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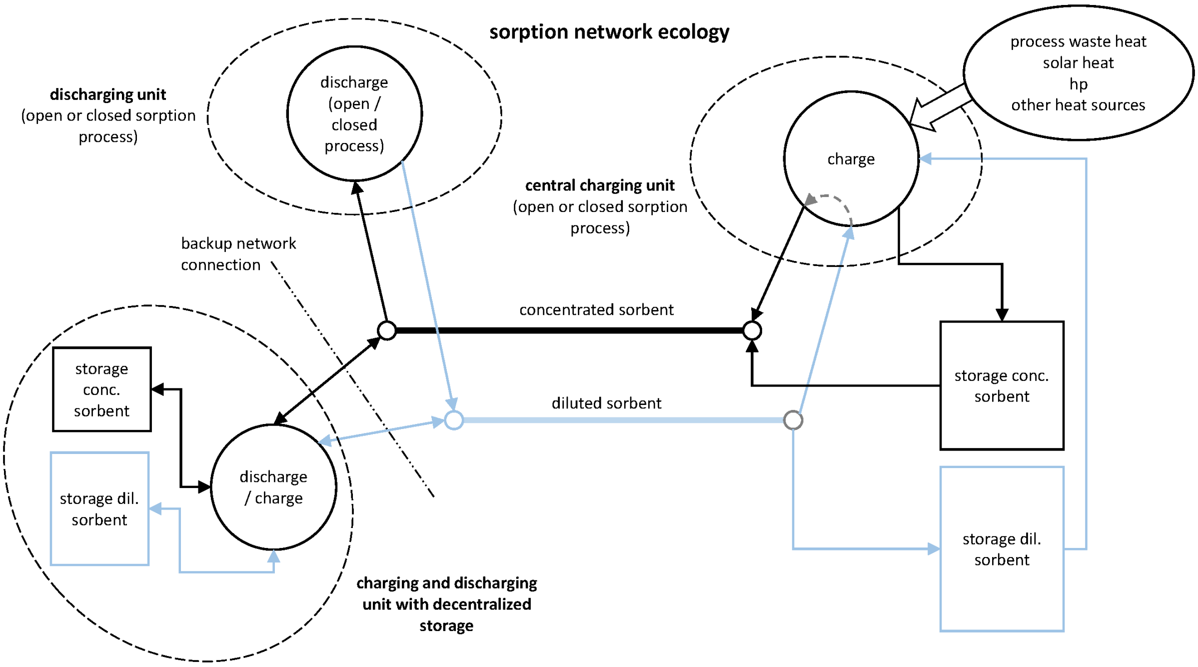
TCology

Thermo-Chemical Network Ecology – Case study and technology potentials



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Zusammenfassung

Das TCology-Projekt untersuchte das Potenzial thermochemischer Netze für deren Anwendung in der Wärme- und Kälteversorgung und Klimatisierung. Ziel des Projekts war es, zu verstehen, wie thermochemische Netze dazu beitragen können, die Herausforderung einer besseren Nutzung erneuerbarer Energien in der Fernwärme- und Fernkälteversorgung durch ihre Fähigkeiten zur verlustfreien thermischen Energieverteilung und Langzeitspeicherung zu bewältigen. Das Projekt identifizierte und charakterisierte geeignete Anwendungen, die durch Sorptionsprozesse abgedeckt werden können, verschiedene Prozesstypen und Arbeitsflüssigkeiten sowie die optimalen Betriebsbedingungen. Ein Vergleich mit herkömmlichen DHNs ergab einen allgemein geringeren Strombedarf und eine höhere Energie- und Exergieeffizienz bei TCNs. Als eines der Hauptmerkmale von TCNs zeigte sich die Integration von erneuerbaren Energien durch saisonale Lastverschiebung. Die Hauptherausforderungen von TCNs sind nach wie vor Unsicherheiten aufgrund des niedrigen TRLs der Hauptkomponenten und daher fehlende zuverlässige Kostenschätzungen. Eine Stakeholder-Analyse indentifizierte verschiedene potentielle Investorengruppen, darunter Industrieunternehmen, Entwickler/Betreiber von Wärmenetzen und den öffentlichen Sektor.

Résumé

Le projet TCology a exploré le potentiel des réseaux thermochimiques pour leur application dans la fourniture de chaleur et de froid et la climatisation. L'objectif du projet était de comprendre comment les réseaux thermochimiques peuvent contribuer à relever le défi d'une meilleure exploitation des énergies renouvelables dans le chauffage et le refroidissement urbains grâce à leurs capacités de distribution d'énergie thermique sans perte et de stockage à long terme. Le projet a permis d'identifier et de caractériser les applications appropriées couvertes par les processus de sorption, les différents types de processus et les fluides de travail, ainsi que les conditions limites nécessaires pour une performance optimale. Une comparaison avec les DHN traditionnels a été présentée, révélant des demandes d'électricité généralement plus faibles et des efficacités énergétiques et exergétiques plus élevées pour les TCN. L'une des principales caractéristiques des TCN est l'intégration réussie des énergies renouvelables par le biais d'un déplacement saisonnier de la charge. Les principaux défis des réseaux transeuropéens restent les incertitudes dues au faible TRL des principaux composants et donc au manque d'estimations fiables des coûts. L'analyse des parties prenantes a mis en évidence l'intérêt de divers groupes d'investisseurs potentiels, notamment les entreprises industrielles, les développeurs/exploitants de réseaux thermiques et le secteur public.

Summary

The TCology explored the potential of thermochemical networks for their application in heat and cold supply and climatization. The goal of the project was to understand how thermochemical networks can contribute to addressing the challenge of better exploitation of renewables in district heating and cooling through its capabilities of lossless thermal energy distribution and long-term storage. The project identified and characterized suitable applications to be covered by sorption processes, different process types, and working fluids, along with the boundary conditions needed for optimal performance. A comparison with traditional DHNs was presented revealing generally lower electricity demands and higher energy and exergy efficiencies of TCNs. As one of the main features of TCNs, the successful integration of renewables through seasonal load shifting could be confirmed. Main challenges of TCNs remain uncertainties due to the low TRL of the main components and hence a lack of reliable cost estimates. Stakeholder analysis highlighted the interest of potential investor groups, including industrial companies, thermal grid developers/operators, and the public sector.

Take-home messages

- TCN is a promising and alternative concept for communal heat and cold supply, building upon local exploitation of environmental heat similarly to 5^{th} generation, low-temperature district heating systems.
- In contrast to hydronic DHNs, TCN offers lossless storage and distribution enabling a successful seasonal load shifting and thus integration of renewable energy sources such as solar.
- A performance comparison with DHNs generally shows higher energy and exergy efficiencies for the heat generation and distribution with TCNs.
- The higher complexity of the equipment for TCNs along with its low TRL makes it difficult at the moment to evaluate the true cost of TCNs and thus market potential.

Contents

Abbreviations

ANN	artificial neural network
CHP	combined heat and power
COP	coefficient of performance
CS1,2,3	case study 1,2,3
DHN	district heating network
DN	diameter nominal (pipe diameter)
DHW	domestic hot water
GHG	greenhouse gas emissions
HVAC	heating ventilation, air-conditioning
HTF	heat transfer fluid
HP	heat pump
KPI	key performance indicators
LiBr	lithium bromide
LiCl	lithium chloride
NaOH	sodium hydroxide
RH	relative humidity
R&D	research and development
SFH	single-family home
SH	space heating
STES	seasonal thermal energy storage
SWOT	strength, weakness, opportunity, threat
TC	thermochemical
TCF	thermochemical fluid
TCN	thermochemical network
TMY	typical meteorological year

1 Introduction

1.1 Background information and current situation

This project is mainly motivated by i) the **large potential of district heating and cooling networks** for the integration of renewables and thus decarbonization of the heating and cooling sector in Switzerland and ii) the significant **potential of liquid sorption processes for efficient energy conversion, distribution, and storage**.

Based on these identified potentials, the project aims to combine the thermal network solutions with the sorption processes and thus find synergies and explore new solutions to meet the future challenges of renewable heat and cold supply for the building and the industry sector.

The project studies **thermochemical networks** (TCN), their suitability for energy transport, along with a combination of different terminal applications connected to the network, including industrial drying processes, climate control (heating, cooling, and dehumidification), and energy storage. The loss-free, long-term energy storage is an inherent feature of the thermochemical network and a pivotal element in decarbonizing the heating and cooling sector.

Thermochemical networks are based on applying a known technology (absorption heat pump) in a new context. This sees the sub-processes, traditionally regarded as a simultaneous overall process, in a spatial and temporal split. The focus is on the liquid working fluid (sorbent), in which a "chemical potential" is stored that can be used to change the temperature of heat release. This means that useful heat or cold can be generated from ambient heat by reducing the chemical potential. Compared to conventional heat transfer media, the main advantage of such a "potential carrier" is that the stored potential is retained without losses over time. With thermochemical energy supply networks, renewable energy sources can thus be integrated more efficiently, and waste heat sources that were previously not economically usable can be tapped. Another advantage of thermochemical networks is the high storage energy density of the transport medium. If one compares classic hot water storage tanks (at dT=70K) with thermochemical storage, the energy density of the latter is higher by a factor of up to 5 [1]. The application spectrum of thermochemical networks is vast and includes both industrial processes (e.g., drying processes) as well as building air conditioning. The advantage of air conditioning systems is the possibility of simultaneous (i.e., realizable in one process step) adjustment of air temperature and humidity - therein lies a further potential for a new generation of building air conditioning.

1.1 Purpose of the project

The project takes a holistic perspective on the topic of thermochemical networks. It aims to explore this novel field of research by defining possible applications, process types, suitable network structures and typologies, and potential synergies with classical hydronic thermal networks. It thus aims at **laying the foundations for what we call the "thermochemical network ecology"**.

Specifically, the project addresses and identifies various features of TCNs, **compares competitive advantages and synergies with classical heating and cooling networks, and defines process parameters for the operation and various terminal applications** (heating, cooling, energy storage, drying/dehumidification). Further, it **defines synthetic and real cases to study the performance of TCNs** and compare them to state-of-the-art heating and cooling networks. With this analysis, a better understanding of the competitive advantage of this novel technology and the synergy potentials are being recognized.

Beyond the physical perspective of the novel network solution, a market perspective is engaged as well. An analysis of the specific **value proposition and identification of possible business cases is presented for various network cases and combinations of terminal applications**. This should lead us to understand where there is the most significant potential from a market perspective and enable the comparison to the energy performance perspective. Business case identification is based on analyzing the actors involved in the value-creation process and their interactions. Due to the novelty of the technology, this is complemented by an assessment of the current state and future requirements for the different actor groups' resources and activities.

1.2 Objectives

The following **main research questions** guide the research presented in this project:

- What are the **opportunities** (SWOT) of thermochemical networks, and how do they compare to classical hydronic networks?
- What **terminal applications** can be met with liquid sorption processes, including open and closed process types?
- How are different terminal applications best combined by means of thermochemical networks?
- What are **optimal network** structure, typology, operation, and process **parameters**?
- Under which **conditions**/for what **cases** do thermochemical networks perform best or are most competitive?
- How does this translate to different **value propositions** and potential **business cases**?
- How is the **energy performance** for different cases compared to hydronic networks?
- What are the **potential synergies** of different network solutions (hybrid hydronic/ thermochemical)?

Answering the above questions translates into the following **main goals**:

- Definition of the **thermochemical network ecology** with an understanding of possible terminal applications, network integration, and synergies with classical hydronic networks
- Definition of relevant synthetic and real load/supply cases, **performance analysis, and comparison** to classical network solutions
- Identification of **value propositions** and potential **business cases** of different network/application configurations.
- Recommendation for further **research and industry collaboration**

2 WP1 - Identification/definition of thermochemical network ecology

A thermo-chemical network ecology defines all the elements necessary, and their interaction, to exploit a thermochemical potential in a TCN, as an alternative to traditional hydronic thermal networks. Accordingly, in this section is presented a comprehensive study of suitable processes and terminal applications; the interaction of these elements within a TCN; the identification of suitable TCF; and the value proposition of TCN.

2.1 Identification of suitable processes and terminal applications

2.1.1 Charging process

During the charging process, water is driven out from the sorbent solution, i.e., a diluted solution is brought to a higher concentration. In this report, the diluted solution is named flow, and the concentrated solution return (-flow). The concentrated solution is fed back into the TCN, and the water driven out is released into the environment. Charging processes can be classified into open and closed (see Figure 1). In the former, the air is taken in from the environment and exhausted with a higher water load. While in the latter, only water is exhausted. Some sorbents are suitable for open and closed processes, but others can react with the air's components. That makes them less suitable for open processes, e.g., NaOH reacting with CO_2.

