Thermochemical storage networks for integration of renewable energy sources through seasonal load shifting

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Abstract. Thermochemical networks are a rather new subject in research and support our goal to lower winter electricity demand and foster the integration of renewable energy sources. This paper takes a first step towards a performance analysis of thermochemical networks and a comparison to a classical district heating network for a virtually defined network of 1.3 km length, assuming a space heating load of 204.7 MWh represented by 33 residential buildings. The performance comparison is done for winter operation when space heating demand is present. The simulation results clearly revealed that for the classical district heating system, thermal and pressure losses lead to a significant increase in the loads, further increasing the electricity demand for the heat pump and the circulation pump. Conversely, for the thermochemical network, no compressor is needed to extract the heat from the boreholes and the circulation of the sorbent solution was found to be minute, leading to a negligible electricity demand for space heating supply. This resulted in a very high electric COP as well as a high exergy efficiency compared to a classical district heating system. Further, the volumetric energy storage density was compared, recording a 2 to 22.3 times higher value for the thermochemical network.

1. Introduction

With phasing out fossil fuels and substituting them with renewable energy sources to decarbonize our energy system, there is an increasing need for energy storage. The biggest challenge thereby lies in seasonal or long-term energy storage. Like other European countries, in Switzerland, heat demand makes up for more than 50% of the total final energy demand [1]. Consequently, the heating sector as such and the thermal energy storages play a vital role in the energy transition.

Recently, district heating networks (DHN) are gaining much attention and are seen as a means to decarbonize the heat sector. This is true as there is the possibility to better integrate waste heat, e.g., from waste incineration plants or to integrate renewables and potentially decarbonize the heat supply for a large number of buildings at once. Currently, in Switzerland, there is still a lack of renewable energy integration into heat generation for networks because of a lack of thermal energy storage (TES) and even more, large-scale seasonal thermal energy storage (STES) being implemented. The only renewable energy source vastly used is wood, a stockable, chemical energy carrier that hinders further integration of TES and STES in DHNs. The potential for STES in Switzerland is big and still untapped. The potential benefit of it can be observed in other countries, such as Denmark, being the worldwide leader in the implementation of solar district heating. There, several large pit storages are implemented along with solar collector fields and heat pumps for the integration of solar energy and excess electricity from wind power to decarbonize the heat sector [2]. Different TES technologies qualify for STES [3].

These are mostly large-scale sensible storages such as borehole thermal energy storages (BTES), pit storages (PTES), tank storages (TTES) but also aquifer storages (ATES).

An interesting alternative to sensible storage is thermochemical storage. This type of energy storage is characterized by a reversible reaction taking place where in the charging phase, heat is required to split a chemical compound into two components that are stored separately and recombined in the discharging phase whereby heat is being released again [4]. As in this case no heat is stored directly but the chemical potential, this storage allows for lossless storage for long periods of time (the losses only occur during charging and discharging). For this reason, this mechanism allows for the implementation of STES also at small scales, e.g., building scale and features higher volumetric energy storage densities than sensible water storages.

There are different categories of thermochemical energy storage whereof sorption storage plays an important role in low-temperature applications such as space heating (SH) in buildings [5]. Within this category, liquid sorption storage is another subclass that uses gas-liquid reactions based on salt solutions.

One of the benefits of liquid sorption storage is that the sorbent can be easily transported by pumping. This allows combining the features of lossless storage and distribution by pumping with a so-called thermochemical (storage) network (TCN). The chemical potential is available or built-up through a charging process at one point in space and can thus be transported and made available in another space through discharging, employing a TCN. The network thus acts as distribution and storage at the same time, where the storage can be extended with additional storage capacity using simple, uninsulated tanks.

The TCN approach is little known yet and was initially explored in the European Horizon 2020 project H-DisNet1. While the project was successful in implementing individual applications such as e.g. humidity and temperature control in greenhouses [6], there are still several unanswered questions about the network as a whole. This includes details of network design, scale-dependent performance, the extension to other terminal applications and process types, including closed sorption processes for energy storage, buffer and seasonal storages, fluid concentration control, as well as the network management thus, more research is necessary.

It is the specific aim of our research carried out in the frame of the project "TCology" (Swiss Federal Office of Energy SI/502368-01), to assess the technical and practical potential of TCN along with its applicability in the Swiss context. This article presents a very first step towards integrating a closed sorption reactor for space heating supply and a comparison to a classical hydronic network.

