A THEORETICAL STUDY OF THE IMPACT OF USING SMALL SCALE THERMO CHEMICAL STORAGE UNITS IN DISTRICT HEATING NETWORKS

Basciotti D.[1], Pol O.[1]

[1] **Energy Department, Austrian Institute of Technology, Giefinggasse 2, Wien, 1210, Austria**

daniele.basciotti@ait.ac.at

ABSTRACT

If absorption chillers (AbC) are connected to district heating (DH) networks, the rather low temperature drop on the generator side (below 10 K) leads to return temperature increase in the network. This limits the maximal number of chillers which can be operated simultaneously, if there are precise requirements on the maximal accepted return temperature. As desiccant cooling systems (DEC) work with higher temperature drops on the heating side and thus would maintain the return temperature of DH network at low levels, they are more suitable for integration in DH networks than AbC. The simulation study assesses the performance of DH networks integrating DEC systems realised as Thermo Chemical Storage units (TCS) and leads to a comparison, with appropriate indicators, with decentralised small-sized AbC. An overview of the state of the art of computational models for DH and TCS is carried first. The simulation results of a theoretical case study show a sensible reduction of the share of distribution losses in the DH network, resulting from an increased use of heat from the DH network (advantage obtained also by using AbC). In addition there is no limitation in terms of cooling power installed, as the return line temperature benefits from the TCS charging phase (average return temperature can be reduced up to 2°C in the cases considered), representing the main advantage compared to AbC. Last, recommendations on the preferred temperature drops of the heating coil in the DEC system are formulated as result from a sensitivity analysis. Additional investigations would be necessary to derive an optimised control strategy in the storage charging phase and the influence of the TCS position with respect to the network.

NOMENCLATURE

ΔT	Temperature drop by the adsorption process, °C
Y_F	Inlet humidity, kg/kg
ΔH	Heat of adsorption, kJ/K
C_{pb}	Heat capacity of air, kJ/kg.K
s	Coefficient of simultaneity, -
$Q_{max,Op}$	Maximum heating load in operation in the time-interval, kW
$Q_{installed}$	Installed heating capacity, kW
Q_{losses}	Total share of heat losses, %
$Q_{consumed}$	Total heating consumption, kWh
$Q_{produced}$	Total heat produced, kWh
T_{max_ret}	Maximum return temperature, °C
$\overline{T}_{drop}$	Average temperature drop, °C
COP_{cool}	Coefficient of performance for cooling, -

INTRODUCTION

The limitations for using AbC in existing DH networks are described and assessed in many works [1,2,3]. In particular, the return temperature increase in the DH network limits the maximal number of chillers which can be connected and operated simultaneously; this is particularly relevant if networks are used as cooling loops of gas engines. Problems appear in the time when the heating load for the AbC is high compared to the total load of consumer substations. The necessity to combine AbC with processes with a higher temperature drop on the driving side is often cited [1,2,3], as well as the necessity of storage and load management in order to avoid simultaneous operation of many chillers. However, additional storage equipment would lead to additional costs which are not acceptable because of the limited economical feasibility of AbC in combination with DH. DEC systems, if equipped with a sufficiently high amount of sorption material, can be considered as TCS from the perspective of the heat supply technology (DH) they are connected to. On the other side, as they are used for air dehumidification in a sorption cooling system, they can be assimilated to virtual cooling energy storage. All these advantages have led to the idea of combining TCS with district heating networks and the only found documented demonstration plant is operating in Munich, Germany as reported in [4].

STATE OF THE ART OF COMPUTATIONAL MODELS OF TCS AND DH NETWORKS

Computational models of TCS and DH networks have been developed at different levels, depending on the targets followed when analysing the systems (assessment of overall system performance or detailed physical modelling of a component).