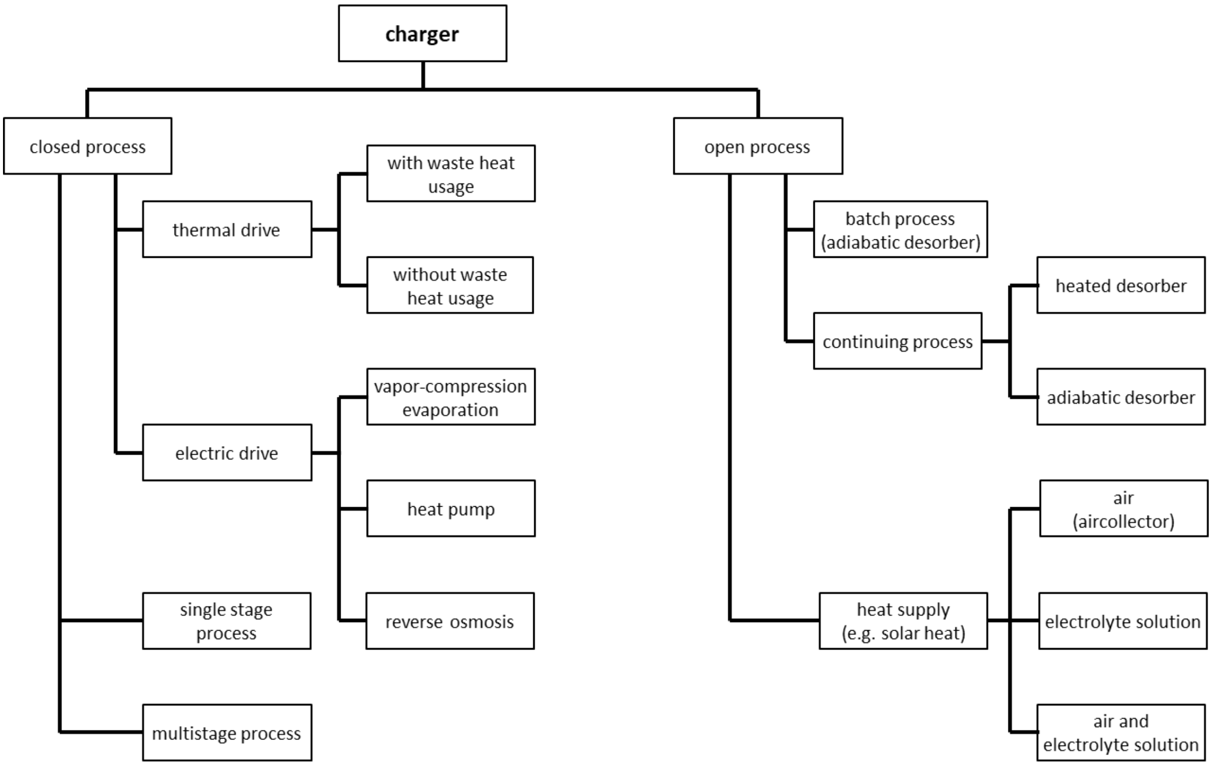

Figure 1: Overview and classification of different regeneration processes.

Thermal-driven regeneration (charging) in closed processes

The regeneration in a closed thermal-driven process with waste heat usage can be implemented in combination with a CHP (Figure 2). In this case, waste heat from gases at approx. 500°C can be fed into the desorber at 120-150°C (T_E). While the condenser condensates at 100°C, it can deliver a flow temperature of 90°C (T_N).

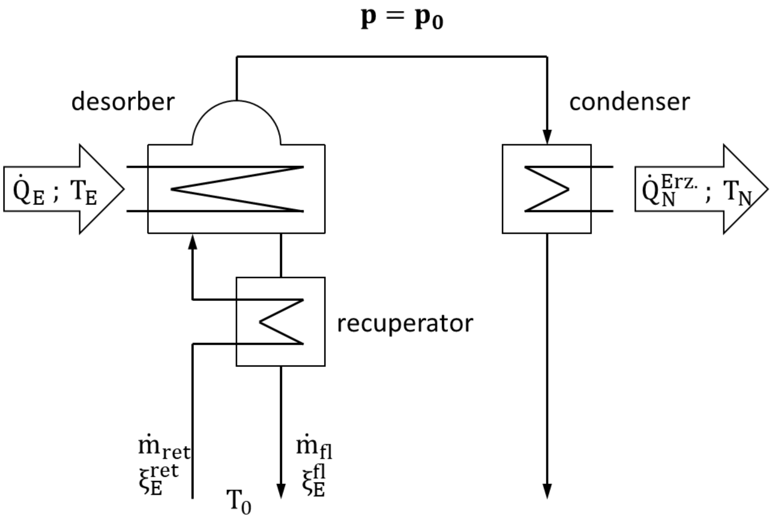

Figure 2: Closed process regeneration with thermal drive with waste heat usage.

Application 1: Implemented in a combined heat and power plant (CHP) at Sporthochschule Köln [2]. Combustion heating power is twice 970 kW, using calcium nitrate for waste heat recovery of 115 - 155 kW. Built in 2004.

Application 2: In a combined heat and power plant in Berlin-Buch (Figure 3), a thermal heat recovery is installed [3]. Combustion heating power is 4.4 MW, using calcium nitrate for waste heat recovery of 310 - 480 kW. Built in 2006.

Figure 3: Charging in a thermal power plant in Berlin-Buch. Components: a) phase separator, b) condenser, c) desorber.

In closed thermal-driven processes, an alternative to using waste heat for regeneration is using solar thermal or general waste heat at temperature levels between 50°C to 80°C ($\dot{Q}_E$) (Figure 4). In this case, the condenser would work at a temperature of 30°C (T_0). These temperatures apply for p = 40mbar.

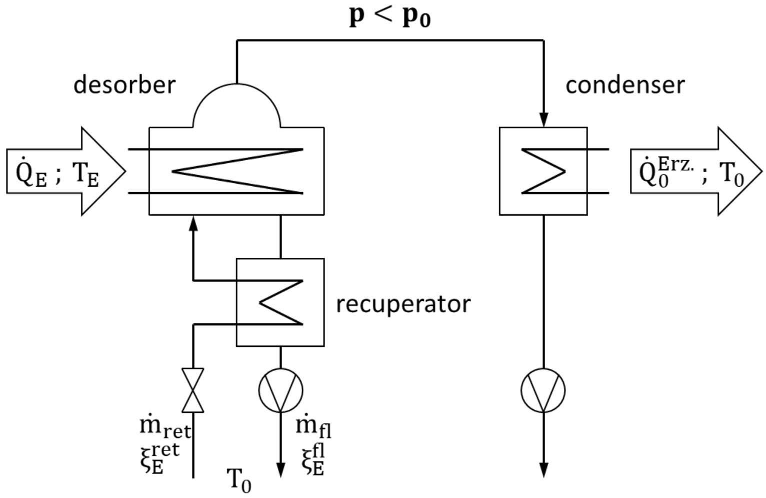

Figure 4: Closed process regeneration with thermal drive without waste heat usage.

Application 3: Regeneration in a closed process studied by Empa (Figure 5) for seasonal sorption storage applications [4]

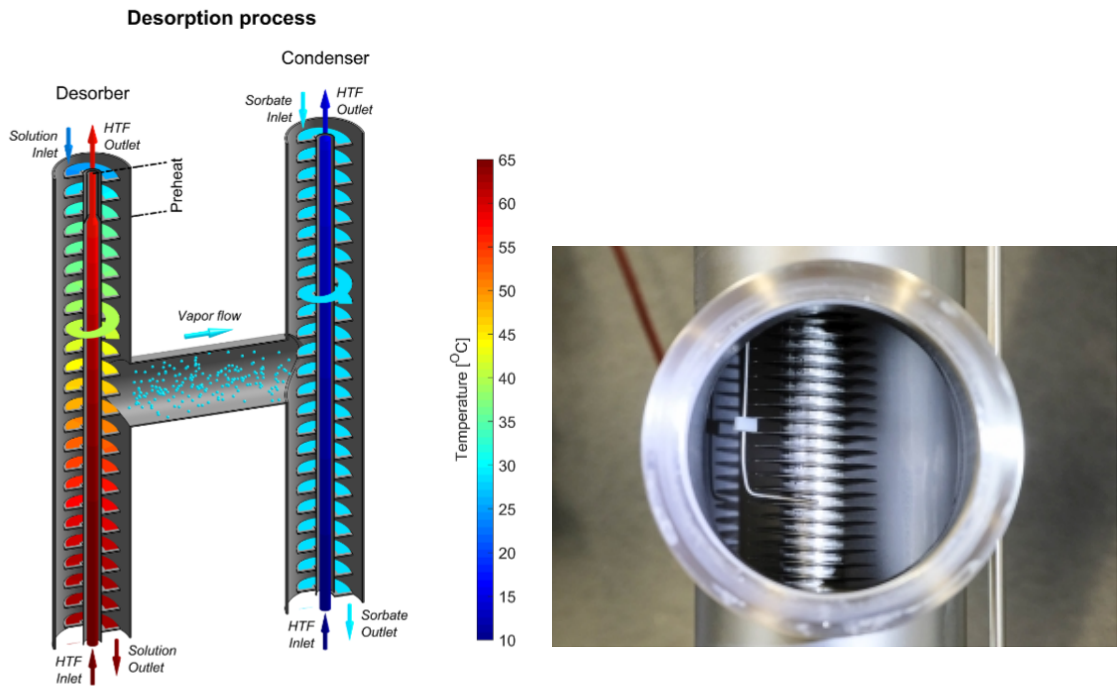

Figure 5: Desorption process with thermal drive (from [4]).

Electric-driven regeneration (charging) in closed processes

Electric-driven regeneration in a closed-process (see Figure 6) could be achieved using photovoltaic surplus energy (P_E). The electric drive can be integrated using a heat pump or a vapor-compression evaporator. Desorber temperature is between 120°C and 150°C. When using a heat pump, the condenser temperature is 100°C.

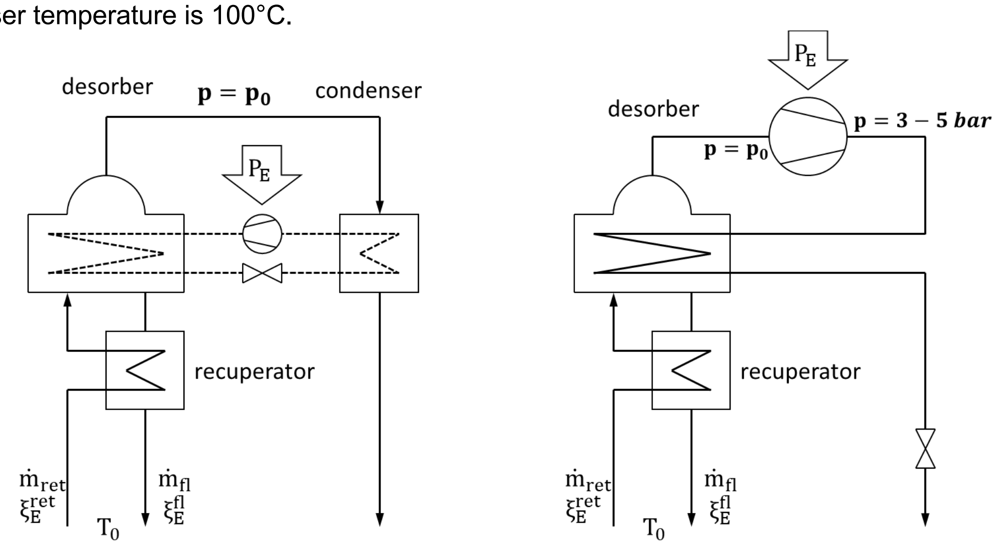

Figure 6: Regeneration with electric drive, using a heat pump (left), using a vapor-compression evaporator (right).

Regeneration (charging) in open processes

In open processes, heat supplied to the desorber to regenerate the solution can be applied to the sorbent ($\dot{Q}_E^{EL}$) or the air ($\dot{Q}_E^{L}$) or both (see Figure 7). Adding heat to the air is limited because of the air heat capacity thus, it involves high temperature differences and thus source temperatures. The performance depends on ambient air conditions (T_L^{WE}, φ_L^{WE}) and solution temperature at the inlet. One possible desorber configuration is with random packing.