2. Methods

The performance of the TCN is evaluated and compared to the hydronic DHN for the task of space heating using annual simulation. To this end, an idealized case is defined and implemented in the Modelica simulation environment. Only the winter operation with space heating demand is considered and compared.

2.1. Case study definition

The case studied comprises a heat generation site, a heat/chemical potential distribution network of defined cumulated pipe length and a space heating load.

2.1.1. Space heating load

The total space heating load is calculated based on an aggregation of multiple single-family homes. A fictitious network was picked, characterized by: 0.25 MW rated power, 204.7 MWh of energy demand and a network length of 1.3 km. The scaling of the space heating load was done based on the energy demand from the grid resulting in 33 buildings.

For the base load of the SFH, a building with an annual space heating intensity of 45 kWh/(m^2*a) from the simulation reference framework [8] was implemented and simulated in EnergyPlus. The simulation was performed assuming floor heating with fixed mass flow, and supply and return

[1] https://www.h-disnet.eu

temperatures following an ambient temperature-dependent heating curve. At peak heating load, these are 35.6 and 32.3 °C, respectively. These temperatures are important for the evaluation of both, the ground-source heat pump and the sorption reactor performance.

2.1.2. Hydronic DHN (reference). For the classical DHN case (*Figure 1*), an ideal ground-source heat pump was assumed with a fixed source temperature on the evaporator side and a fixed sink temperature for heat rejection to the DHN. The heat pump's capacity was controlled to cover the space heating loads plus the thermal pipe losses. The water circulation in the DHN was fixed, and the return temperature of the network was calculated based on the space heating load and the defined supply temperature. All the models used in this scenario were implemented using the Buildings library [9] in Modelica.

The input parameters for the simulation were selected in the following procedure: **1)** setting the condenser outlet temperature of the heat pump to 45°C, **2)** setting the heat pump capacity to cover space heating loads plus pipe losses, **3)** adjusting the mass flow in the ground heat exchanger (GHX) loop to receive an evaporator outlet temperature of 1 °C (with a fixed inlet temperature of 5°C) at peak heating load, **4)** setting the mass flow rate in the network to reach a minimum return temperature of 34°C (~1 K above the minimum return temperature from the heating loop of the building), **5)** selecting the pipe diameter (DN65) to get a pressure drop of around 150-250 Pa/m in the network (supply and return together) as recommended in [10].

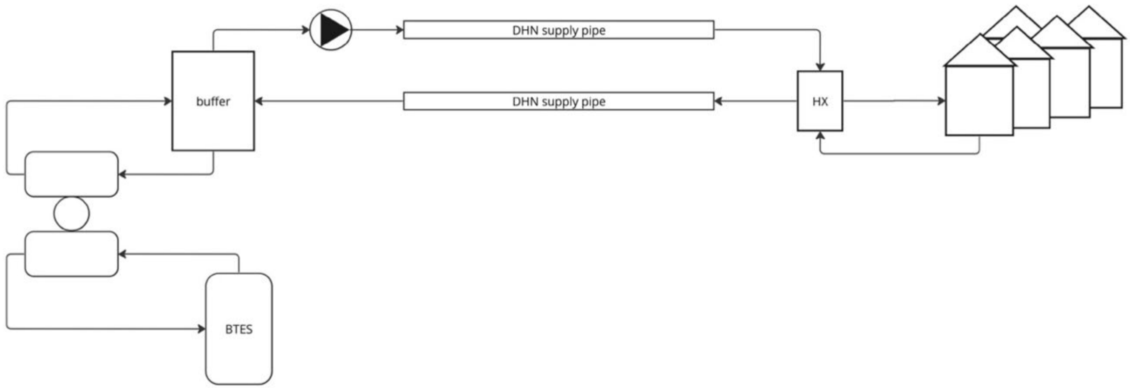

Figure 1. Classical, hydronic DHN network with ground-source heat pump, distribution network and heat exchanger at the load side.

2.1.3. TCN. The TCN case (*Figure 2*) differs from the DHN case as it employs a local sorption reactor with a ground heat source for space heating at the building site. A closed sorption reactor as presented in [11], using sodium hydroxide and water as a working pair is assumed.