Modelling approaches for DH networks

Modelling the dynamic behaviour of a DH network requires modelling both hydraulic and thermodynamic aspects of the system (pressure distribution, pump requirements, heat losses, temperature distribution in the network, etc.). Computational models of networks take into account the network topology, individual pipe properties, material properties, pumps, etc. Under these conditions DH simulation software enables a comprehensive overview of the network, thus supporting initial design and subsequent network modifications. Many commercial network simulation environments are available: SisHyd [5], Sir3S [6], Apros [7], Stanet [8], Dymola [9], T*SOL Professional [10], EC.GIS [11]. Analysis of these existing commercial tools pointed out advantages in simulating complex DH networks with Modelica/Dymola for research purposes, summarized as following:

- Bi-directional fluid flow, necessary to model intermeshed networks
- Possibilities to combine buildings' models developed in the same modelling environment
- Possibilities to integrate models of other engineering fields (material properties, thermo-mechanical stresses…), by using available libraries
- Possibility to consider instationary effects and dynamic hydraulic phenomena
- Possibility to implement customised control strategies

Modelling approaches of adsorption and desorption processes

[12] presents a broad literature review of different modelling approaches for sorption and desorption processes applied on desiccant wheels. Two different types of approaches can be derived:

- Heat and mass transfer models, which are too detailed for the project needs as the analysis is done at a system level (district heating network);

- Empirical models, which describe the current state of the TCS unit in function of defined input data (inlet air temperature and its relative humidity).

Considering the project aim, the physical modelling approach is too detailed, as the analysis is done at a system level (from the district heating point of view). Thermodynamic equations are needed in order to describe the current state of the TCS unit in function of defined input data (inlet air temperature and its relative humidity) and they can be determined in an empirical way. In this way the silica gel fixed bed is modelled by using characteristic curves taken from literature [13].

The outlet temperature during the adsorption process is obtained by calculating the temperature increase as proposed by [13].

$$\Delta T = Y_F \Delta H / C_{pb} \tag{1}$$

where Y_F – inlet humidity, kg/kg; ΔH - heat of adsorption, kJ/K; C_{pb} - heat capacity of air, kJ/kg.K.

The outlet absolute humidity is calculated by considering a fixed desiccant bed which would be large enough to remain non-saturated during the entire adsorption process. This assumption means that there is always enough dry sorption material and the outlet absolute humidity can be lowered to 0.006 kg/kg regardless the inlet conditions, which of course represents very ideal conditions. Total amount of material needed is calculated by linearising moisture isotherm curve for silica gel [13].

SIMULATION PROCEDURE AND WORK FLOW

The storage models (silica gel bed) [13,14,15] of the desiccant cooling system and of the district heating network, computing the dynamic or steady-state response, are all developed in Modelica on the basis of the Modelica Fluid library [18]. It is a desiccant cooling system (DEC) with the desiccant wheel replaced by a large fixed bed (storage), Figure 1.