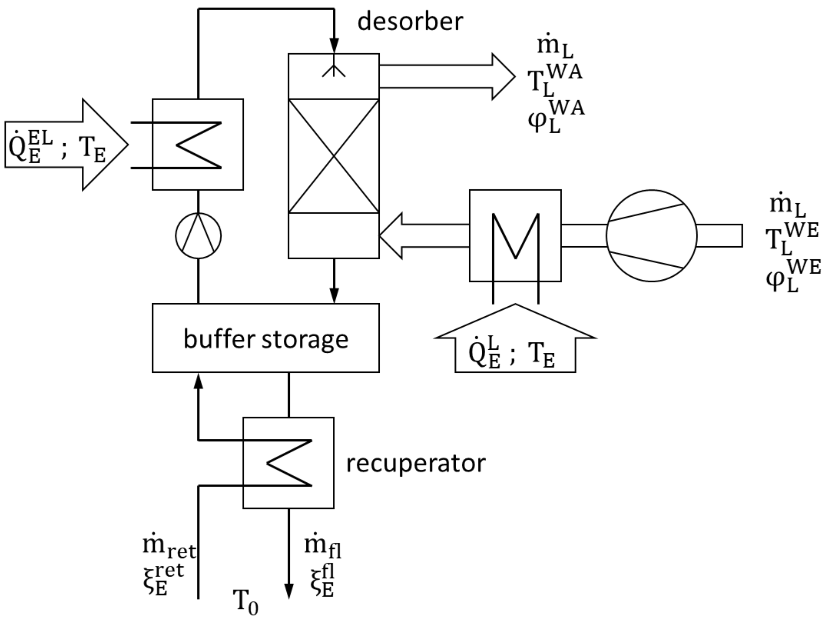

Figure 7: Open process charger in a batch process with heat supply for the air and the sorbent solution.

Application 4: This process is applied in the research project "Gewächshausklimatisierung" (Figure 8) [BFE SI/502038-01] in a Greenhouse in Wangen, close to Zurich, Switzerland. The sorbent selected is magnesium chloride. The desorber in Wangen applies heat to the solution (Q_{EL}) and works at a solution flow temperature of 45°C.

Figure 8: Desorber / Charger in the project "Gewächshausklimatisierung".

2.1.1.1. Discharging process

In the discharging process, the chemical potential in a concentrated sorbent solution is used to shift ambient heat to a usable temperature level, to provide cooling or dehumidify moist air. In discharging, the solution gets diluted and is returned to the TCN. Similar to the charging process, discharging processes can be classified into open and closed processes (Figure 9).

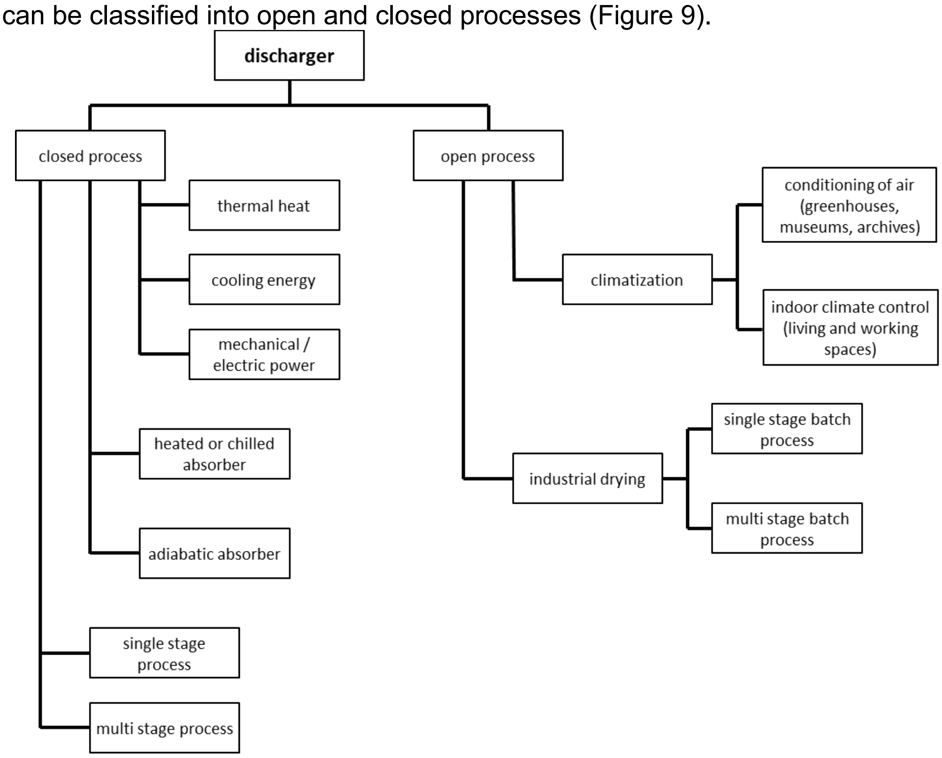

Figure 9: Overview and classification of different discharger processes and applications.

Discharging in closed process for heating

The closed process of thermal heating (Figure 10) is working under sub-atmospheric pressure (e.g., 10 mbar). This process works like a heat pump with an evaporator temperature of e.g. 7°C (T_0). Depending on the sorbent and its concentration/state of charge, resulting in a heating temperature of e.g. 45°C (T_H).

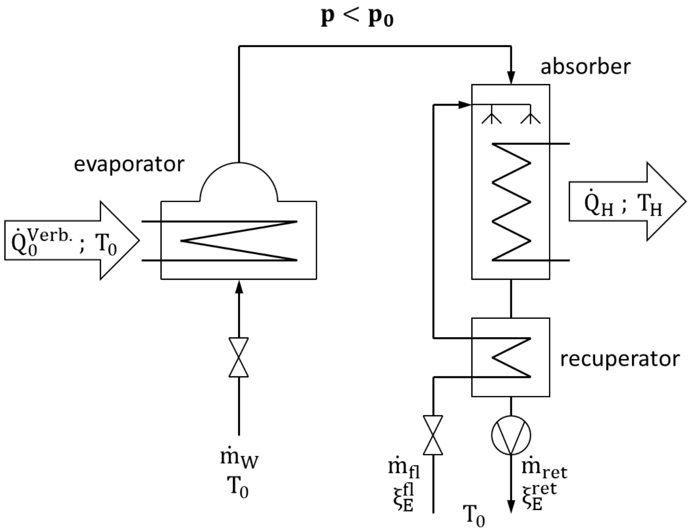

Figure 10: Closed process thermal heating.

__Application 5:__ An example of this process using sodium hydroxide is found in [4] (Figure 5).

Discharging in closed processes for cooling

The closed process applied for cooling is similar to the one applied for heating. However, in this case it is not integrated a recuperator. Evaporator and absorber temperature are on around the same level as in the heating process. But the heat at the absorber ($\dot{Q}_0^{Verb.}$) is rejected to the heat sink and the temperature at the evaporator is the flow temperature (T_K) for cooling usage.

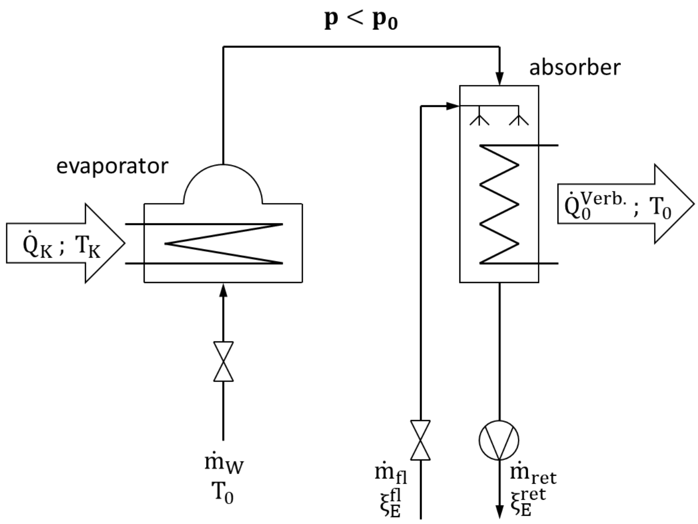

Figure 11: Closed process cooling energy.

Discharging in closed processes for generating mechanical or electric power

The closed process for mechanical or electric power (Figure 12) is also known as “Honigmann-Process”. Named after Moritz Honigmann who developed a fireless locomotive (Figure 14) in 1883 using this process with sodium hydroxide. A sorbent is heated up and evaporates water in a heat exchanger. The pressure change in water is used to drive a steam engine or similar (P_N), reducing its pressure over the engine the steam is brought in contact with the sorbent. The condensing sorbent releases absorption heat evaporating more water. The cycle runs until a certain concentration in the sorbent is reached.

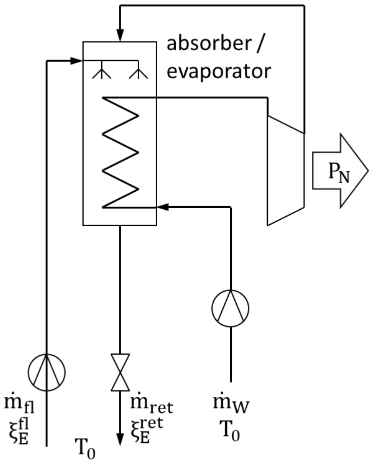

Figure 12: Closed process mechanical / electric power

Jahke [5] estimated and compared the performance of different process (Table 1):

Technologie	Energiedichte Gravimetrisch Wh/kg	Volumetrisch kWh/m^3	Wirkungsgrad %	Selbstentladung %/Tag	Lebensdauer Zyklisch Zyklen	Kalendarisch a
Mechanische Energiespeicher						
Pumpspeicherwerke	0,3-1,4	0,35-1,1	70-82	0-0,5	12800-33000	40-100
Druckluftspeicher (CAES)						
diabat (z.B. Huntdorf)		2-7	40-55	0-10	8620-17100	40
adiabat		2-8	60-68	k.A.	-	k.A.
Thermische Energiespeicher						
Sensible Wärmespeicher	10-50	100-300	45-75	k.A.	5000	k.A.
Latentwärmespeicher (PCM)	49-97	113	75-90	k.A.	5000	k.A.
Thermochemische Wärmespeicher (TCS)	120-960	120-250	80-100	k.A.	3500	k.A.
Honigmann-Energiespeicher						
Strom zu Lösung zu Strom	5 [4]	8	50-70	0	k.A. [5]	k.A. [5]
Wärme zu Lösung zu Strom	5 [4]	8	4-5 [4]	0	k.A. [5]	k.A. [5]
Wärme zu Lösung zu Wärme	120-960	120-250	80-100	0	k.A. [6]	k.A. [6]
Wärme zu Lösung zu Kälte	120-960	120-250	80-100	0	k.A. [6]	k.A. [6]

Table 1: Excerpt of A. Jahnkes dissertation [5].

Application 6: TU Berlin studied the Honigmann-Process in a scaled device (Figure 13) using a lithium bromide – water solution [5].

Figure 13: Test facility at TU Berlin, a) evaporator, b) absorber, c) expansion machine [5].

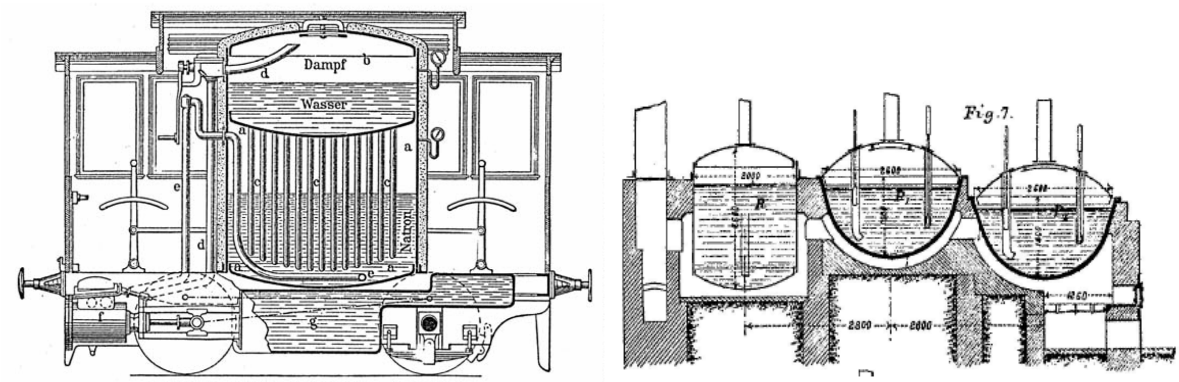

Figure 14: Honigmannsche soda locomotive (left) and the charging boilers (right) (from [6], page 890).