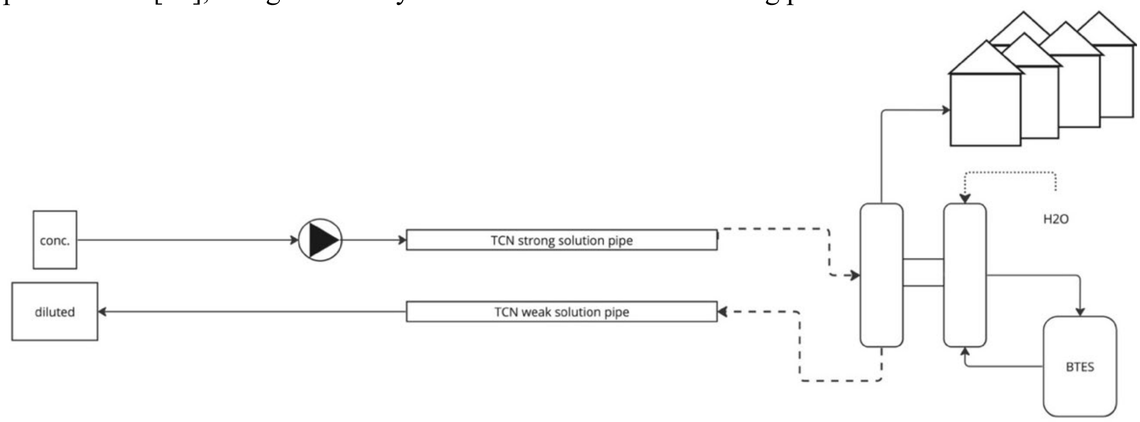

Figure 2. TCN with sorbent tanks, sorbent solution distribution network and ground-source coupled sorption reactor at the load side.

Similarly to the DHN case, a distribution network is assumed, carrying a thermochemical fluid instead of water. The same distance between the load and the generation site was chosen for comparability reasons. The generation, in this case, was virtualized and not simulated. It would represent any possible waste heat source or renewable heat generation unit such as solar collectors or electric heat pumps operated with PV to regenerate the thermochemical fluid during summer.

In the simulation, we assume the availability of regenerated thermochemical fluid (aqueous NaOH solution) with a fixed concentration of 45wt% that can be used for discharge during winter time. This maximum concentration was chosen such that for the selected soil temperature of 5 °C the solidification temperature of aqueous sodium hydroxide is not reached. The sorption reactor is modelled ideally assuming equilibrium conditions similarly as described in [12] and implemented in Modelica.

The input parameters for the simulation were selected in the following procedure: **1)** setting the sorption reactor capacity by scaling the sorbent solution mass flow to match the space heating load (no thermal losses in the network), **2)** setting the mass flow in the GHX loop to receive an evaporator outlet temperature of 1°C at peak heating load.

Assuming the same pipe diameter as in the hydronic DHN, the pressure drop for the circulation of the sorbent solution is calculated along with the electricity demand of the circulation pump, assuming a constant efficiency of 70% (similar to the model used by Modelica in the DHN case).

2.2. Performance metrics

The performance comparison between the DHN and the TCN is done based on a set of key performance indicators that are defined in the following:

$$\text{Energy efficiency} = \frac{space\ heating\ demand}{total\ heat\ supplied}$$

$$\text{Exergy efficiency} = \frac{exergy\ demand\ space\ heating}{total\ exergy\ supplied} = \frac{\left(1-\frac{T_{ambient}}{T_{room}}\right)*space\ heating\ demand}{E_{el,hp}+E_{el,circ}+\left(1-\frac{T_{ambient}}{T_{supply}}\right)*heat\ supplied}$$

$$\text{Electric COP} = \frac{space\ heating\ demand}{total\ electricity\ supplied}$$

$$\text{Energy storage density}_{\text{TCN}} = \frac{total\ heat\ demand}{volume\ of\ energy\ carrier\ medium} \quad [\text{kWh/m}^3]$$

$$\text{Energy storage density}_{\text{DHN}} = \frac{total\ heat\ demand}{water\ volume\ for\ \Delta T=(T_{supply}-\bar{T}_{return})} \quad [\text{kWh/m}^3]$$

2.3. Summary of input parameters

Table 1 presents an overview of the input parameters used in the simulation and the comparison of the hydronic DHN with the TCN.