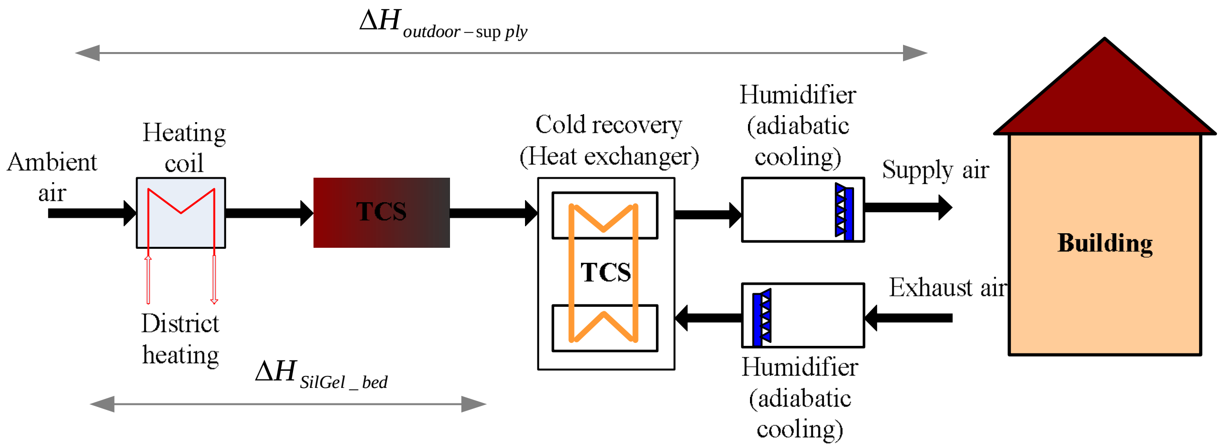

Figure 1. DEC system design

The choice of a daily storage capacity is required, since the target is to shift heating loads (heating is used for desorption of the desiccant material) from day to night. As first step, simulation of an open sorption storage unit is performed and partly validated by using monitoring data.

Following input data is gathered for the network simulation:

- Heating loads from an existing DH network [2]
- Assumed cooling load profiles for a typical office building

Cooling loads for a typical office building are used as input for the storage simulation (adsorption) to calculate the heating loads in the desorption phase and the total mass of sorption material (simulation of the cooling phase and the "storage phase" are performed in two different steps). In first approximation, an iterative approach to size the network piping is used, considering the total heating loads for domestic hot water preparation at other consumers connected to the network and for desorption of the silica gel bed. The network design is based on the maximally accepted fluid velocity in the piping and the heat losses minimisation. Different scenarios are considered for the assessment of the system by varying cooling load, temperature drop of the heating coil and the desorption time, Figure 2.

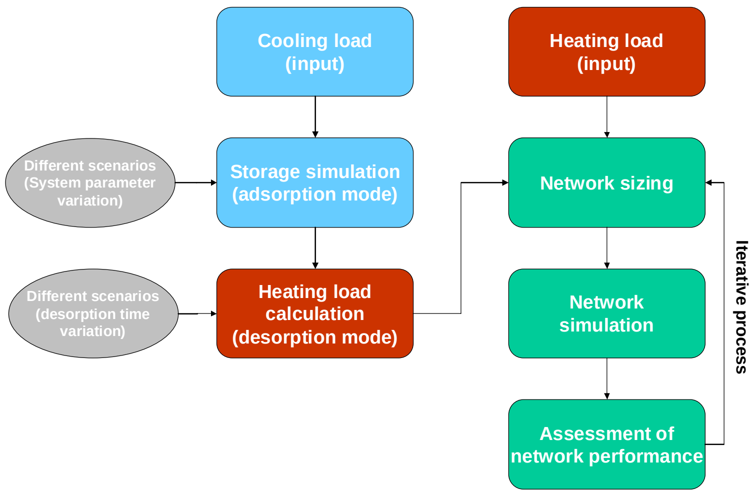

Figure 2. Workflow description

DESCRIPTION OF THE SYSTEM MODELLED

DH network: model and parameters

A theoretical small-scale DH network is used for the assessment. The system consists of a centralized hot water generation at a temperature level of 90°C distributed through the district heating network to the consumer substations. The length of supply line of the network is 375 m, as shown in Figure 3. Different load profiles are taken from a real network (data from [2]) in order to model a realistic behaviour of the DH network. The DEC system (TCS) is considered as a consumer connected to the network. The load profile, defined by temperature drop and mass flow rate of the heating coils heating up the air stream for regeneration, is calculated from the storage simulation in specific conditions.

The heat exchanger used for heating up the air stream in the regeneration process is not modelled in detail and a sensitivity analysis is performed by varying the temperature drop in the water side in the range between 30°C and 45°C, corresponding to observed levels of temperature drop in reality (monitoring data from the DEC solar cooling system of the office building ENERGYBase in Vienna, Austria [19]).

A second sensitivity analysis is done by varying the size of the storage unit, by changing the mass flow rate of the substation (with a fixed regeneration time). The size of the cooling system is modified between 12 kW and 48 kW, which consequently has an impact on the size of the fixed bed to be used to adsorb humidity in the cooling mode. The time interval of usage of the cooling system is chosen between 8:00 and 17:00, corresponding to office use schedule.