Discharging in open processes for climatization

The open process for climatization (Figure 15) is divided into the conditioning of air and indoor climate control.

Conditioning of air *where* humidity and temperature are adjusted simultaneously and brought to a defined point regardless of the conditions at the air inlet. It can be of special interest in greenhouses, archives, and museums.

Indoor climate control compensates for heat and humidity losses and gains to reach the demand. Indoor climate control is used in living and working spaces.

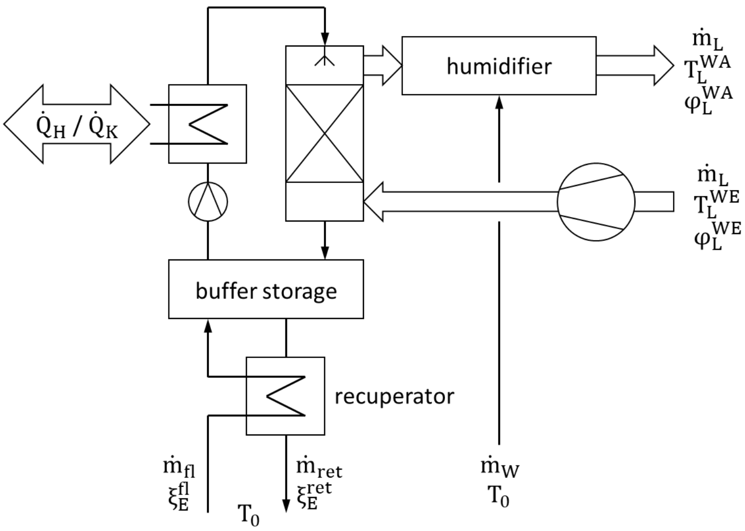

Figure 15: Open process for climatization.

Application 7: An open process for conditioning of air has been applied in "Gewächshausklimatisierung" (Figure 19) [BfE SI/502038-01] in Wangen close to Zurich. The installation is the award-winner of "Watt d'Or" 2020 [7,8].

The results from Wangen are also implemented in the EU Horizon 2020 project "The Greefa" [9]. In a 600 square meter greenhouse, nine absorbers are installed. Working with magnesium chloride the absorbers control the conditions of the air matching the plant's needs. In the greenhouse, the assessment of energy- and mass- balances are part of the research. Experimental testing and optimization are important parts of the project. Analyses promise a reduction in heat demand of 53% (Figure 16) [BfE SI/502038-01].

In a simulation of a TCN (Figure 17) for the greenhouse in Wangen [10], the integration of a combined heat and power station with the regeneration process recovers otherwise unused waste heat in summer, equivalent to 40 kW. In this study, it is estimated that the TCN annually uses 750 m^3 of solution and requires a seasonal storage of 210 m^3. Alternatively, the charging process of the solution could be done using solar heat which would require an area of 350 m^2 of solar collectors. This TCN could cover an annual heat demand of 110 MWh.

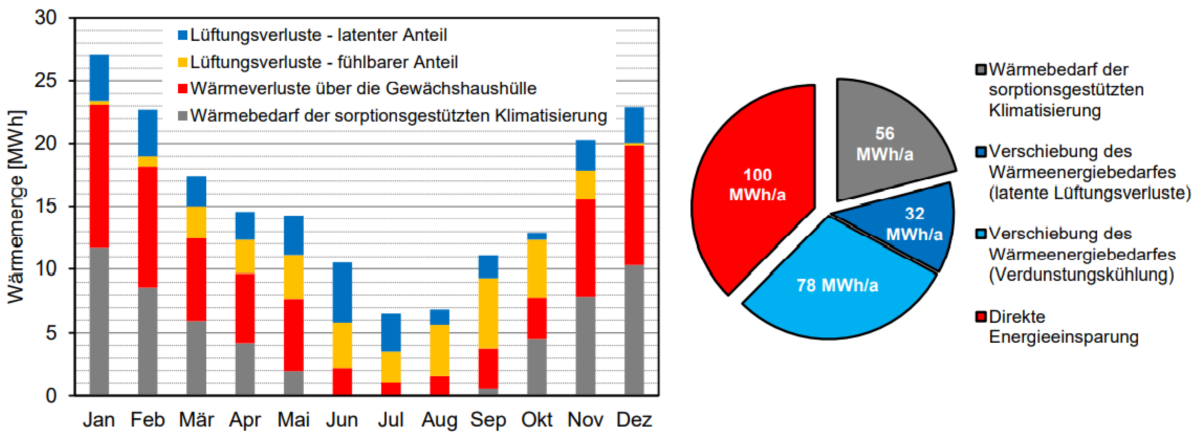

Figure 16: Direct heat savings and indirect heat savings (charging) covered by renewable or waste heat [BfE SI/502038-01].

Figure 17: Idea of a TCN around the greenhouse (from [10]).

The absorber takes the exhaust air at the top of the greenhouse and after adjusting temperature and humidity it supplies the conditioned air at the plants level as shown in Figure 18.

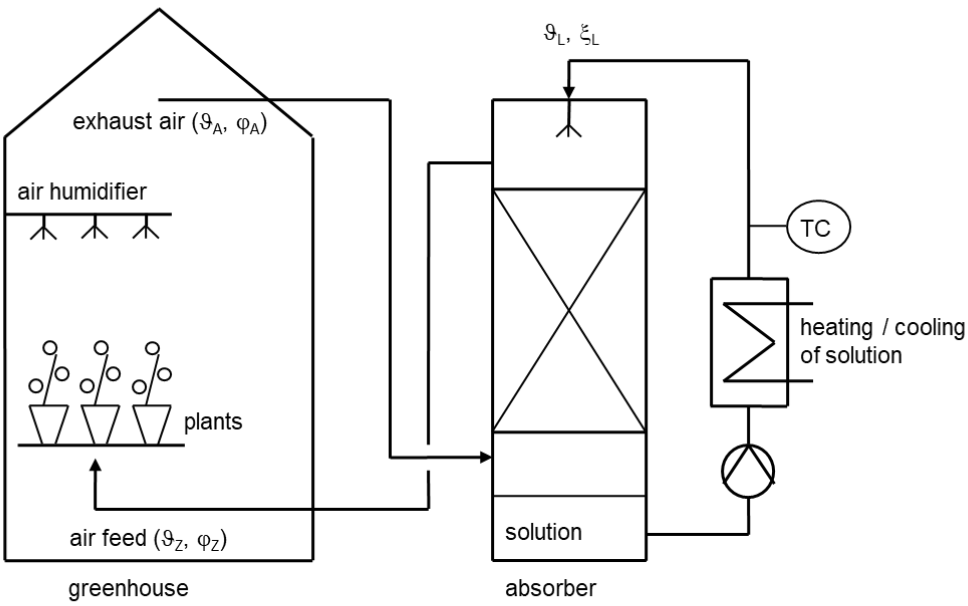

Figure 18: Schematic construction of the "The Greefa".

The plant tables in the greenhouse are equipped with walls (Figure 19) to allow for the generation of a local climate, regardless of the overall conditions in the greenhouse.

Figure 19: Demonstrator greenhouse with the desorbers in red.

Application 8: The open process of climatization (Figure 15) is applicable also for office/living spaces. In an ongoing research project at ZHAW IEFE. The prototype (Figure 20) is designed to heat, cool, humidify and dehumidify an office room of 60m^2. Further, an increase in indoor air quality and a reduction of germs is expected.

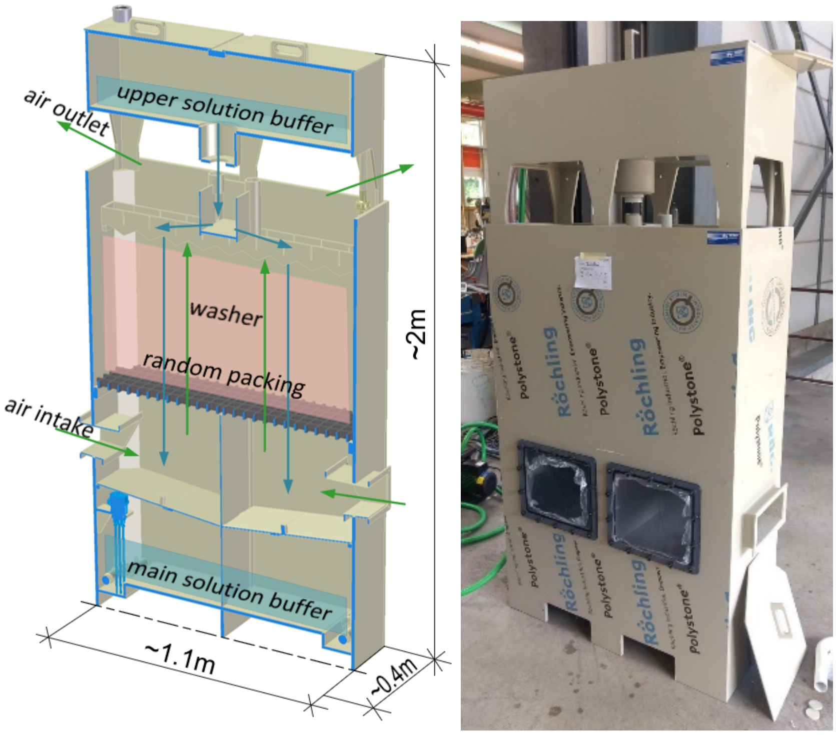

Figure 20: Office indoor climate control device, prototype for research at ZHAW.

Two main working modes are envisioned. Cooling and dehumidification (Figure 21) or heating and humidification (Figure 22). For the case of cooling and dehumidification (Figure 21) target room conditions are set to 23°C and relative humidity (RH) 65%. The solution temperature is set to 25°C. For a sorbent solution concentration of 35 wt% the absorber dehumidifies the air at 25°C to ~7.5 g/kg. An adiabatic cooler humidifies the air and cools it down to ~18°C, which is the air outlet of the device.

This is enough to compensate for the heat and moisture gains of the room, including gains due to transmission, air change, persons, and electric devices.

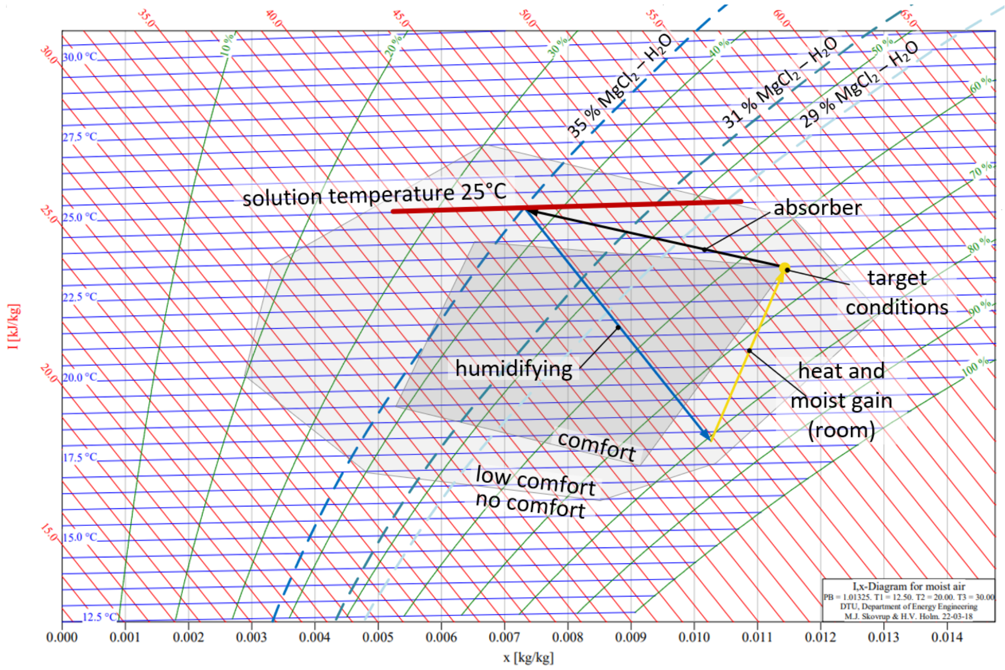

Figure 21: Cooling and dehumidifying with the indoor climate control device.

The heating and humidification (Figure 22) case is set to target conditions of 19° C and RH 38%. The solution temperature is set to 21.5°C. With a sorbent solution concetration of 35 wt% the absorber humidifies and heats up the air to the outlet conditions of 21.5°C and RH 37%. This compensates moisture losses and part of the heat losses of the room.

