbol	Unit	Description
$S_{p,l}^{s,n}/S_{p,l}^{e,n}$	-	set of pipes starting/ending at node l
S_{ps} / S_{pr}	-	set of supply/return pipelines
$S_{ps,i}$ / $S_{pr,i}$	-	set of supply/return pipes connected to heat exchanger i
S_{pu}	-	set of pumps
T_a	°C	ambient temperature
T_w	°C	vector of walls temperatures
$T_{z,i}$	°C	indoor temperature of zone i
$t_{delay,j}$	s	transmission time delay in pipe j
Δt	h	Sampling time
u_i	-	on/off state of unit i
v_j	m/s	velocity of medium in this pipe
α_i	EUR/kWh	cost of heat production by heat generation unit i
β	EUR/kWh	electricity price
$\beta_{c,i}$	EUR/kWh	cost of thermal energy production by electric chiller i
$\gamma_{on,i}$/ $\gamma_{off,i}$	EUR/h	penalties for starting up/shutting down unit i
$\delta_{i,j}$	-	binary parameter that is 1 if unit i is connected to the TES j and is 0 otherwise,
$\eta_{he,i}$	-	efficiency of heat exchanger i
$\eta_{in,i}$ / $\eta_{out,i}$	-	charging / discharging loss factor of TES $\boldsymbol{i}$
$\lambda_{s,i}$	-	loss factor of TES $\boldsymbol{i}$
$\mu_{loss,j}$	1/m	thermal power loss coefficient of pipe j
$\mu_{p,j}$	1/(mkg)	pressure loss coefficient of pipe j
ρ	kg/s	medium density
$\underline{\tau}_{on,i}$/ $\underline{\tau}_{off,i}$	h	minimum duration of time for which unit i must be kept on/ off
ϕ_i	-	heat to power ratio of CHP unit i

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