Silica gel is used as sorption material due to its low temperature requirements for desorption, suitable for application in connection with district heating networks. In the defined control strategy the heating is provided to the bed through a heating coil during the night from 22.00 with desorption time of 2.5 h, 5 h and 10 h.

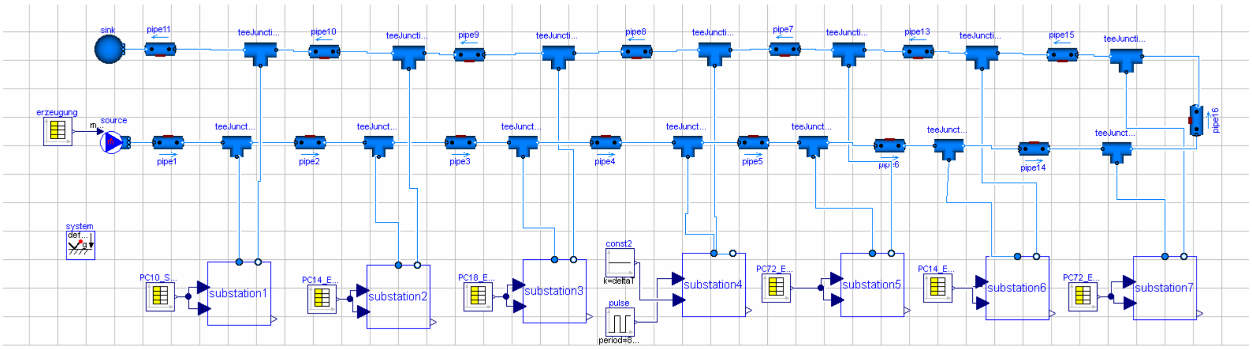

Figure 3. District heating network model configuration in Dymola

In the DH simulation as well as in the cooling system the electricity consumption for the pump and the ventilator is not calculated, because the focus is put on the heat distribution and use. Modelica model of the DH network is shown in Figure 3. Each component for the modelling of the network and the heat production/loads is taken from the Modelica.Fluid libray, part of the Modelica Standard Library 3.1 [20].

Load profile: heating and cooling load

Heating load profiles for domestic hot water are taken from the monitoring data of [2]. The heating load profiles are related to three different single-family house consumers and a large industrial consumer (storage facilities). As the reference week is in summer they don’t depend on weather parameters (outdoor air temperature or solar radiation). The installed heating capacity of each substation is presented in the Table 1.

Table 1 – Installed heating capacities

Consumer type	Installed heating capacity of substation [kW]
2 x Household size type 1	15
1 x Household size type 2	29
2 x Household size type 3	6
1 x Storage room	127
1 x TCS	12-48

Without considering the TCS the total installed capacity in the network amounts 200 kW. A coefficient of simultaneity of s=0.45 is calculated in the considered summer week, defined as:

$$s = \frac{Q_{Max,Op}}{Q_{Installed}} \quad (2)$$

where $Q_{Max, Op}$ - maximum heating load in operation in the time-interval, kW; $Q_{installed}$ - installed heating load capacity, kW.

The cooling loads used for the simulation of the desiccant cooling system and the calculation of the heating loads corresponding to the charging phase are calculated from typical summer weather data and fresh air requirements for an office building. Outdoor temperature and absolute humidity is taken into account and used for the simulation of the desiccant cooling system as shown on Figure 4. The average outdoor temperature is about 23°C and a peak of 31°C occurs between 13:00 and 15:00. The average absolute humidity is ca. 0.011 kg/kg and reaches a peak of about 0.013 kg/kg.