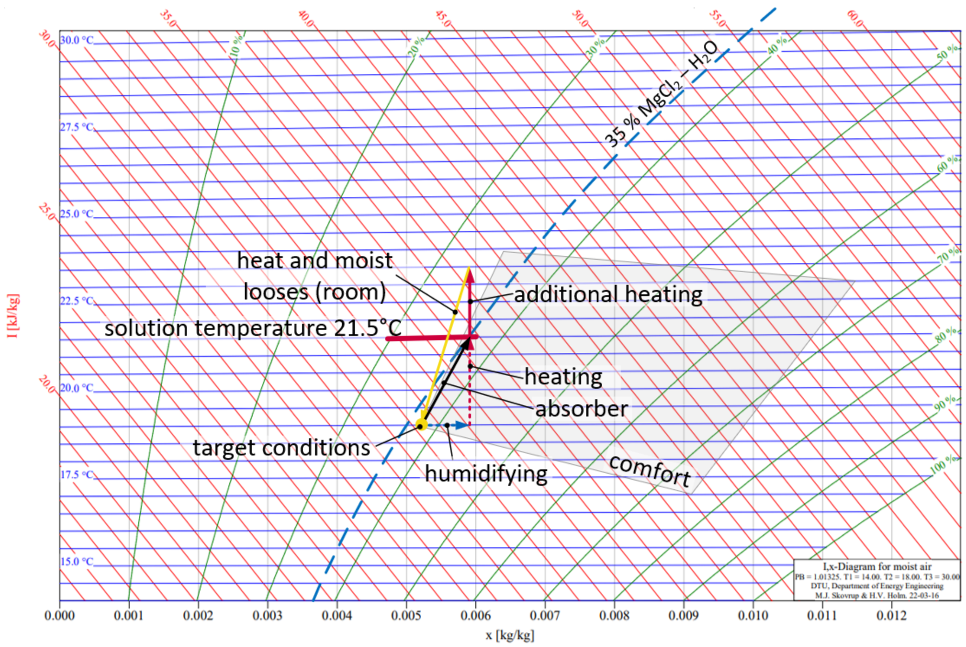

Figure 22: Heating and humidifying with the indoor climate control device.

The control of the system is depending on the conditions of the air in the room, as shown in Figure 23 and summarised below:

1. Device is off (conditions are good)
2. Device is humidifying only (adiabatic cooling)
3. Device is absorbing and humidifying (adiabatic cooling but with dehumidification)
4. Device is absorbing only (low solution temperature)
5. Device is absorbing only
6. Device is absorbing only (absorption releases heat)
7. Only additional heating is on
8. Device is desorbing with additional heating on (low solution concentration)
9. Device is desorbing only (low solution concentration)

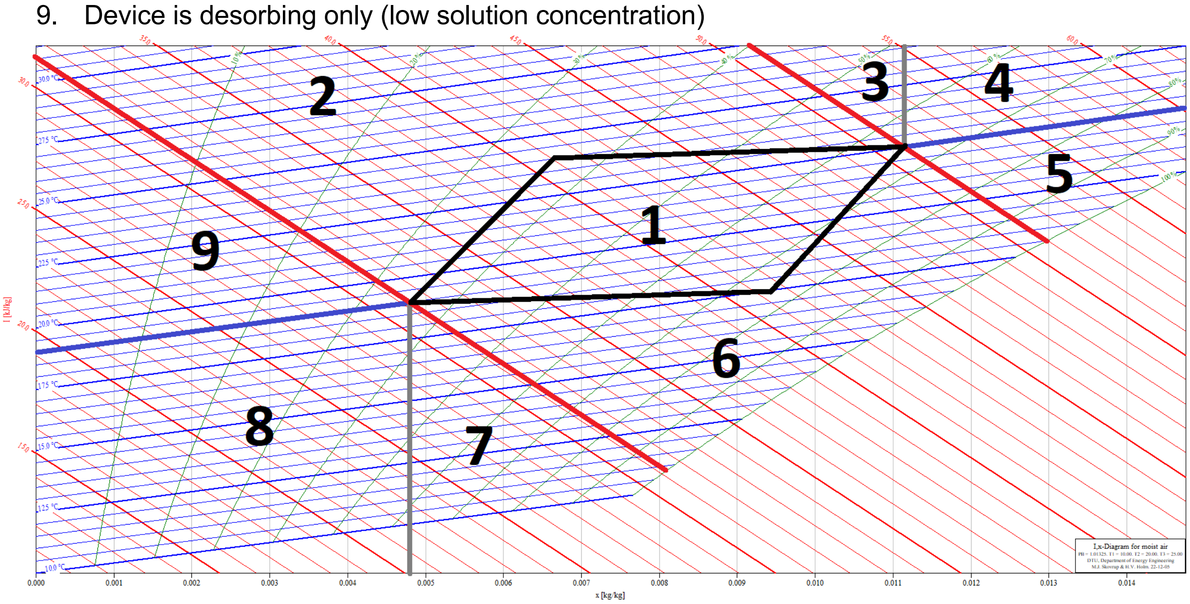

Figure 23: Different modes of the climate control device.

Industrial drying (open) process

The (open) process of industrial drying (Figure 24) is applicable to dry goods. The open is in brackets because the absorber and drying chamber are working with air at atmospheric pressure but the air is not exchanged with the ambient and stays the same during the whole drying process. As a result, sorbents that are not suitable for open processes can be used for this application.

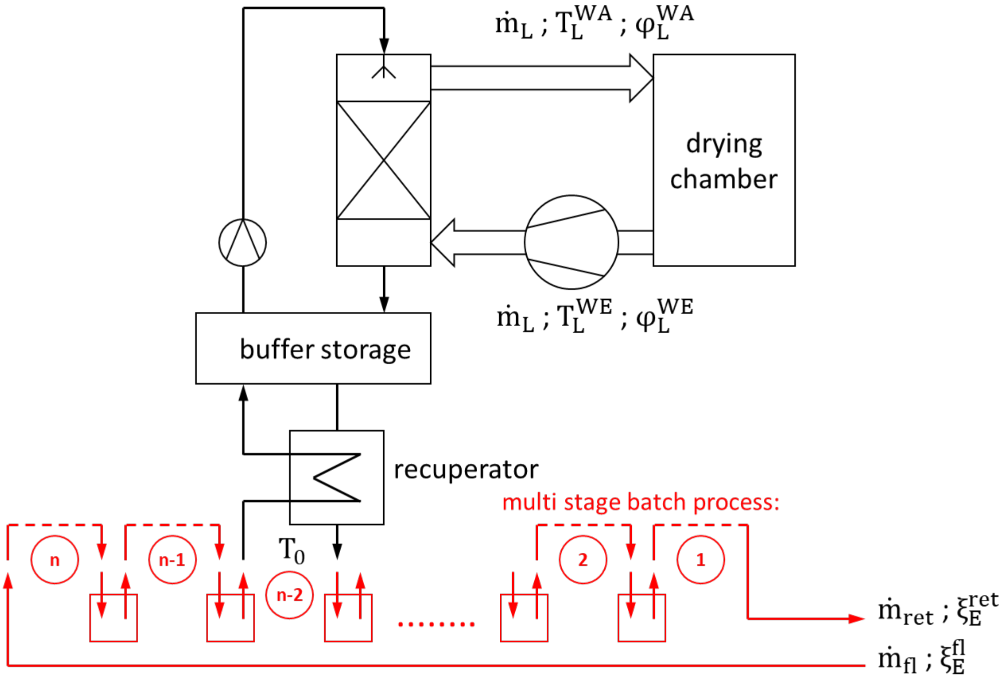

Figure 24: Industrial drying open process.

Application 9: In the research project "Sonitro" (SFOE project SI/502013) by ZHAW in partnership with the company Holderhof Produkte AG, tea leaves are dried with test equipment (Figure 25). The equipment is using sodium hydroxide. Experiments show an increase in tea quality, caused by steady and lower drying temperatures (Figure 26), and a reduced drying duration by 50%.

Figure 25: Project "Sonitro" drying chamber for tea leaves with agitator.

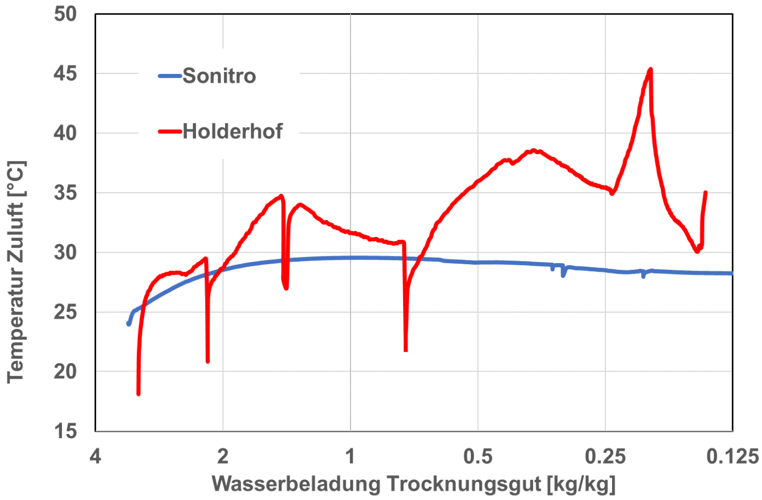

Figure 26: Drying temperature comparison of sorption dryer (Sonitro) and conventional dryer.

2.1.2 Identification of TCN

An example of a TCN, which includes different terminal applications, is shown in Figure 27. This TCN integrates a heat network and has interfaces to the electric demand and supply side. It uses two different TCF in two different cycles, and the potential of the two TCF is interchangeable through an intermediate potential exchanger. As the different TCF match different applications' needs, the benefit of using two TCF is to have a wider range of applications. TCF A is regenerated in a closed process (Figure 2) at a high-temperature level using heat released from a CHP. TCF B is regenerated in an open process (Figure 7) using waste heat at a lower temperature level, using thermal solar or a heat pump. TCF A features a discharging process with a closed process that provides heating (Figure 10) or cooling energy (Figure 11) to the discharging process with an open process for climatization (Figure 15) featured by TCF B.

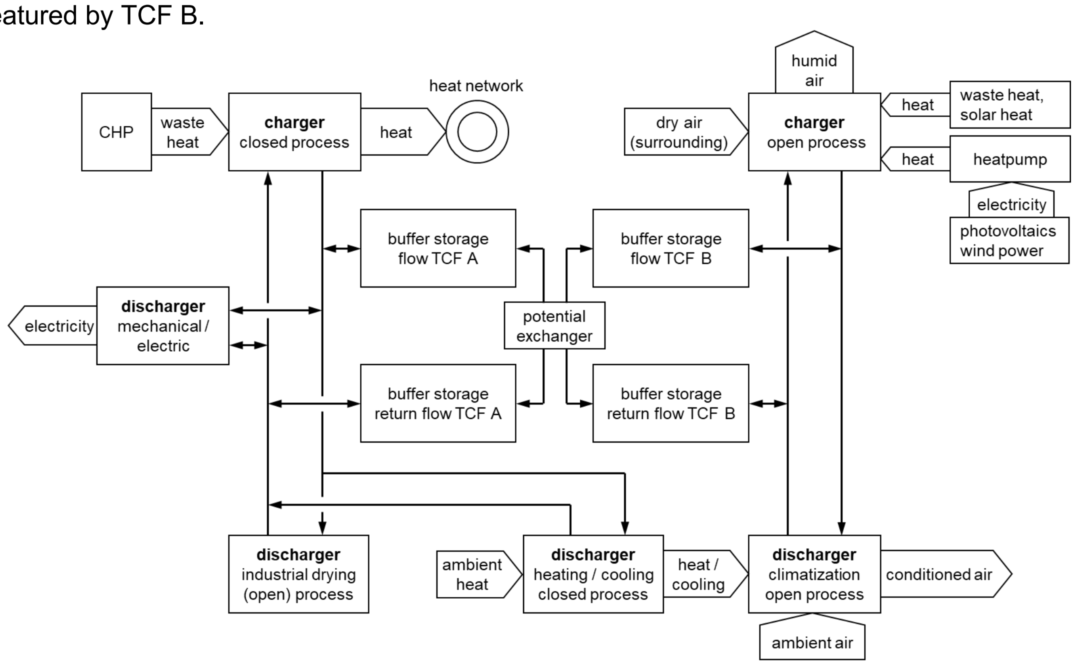

Figure 27: Example of a TCN, using two different types of TCF.