Table 1. Summary of input parameters

global parameters		**hydronic DHN**		**TCN**	
cumulated SH load	204.7 MWh	network supply temperature	45°C	supply concentration	45 wt%
pipe length network	1300 m	Network mass flow	3.2 kg/s	Network mass flow	0.13 kg/s
		DHN pipe diameter	DN65	TCN pipe diameter	DN65
		GHX return temperature	5 °C	GHX return temperature	5 °C
		GHX mass flow	6.5kg/s	GHX mass flow	10kg/s
		Average ground temperature	5°C		

3. Results and discussion

Based on the simulation outputs, the performance of the two different district heating system approaches can be compared. The defined KPIs are listed in Table 2.

Table 2. Summary of KPIs evaluated for the DHN and the TCN

KPIs	*hydronic DHN*	*TCN*
Energy Efficiency [-]	0.72	1
Electric COP [-]	2.45	3117
Exergy Efficiency [-]	0.08	0.51
Storage density [kWh/m³] $_{5K}$	5.3	118.1
Storage density [kWh/m³] $_{50K}$	58.3	118.1
Storage density Ratio TCN:DHN $_{5K}$	22.3	
Storage density Ratio TCN:DHN $_{50K}$	2	

From this table one can make the following observations: 1) The TCN has a higher *energy efficiency* because the transport of sorbent solution does not involve any thermal losses because no heat is transported but only a chemical potential. Heat losses of the absorber in discharging are neglected under the ideal modelling assumptions 2) While the *electric COP* for the DHN appears reasonable, the electric COP for the TCN is huge. This can be explained by the low mass flow rate of sorbent solution needed for the operation of the sorption reactor. As the same network dimension is assumed in both cases, a creeping flow of the sorbent solution with velocities in the order of 0.02 m/s and a Reynolds number of around 11 results. With this, the pumping cost is almost negligible, being in the order of 15 W. This explains the extreme value for the COP in this ideal setting considered. What it properly reflects though is the inherent feature of TCN to drastically reduce the winter electricity demand in winter operation and by this, responding in a desired way to the winter shortage of renewable electricity in the energy system. 3) When comparing the *exergy efficiency*, again, a significant difference by a factor of about 6 can be recorded. This is again mostly due to the fact that the TCN does not show any significant electricity demand neither for circulation nor for heat generation. In this case, the thermochemical fluid and the chemical potential it carries substitutes the electric energy needed by the compressor of the electric heat pump in the DHN case. 4) Looking at the volumetric energy storage density, in the simulated case the density in the DHN case is really low because of the small temperature difference between supply and return in the network of about 4.5 K on average. Even if the hydronic network was operated with a low temperature difference a sensible storage would be operated and charged to a higher temperature to increase the storage capacity. For a realistic temperature difference of 50 K, the storage density would be 58.3 kWh/m3. For the TCN, the recorded storage density is 118.1 kWh/m^3. This is higher by a factor of 22.3 or 2 respectively, compared to the sensible water storage. In absolute terms, this storage density is still low (compared to the possible 300 kWh/m3 reported in [12]) as the maximum NaOH concentration employed was 45 wt% and the concentration difference across the sorption reactor was low. The reason for this is the relatively high return temperature from the building's space heating loop. To optimize for sorption storage capacity, the heating system would have to be optimized towards minimum return temperatures, allowing low sorbent concentrations to be reached in the reactor in discharging mode.

With the boundary conditions set in the simulations, to store the energy needed to supply the buildings, in the DHN case a tank volume of 52'870 m3 would be needed under the assumption of an ideal storage without thermal losses. In the TCN case a storage volume of 1'517 m3 would be needed to hold the concentrated and 1'733 m3 for the diluted sorbent solution. To calculate the volumetric storage density, the volume of the diluted solution was considered. For an actual implementation of a TCN, not all the sorbent solution would have to be stored seasonally but a continuous regeneration could take place to further reduce the need for total storage capacity.

4. Conclusion and Outlook

Even though many strong assumptions were made in the modelling, considering ideal equipment along many parts of the district heating systems, the study of the two types of networks and their performance comparison revealed some of the key features of the TCN. The most interesting features of TCN are its extremely low electricity demand in winter, stemming from the ultra-low circulation and the substitution of the compressor in an electric heat pump with the sorption potential available in the thermochemical fluid. Further, the absence of continuous heat losses during storage are a big plus, making the TCN also more energy efficient.

For future studies regarding TCN, simulation models need to be refined to allow for more accurate and realistic comparison and understanding of the limitations of the approach. Further, questions towards the real implementation of TCN need to be addressed in order to better understand the technical challenges.

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