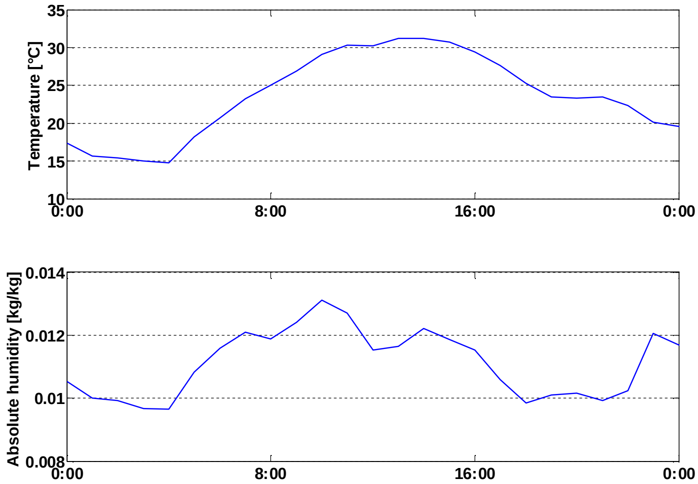

Figure 4. Outdoor temperature and absolute humidity of air

Cooling load calculation is performed for a reference day and then used for the entire week of interest in the network simulation. Assumptions considered to derive the supply mass flow rate to the room are reported in Table 2.

Table 2 – Assumptions for the cooling load calculation

Building type	private office
Useful floor area	120 m²
Air change rate	4 1/h
Supply air rate	1250 m³/h

DEC system simulation

The simulation of the DEC system provides the total amount of energy for desorption and the mass of silica gel needed for the fixed bed, representing the starting point for the storage simulation. Considering the energy needed for desorption, heating loads with constant mass flow rate are calculated and used in the network simulation. The desiccant cooling system model is developed in Modelica and presented in Figure 1, where the cold recovery (heat exchanger) model, considering a constant effectiveness, and the humidifier model are taken from the LBL building library 0.8.0 [21].

For the “cold recovery” and the humidification process control a sensitivity analysis is done, by considering a range of constant effectiveness for the heat exchanger and different control strategies for the humidification of the supply air, Table 3. Performance of the cooling system is assessed with two different indicators, COP_{cool} and the maximum cooling load provided $Q_{cool\ Peak}$.

Cooling (total and sensible) and heating energy (in desorption phase) are calculated as:

$$Q_{cooling} = \int \dot{m}_{flow} \Delta H_{outdoor-\sup ply} dt \tag{3}$$

$$Q_{sensible} = \int \dot{m}_{flow} cp_{air} \Delta T_{outdoor-\sup ply} dt \tag{4}$$

$$Q_{heating} = Q_{des} = \int \dot{m}_{flow} \Delta H_{SilGel\_bed} dt \tag{5}$$

$$COP_{cool} = \frac{Q_{cooling}}{Q_{des}} \tag{6}$$

Referring to outdoor conditions specified in Figure 4, the simulation results of the reference day for the different cases are summarized in Table 3. By increasing the heat exchanger effectiveness, COP_{cool} of the system increases and the supply air to the room decreases (due to the effect of the cold recovery). Changing the supply air humidification control strategy has an irrelevant effect on COP_{cool} but this contributes to decrease the supply air temperature into the room (due to the evaporative cooling effect).

Limitations on the system design are formulated on the basis of supply temperature requirements. In order to guarantee a supply air temperature in the range 20°C -22°C (with a relative humidity ratio of 50 %) the heat exchanger effectiveness has to be at least 0.8.

Table 3 –COP cooling, $Q_{cool\ peak}$ and supply air temperature for the different scenarios

HeX effectiveness [-]	**Supply %RH**	COP_{cool} **[-]**	$Q_{cool\ peak}$ **[kW]**	**Supply air temperature [°C]**
0.75	**50**	0.617	9.7	22.1
0.8		0.692	10.9	21.2
0.85		0.766	12.0	20.2
0.9		0.841	13.1	19.3
0.85	35	0.772	12.1	23.1
	40	0.770	12.0	22.1
	45	0.768	12.0	21.1
	50	0.766	12.0	20.2

The system design derived from Table 3 considers a heat exchanger effectiveness of 0.85 and a supply air humidification at 50% RH. The choice is done by considering a compromise between an affordable solution for the HX (0.9 represents a very high value for HX effectiveness) and a high value of the COP_{cool}.