In this network, TCF A could for example be sodium hydroxide, as it is only suitable for closed processes. And TCF B could be magnesium chloride, as it is suitable for open processes. Buffer storages can be added in any part of the network. The network can store chemical potential lossless over time. This makes it possible to reduce transport speed to a minimum and thus to reduce pumping cost.

2.1.3 Identification of suitable sorbents (TCF)

The sorbents considered are hygroscopic fluids i.e., fluids attracting water. Water, as the working medium, is highly available in the environment and doesn't need to be transported separately. Solving water in a sorbent lowers the chemical potential of the water. With more water and lower sorbent concentration the potential difference to pure water is getting smaller. The chemical potential difference shifts the condensing/boiling temperature of the water. This effect can make environmental heat exploitable to provide heat at a utilization level. Conversely, it can use the ambient temperature as a heat sink and provide cooling at a utilization level. Just like an electric heat pump but without the use of electrical/mechanical energy. Another application of the shifted condensing temperature of the water is the drying process at low temperatures. The sorbents analysed in this work are selected by hygroscopic properties and the risk of harmfulness (toxicity) [11].
The temperature lift and the minimum achievable air humidity depends on the concentration of the TCF. The minimum system temperature sets the boundaries for the maximum concentration in TCN. The limiting effect is the solubility of the TCF which is depending on temperature (Figure 28). Diluting salt lowers the freezing point of the water, but above the eutectic point, this effect is inverted. Exceeding the maximum soluble concentration leads to the separation of salt sediment (crystallization), resulting in component failures such as in heat exchangers, pumps and pipes.

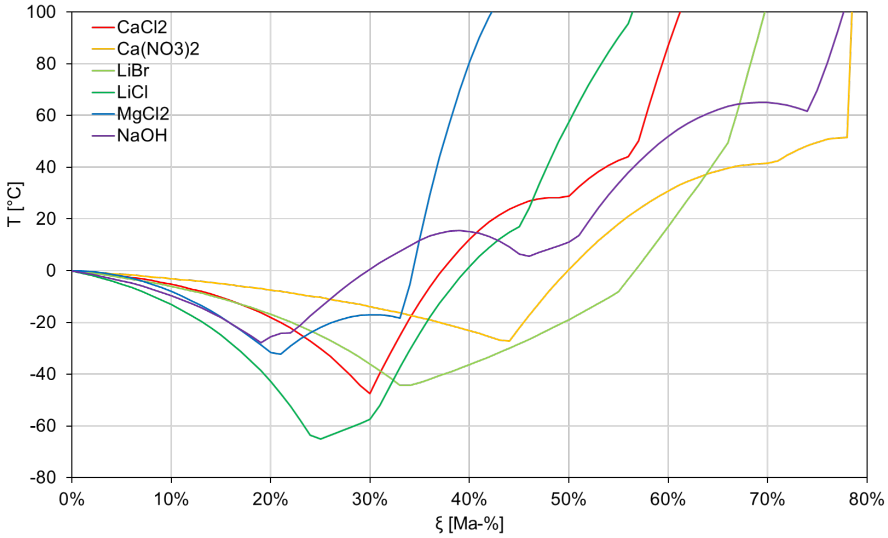

Figure 28: Solubility of different sorbents in water.

The concentration of the TCF shown in the following considerations corresponds to the saturation concentration at the minimum system temperature.

Temperature lift and heating

The different solutions have different potentials of temperature lift. The temperature lift is evaluated based on the difference of the chemical potential of pure water and water in the sorbent solution together with the assumption of a reversible thermodynamic process. The graphic below (Figure 29) shows the temperature lift for different sorbents for a minimum system temperature of 10°C.

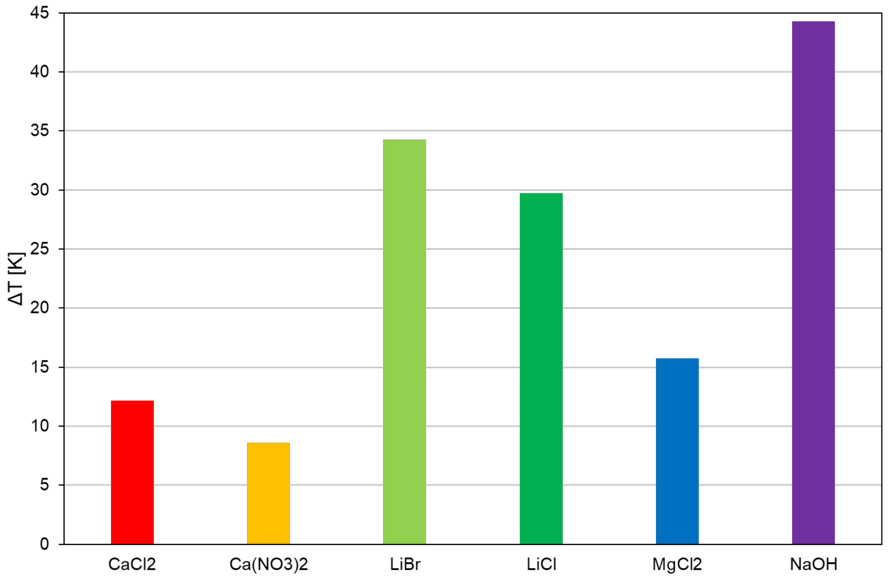

Figure 29: Temperature lift of different sorbents for a minimum system temperature of 10°C.

As the heating process can be applied in multiple stages, the temperature lift can be summed-up for every stage. Figure 30 presents an example where a heating temperature of 45°C is reached by an ambient temperature source of 7°C and a minimal system temperature of 10°C. For this scenario, using NaOH only requires a single stage and using $MgCl_2$ would require three stages.

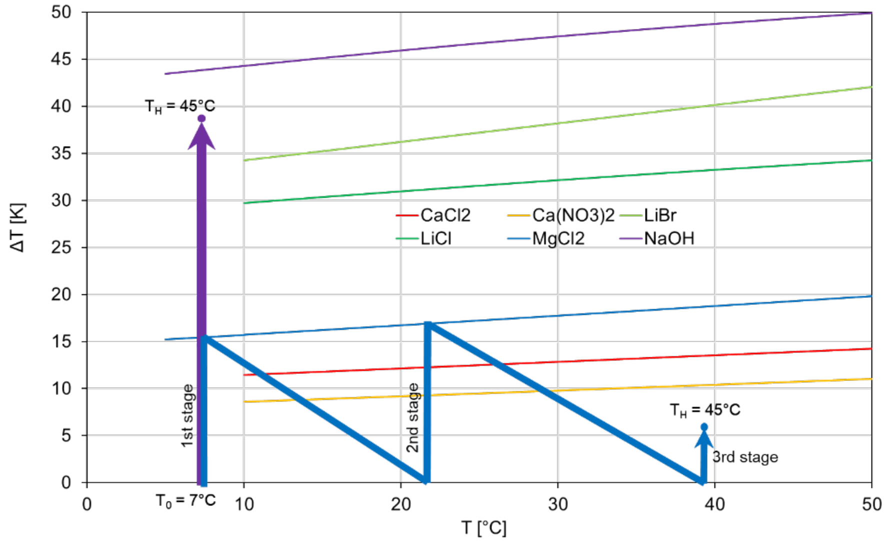

Figure 30: Temperature hub for different ambient temperatures, and minimum system temperature of 10°C.

The temperature lift depends on the minimum system temperature and shows a direct correlation with solubility (Figure 31).

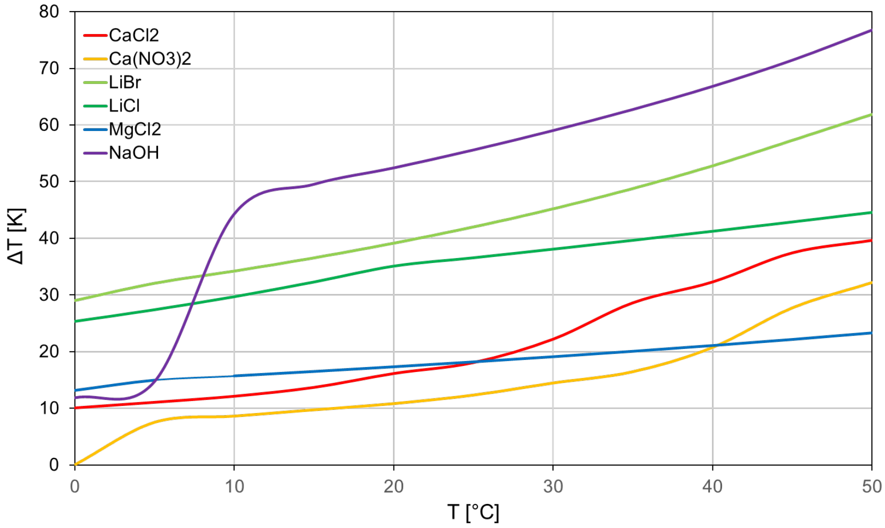

Figure 31: Temperature lift against minimum system temperature.

Dehumidification in industrial drying and climatization

For climatization applications (Figure 15) and industrial drying (Figure 24), the minimum possible relative humidity that can be reached in the air is a critical parameter. Figure 32 shows this minimum humidity level that can be reached with different TCF at a minimum system temperature of 10°C.

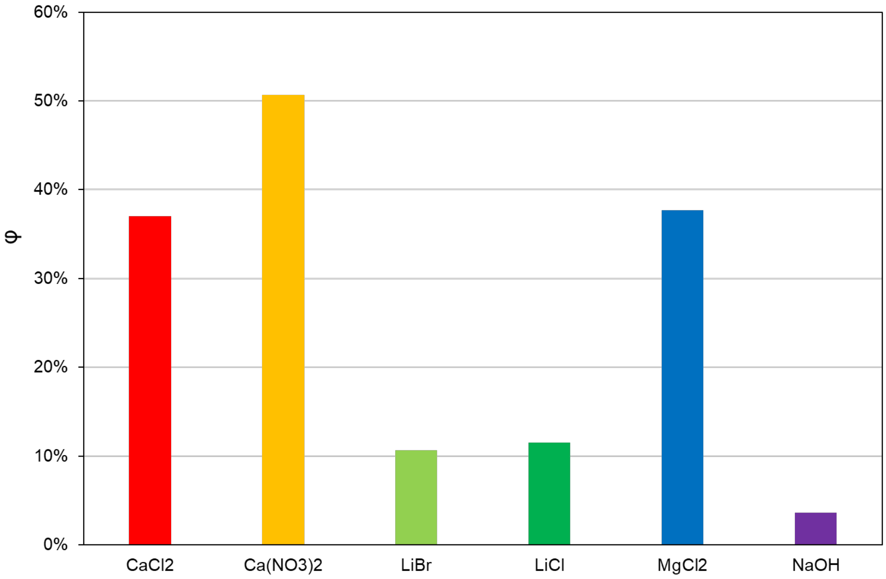

Figure 32: Dehumidification of air, minimum possible relative humidity, for a minimum system temperature of 10°C.

In Figure 33 the conditions which are required for industrial drying of goods are highlighted (in red). Accordingly, the suitable solutions for these applications are sodium hydroxide, lithium bromide and lithium chloride. While calcium chloride doesn't perfectly fit, it might be considered.

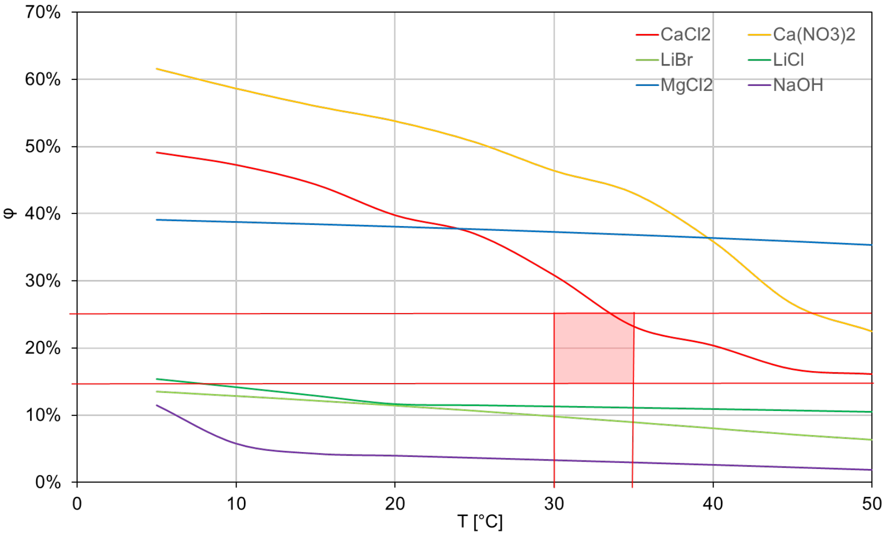

Figure 33: Conditions in a drying process, minimum possible relative humidity over minimum system temperature.

Sodium hydroxide is used in the project “Sonitro” (0).
The area highlighted in red in Figure 34 delimits the conditions required in office/living spaces. Magnesium chloride and calcium chloride are both perfectly suitable. Sodium hydroxide, lithium bromide and lithium chloride are suitable too. But sodium hydroxide is not suitable for open processes because it reacts with carbon dioxide (present in ambient air) and generates sodium carbonate. Finally, it is important to mention that lithium bromide and lithium chloride are highly expensive substances which can limit their implementation [11].

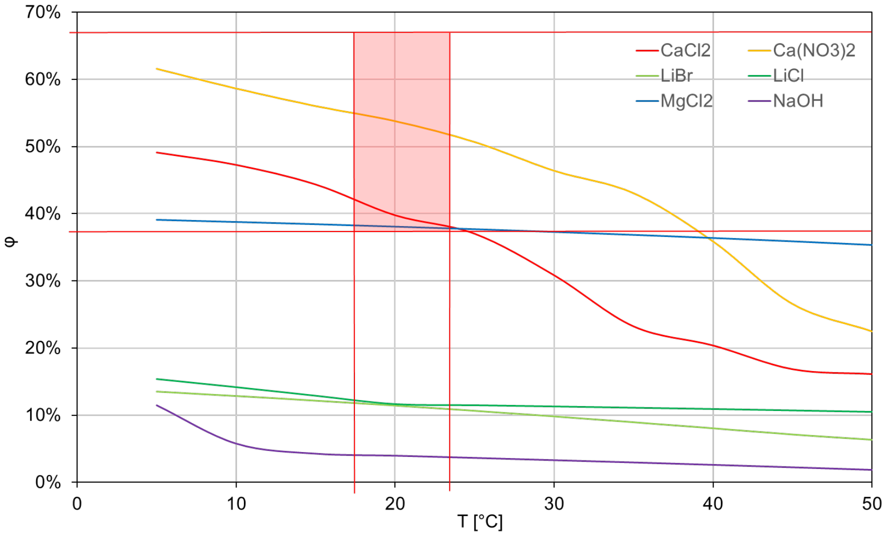

Figure 34: Conditions for an office/living space, minimal relative humidity depending on minimum system temperature.

For the indoor climate control device prototype (Figure 21) magnesium chloride is used.

Exergy- and energy density
As the TCF do not store energy but a chemical potential, energy density is not the most suitable performance indicator, instead, exergy density is more appropriate. The exergy density is directly

defined as the difference of the chemical potential of pure water and water in the sorbent solution. Figure 35 shows the exergy density which is contained in maximum concentrated solution at 10°C in reference to an environment temperature of 10°C.

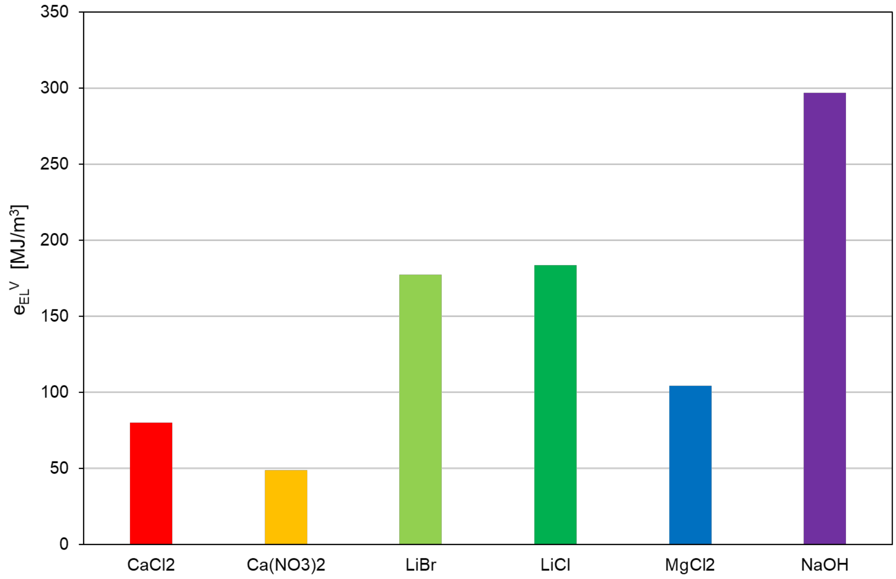

Figure 35: Exergy density at 10°C and minimum system temperature of 10°C.

To derive to the energy density from the exergy density, the Carnot factor can be used. For comparison, TCF used in closed processes for heating applications (Figure 10) considering a temperature lift of 30 K i.e., from 10 to 40°C, corresponds to the energy densities presented in Figure 36. It can be observed that the energy density varies between different sorbents and reaches up to 24 times the energy density of regular water with flow-/return- temperatures of 10°C / 40°C.

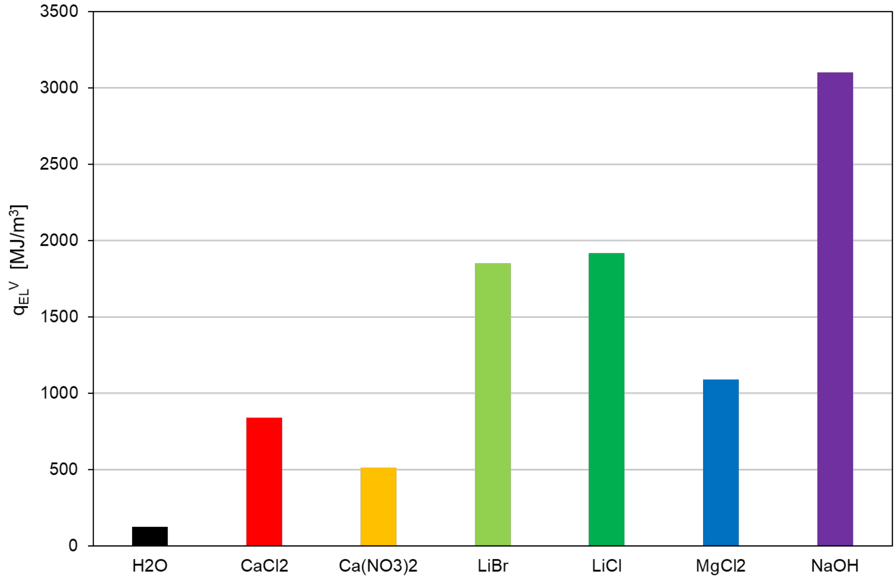

Figure 36: Energy density for 10°C solution temperature and a minimum system temperature of 10°C.

2.1.4 Value propositions and value networks

In the existing literature, various use cases for TCN have been described from a technical point of view. Based on simulation and experimental data, studies have shown the technical and economic potential of TCN for drying, climate control, heating and cooling. However, due to the low maturity of the technology, the literature has so far focused on technical and techno-economic aspects. A stakeholder mapping performed in the H-Disnet project [12] has identified relevant actor groups and their respective priorities, but without specifying the concrete roles they would fulfill in the operation of a TCN. Therefore, there is currently no common conceptual and empirical perspective on (inter-)organizational aspects of TCN, i.e. which actors provide which services within a TCN and how they are remunerated for it.

The aim of socio-technical research in TCology and in subsequent projects is to elaborate viable organizational configurations for the operation of TCN in the context of space heating, cooling and climate control. This entails defining appropriate and mutually aligned business models of the different actors within the value network (e.g. network operator, prosumer, energy provider, etc.) as well as defining a pathway to successful implementation. Due to the low maturity of TCN technology, this is to a large extent a prospective undertaking. Here, the focus lies on determining potential configurations of a local value network around the operation of a TCN. Indeed, there are often many ways to valorize a technical innovation, with vast implications regarding the participating actors, the activities to be carried out and the resources to be acquired by the different partners [13]. With regard to TCN, this is illustrated by the potential value network configurations outlined for two different applications: space heating and humidity control in buildings, and industrial textile drying. These examples were elaborated following existing business models in other areas of the energy sector. In Figure 37, two examples are given for the first application. These two hypothetical configurations are based on the use case described by Geyer et al. [14], where an absorber receives concentrated sorbent solution from a TCN and humid air from an external source to provide heat to buildings. We further assume that the heat input to the TCN comes from an external excess heat source (e.g. from industry) via a desorber. In the first variant, the offering of the TCN operator consists solely of providing, operating and maintaining the infrastructure to transport and store the sorbent solution. The absorber and desorber are operated by the building owners and excess heat providers, respectively. Here, it is also the responsibility of the building owner to ensure a supply of the humid air from an external source. In such a setup, the tariff structure for the building owner may be based on the energy potential delivered, as well as the O&M of the infrastructure. Likewise, the TCN operator may remunerate the excess heat provider per unit of energy delivered. In the second variant, the absorber and desorber are operated by the TCN operator as part of a holistic energy management service offering. Here, pricing may take into account not only the energy potential delivered and infrastructure readiness, but also the service of heating and humidity control, which is now out of the responsibility of the building owner. The excess heat provider outsources excess heat management to the TCN, allowing them to focus on the core business. Likewise, humidity removal is offered as a service to the humid air provider.

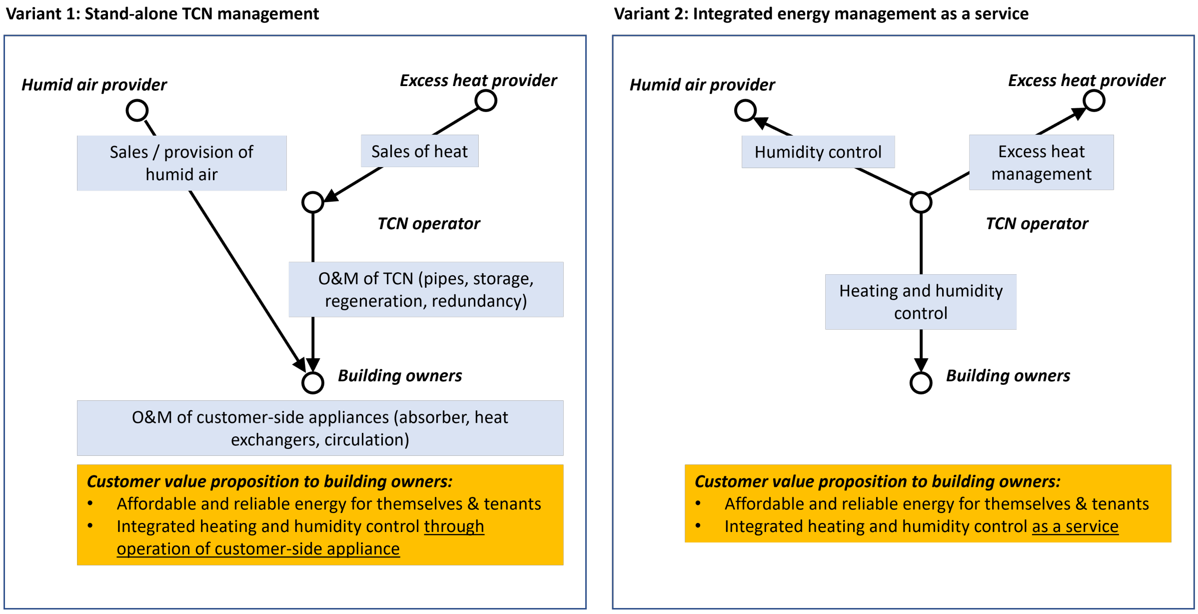

Figure 37: Two possible value network configurations for the application of TCN technology to space heating and humidity control. Nodes represent actors, arrows with blue boxes represent offerings from one actor to another (typically in exchange for a fee), and the orange box represents the system-level value proposition to customers.

Figure 38 shows a potential use case for the application of TCN in the context of industrial textile drying. In this example, the customer is a large laundry that uses a TCN setup to obtain the necessary amount of heat, temperature and humidity during the drying process. This example presupposes that the laundry owns and operates the whole TCN system, and that it invests into solar thermal collectors as a heat source. If the laundry's specific situation allows a large solar thermal plant to be built (e.g. there is ample space for installing collectors), the laundry may choose to sell excess heat to external customers. Thanks to the TCN system, the laundry and its customers benefit from flexibility regarding the time of delivery. In this illustration, there is a direct relationship between the laundry and its customers. However, such a model is also compatible with a TCN that is operated by a third entity (analogous to Variant 2 above).