Network simulation and system performance evaluation

The network design is based on the maximally accepted fluid velocity in the piping and heat losses minimization in the network. From the simulation results a value of DN50 is chosen, [22]. Eleven different scenarios are considered for the assessment of the impact of small scale TCS units in DH networks. The following aspects are considered in the parameter variation and summarized in Table 4.

For the evaluation of the district heating network performance three different indicators are considered:

1. Total share of heat losses in the network, $Q_{losses} = \frac{Q_{consumed}}{Q_{produced}} \cdot 100$

2. Maximum return temperature $T_{\max\_ret}$ in the operating time-interval

3. Average temperature drop $\overline{T}_{drop}$ of the network (drop between the supply and the return line)

The evaluation of the influence of the storage on the network performance is presented in Table 4. As reference scenario, the influence of using an AbC (of the same cooling capacity) in combination with a DH network is considered.

Table 4 – Performance indicators for different scenarios

Scenario	**Cooling load [kW]**	**Temperature drop on the driving side[°C]**	**Desorption time [h]**	Q_{losses} **[%]**	$T_{\max\_ret}$ **[°C]**	$\overline{T}_{drop}$ **[°C]**
Reference 1 (without storage)	-	-	-	19,7	84,0	25,0
Reference 2 (with absorption chiller)	-	-	-	16,0	84,0	19,8
Scenario 1a	12	**40**	**8**	17,7	82,7	25,9
Scenario 2a	24			16,6	82,7	26,5
Scenario 3a	36			15,8	82,7	26,9
Scenario 4a	48			15,2	82,6	27,1
Scenario 1b	**12**	30	**8**	18,7	82,7	24,6
Scenario 2b		35		18,2	82,7	25,3
Scenario 3b		40		17,7	82,7	25,9
Scenario 4b		45		17,3	82,6	26,3
Scenario 1c	**12**	**40**	10	17,7	82,6	25,9
Scenario 2c			5	18,7	83,6	26,0
Scenario 3c			2.5	18,6	84,0	25,7

For all scenarios a value of Q_{losses} above 15% is calculated due to few consumers installed in the network and the fact that the simulation is done for a summer week. Sorption storage units increase the network usage, thus leading a lower share of distribution losses. Total share of losses decreases (in the best case of scenario 4a corresponding to the highest cooling capacity of 48 kW by about 5%, from 20% down to 15%). Temperature drop variation of the heating coils has less influence on the losses reduction, which for a temperature drop in the heating coil of 45°C is about 17.3% of the total energy produced. Desorption time has a small influence on the heat losses of the network, causing a maximum reduction of 2%.

Maximum return temperature appears non-sensitive to cooling capacity or temperature drop of the heating coils. A reduction of maximum return temperature is predictable, since the charging process is scheduled in the time interval where the total heat consumption is low (and the temperature drop of the other consumers is low compared to the one caused by the storage charging process). Reduction of desorption time decreases possibilities to benefit from a reduction of the maximum return temperature, since the beneficial effect of a larger temperature drop (caused by charging the storage) is associated to a smaller time interval.

The average temperature drop between the supply and return line is another important performance indicator. Usage of absorption chillers in combination with DH networks is limited because of their low temperature drop on the generator side. By using the proposed desiccant cooling system, substantial benefits can be achieved. From the analysis of the results the most influencing parameters are the temperature drop of the heating coil and the cooling capacity. Increasing the temperature drop caused by the storage beyond the temperature drop of other traditional consumers has as main effect on the average temperature drop increase (by 1.5°C). Varying the cooling capacity leads to a temperature drop increase of about 2.0 °C. Desorption time has less influence with a maximum increase of 1.0°C.

Analysing the results confirms that particular attention has to be given to the design of the heating coil, which has the main influence on the return line temperature. In the case of a 12 kW cooling capacity, with 40°C temperature drop at the heating coils and a desorption time of 10 h, the return temperature and temperature drop with/without the sorption storage and by using an AbC (12 kW thermal cooling power) are shown in Figure 5. Compared to the AbC which decreases 5°C the average temperature drop, the introduction of a TCS leads to an increase by 2°C compared to the scenario Reference1, being thus more interesting for DH network operation than absorption chillers.

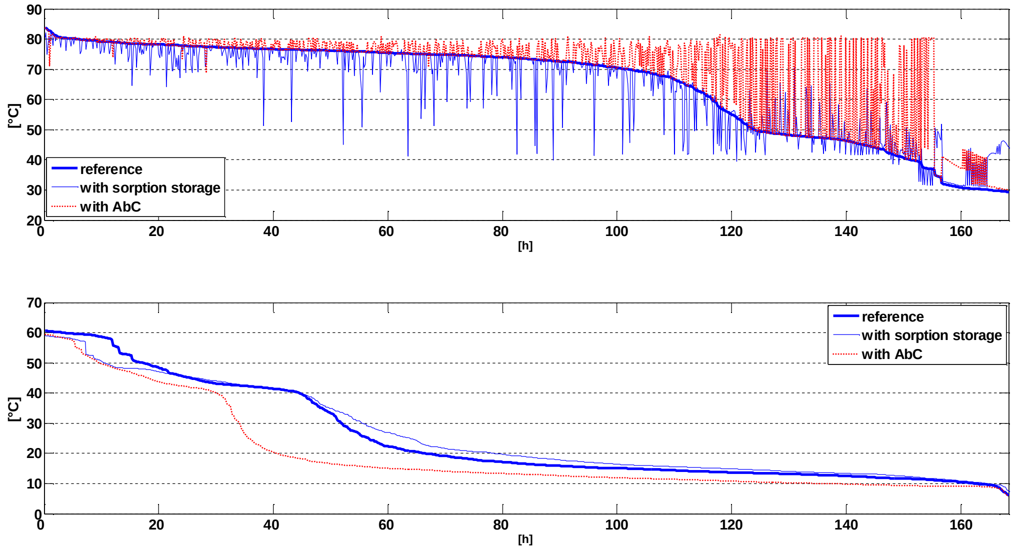

Figure 5: (top) Return line temperature with/without storage and with an AbC; (bottom) temperature drop in cases with/without storage and with an absorption chiller, sorted descending.

CONCLUSIONS AND FUTURE WORK

The aim of the simulation-based analysis was to define conditions whether or not a DEC system with TCS storage can have technical potentials in combination with district heating for cooling applications. The motivation for this analysis comes from the limited possibilities for using AbC in DH networks because of a too high increase of return temperature, thus limiting the number of AbC which can be operated simultaneously. The main conclusions of the feasibility study can be summarized as:

- The share of distribution losses in the DH network can be reduced, resulting from an increased use of the DH network (same advantages by using absorption chillers)
- DEC systems, using heating coils with high temperature drop, may help to decrease the maximum return temperature in comparison to AbC
- There is no limitation in terms of installed cooling capacity, since the return line temperature benefits from the TCS charging phase (the average return temperature can be reduced up to 2°C in the cases considered). This represents the main advantage compared to using AbC

Some aspects (e.g. different climates dependency, liquid desiccant systems instead of solid desiccant systems), which were not analysed in the project, will be explored in future. Target of the future study will be to perform further sensitivity analyses with respect to the storage position in the DH network (influence on the performance of the DH network is expected). Furthermore different control strategies for the desorption operation (charging phase) will be evaluated, in order to determine an optimum for increasing the average temperature drop and decreasing the maximum return line temperature.

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