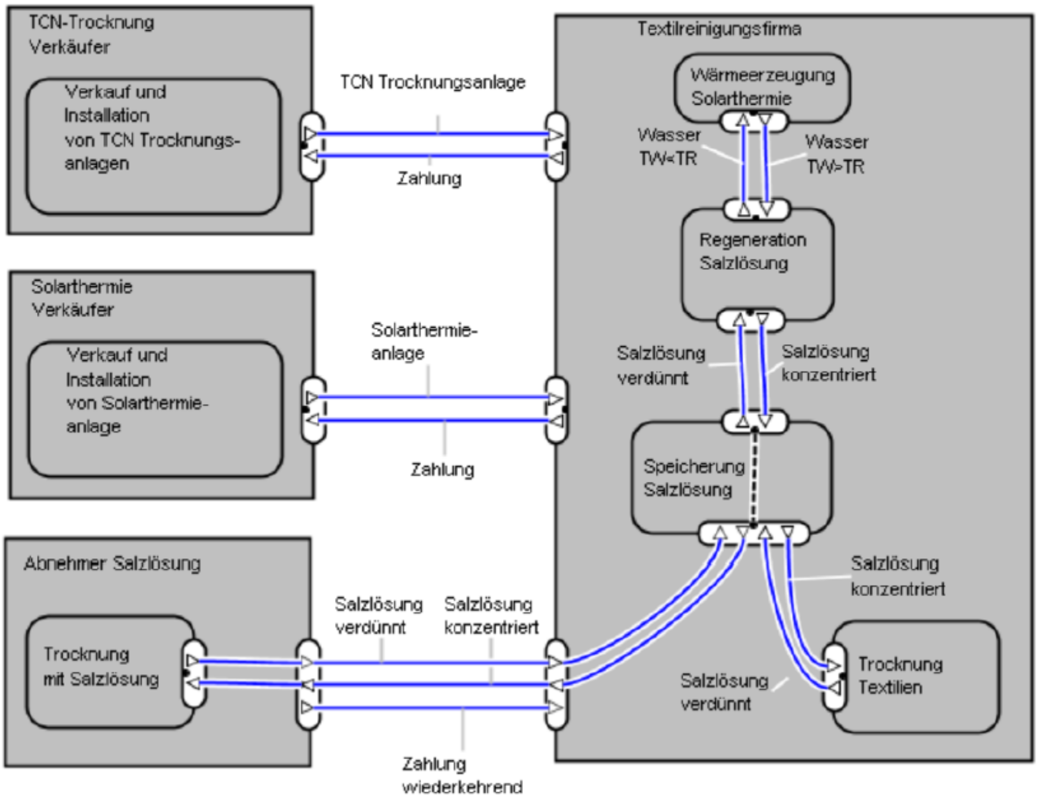

Figure 38: Prospective value network for the use of TCN in the context of industrial textile drying, represented according to the e3Value methodology: Rectangles represent distinct actors, rounded rectangles represent activities, and blue arrows represent exchanges of money, goods or services. Illustration by Manuel Bänziger.

The configurations outlined here were chosen for illustrative purposes and were not yet assessed in depth regarding technical and economic feasibility, acceptance by potential value network members and conformity to the regulatory framework in Switzerland. Rather, the aim at this stage is to demonstrate the suitability of the value network approach to elaborate valorization options for TCN technology. In the next step, a generalized representation of these business model variants was prepared as an input to the stakeholder workshop (see next section).

2.1.5 Stakeholder Workshop

The stakeholder workshop fulfils a triple role: first, it enabled the dissemination of new insights from the TCology project to a range of stakeholders with various degrees of familiarity and prior involvement with the technology. Second, it allowed a high-level discussion of the potential business models for TCN. Third, it enabled the identification of strengths, weaknesses, opportunities and threats (SWOT) regarding the further development and commercialization of TCN technology.

The workshop was held on November 29, 2023, in Winterthur. The list of participants (Table 2) reflects the interest of planning and engineering firms in the workshop. Participants from these firms possess specific experience with thermal grids, facility management in buildings, as well as laundries. In addition, the workshop also included representatives of an energy service company and a municipal administration. Finally, the association “energie bewegt winterthur” attended the workshop as part of their role as a regional information hub for energy topics.

Organizations other than planning and engineering firms showed less interest in participating, so that several invitations were declined. In general, the fact that the technology is not yet commercial was an important factor for negative decisions. However, some respondents declined citing time or resource constraints but expressed interest in the topic and openness for future collaborations. Among the invited participants who declined were facility management companies for buildings and districts, potential excess heat providers, as well as additional energy service companies. However, the fact that the participants regularly collaborate with such companies helped ensure that their perspective was indirectly represented.

Table 2: List of workshop participants

	Organization	**People**
Research: TCology project team	ZHAW: Institute for Building Technologies and Processes	Luca Baldini
	ZHAW: Institute for Energy and Fluid Engineering	Serena Danesi, Raphael Baumann
	ZHAW: Institute for Sustainable Development	Matthias Speich
Industry and Authorities	Anex AG	Felix Frei, Kevin Steiger
	City of Winterthur, construction permitting office	Fabia Moret
	Energie 360° AG	Andreas Abdon
	energie bewegt winterthur	David Peran
	RMB Engineering AG	Jonas Schmid, Ryan Duss
	Schmid Hutter AG	Daniel Roost, Stephan Fendt
	Zeier Engineering AG	Peter Zeier

2.1.5.1 Aspects of the business model

Although existing techno-economic studies point to a potential for viable applications in various sectors [15,16], the economics of TCN are still subject to high uncertainty, due e.g. to the lack of experimental data. For this reason, the discussion about business models was qualitative and high-level. As a starting point to the discussion, a simplified representation of a TCN as a value chain was prepared beforehand (Figure 39). It seems natural to assume that the value network concept would be a better fit to TCN than the value chain [17]. Indeed, it is reasonable to expect a strong influence of network effects on value flows, as is the case for thermal grids [18]. Also, TCN support multiple simultaneous uses and potentially allow their members to act as prosumers, which further contradicts the unidirectional value chain model. Nevertheless, this visualization was chosen as a way to reduce complexity and focus on generic questions of the distribution of tasks between actors in a TCN.

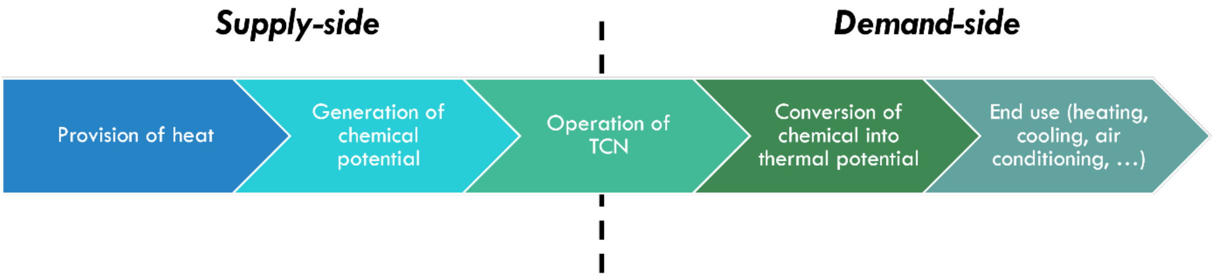

Figure 39: Simplified representation of a TCN as a value chain (input to the workshop)

To further simplify and focus the discussion, possible configurations on the supply-side and on the demand-side were discussed one after the other. For the supply-side configuration, an overview of variants for the interface between a provider of excess heat and the operator of a TCN were visualized beforehand (Figure 40), based on configurations commonly encountered in industrial excess heat recuperation in thermal grids[1]. Participants were asked to comment on the represented variants and to assess their potential advantages and drawbacks, as well as the likelihood that they would be implemented in practice.

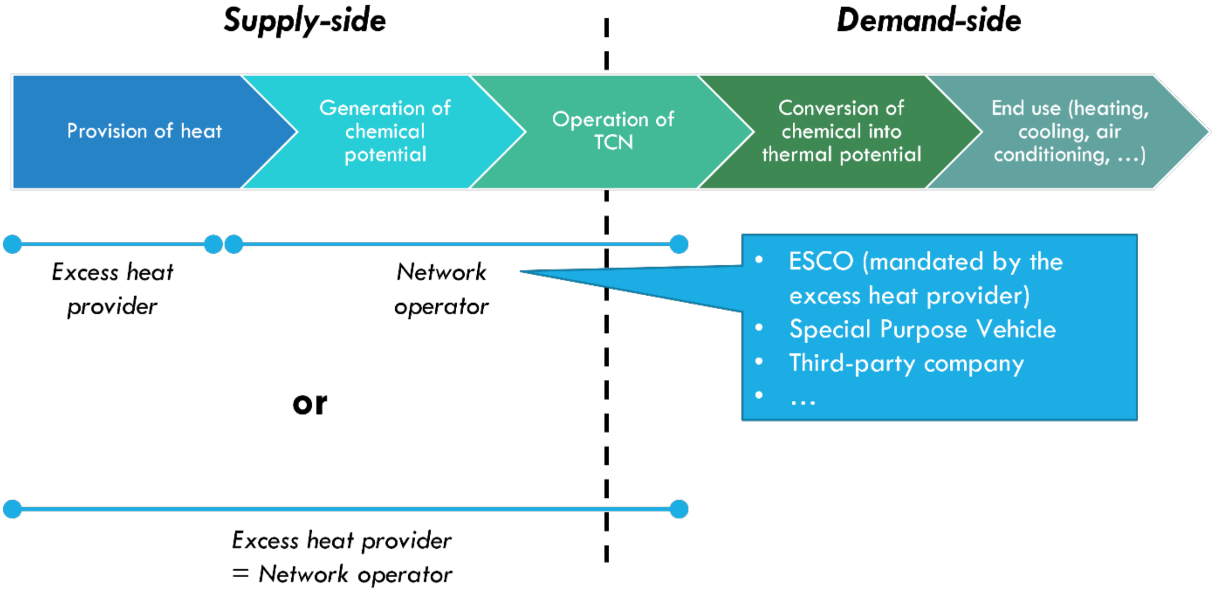

Figure 40: Possible supply-side business model variants (input to the workshop)

Three topics emerged from the ensuing discussion: the value of excess heat and/or of cooling, the potential value of TCN infrastructure, as well as the potential role of the public sector.
It was stated that excess heat, particularly at low temperature levels, was usually not seen as an asset by companies, but rather as a cost factor, as removing it (e.g., through ventilation) can require large investment sums. Indeed, companies tend to avoid waste heat as far as possible, and to invest as little as possible to manage it when it cannot be avoided. On one hand, according to one participant, this makes the second variant (where the excess heat provider, or rather the cooling customer, is also the operator) unlikely to be implemented. On the other hand, it was stated that for the reason above, excess heat removal was potentially very beneficial for companies with excess heat, so that they might be interested in investing in a TCN if it is more advantageous than other solutions for excess heat management[2]. In such a case, the benefit for the company depends on its concrete needs regarding cooling and/or dehumidification. If the TCN is operated by an external organization, the excess heat provider would likely not expect compensation for the heat provided, but rather pay for cooling. In the participants' recent experience, cooling is still very expensive, particularly for applications in industry, commerce, research or hospitals, etc., with low temperature requirements (temperatures between 4°C and 8°C were cited as examples from recent projects). In particular, investment costs for chillers were highlighted. Although new thermal grids are increasingly often realized as low-temperature grids with

[1] We would like to thank Beat Wellig (HSLU) for providing us with relevant case study descriptions.
[2] At this point, it was also pointed out that the willingness to invest by different actors, i.e., their expected benefits, was another important dimension to understand the potential of different business model variants, in addition to the distribution of activities.

integrated heating and cooling, most existing thermal grids are operated at a high temperature and do not enable cooling, which limits the options of industrial companies for cooling. Therefore, a competitive alternative solution for cooling may be attractive, particularly if it can be combined with additional services such as dehumidification.

The potential benefits of TCN versus conventional and low-temperature grids were highlighted in the discussion, particularly regarding the required dimensions for distribution, storage and energy conversion elements. Currently, the construction work to lay pipes represents about 25% of the investment costs for thermal grids, with costs up to 7'000 CHF/m in dense urban areas. As a result, expanding a thermal grid to a new area is often very expensive. Also, space requirements for new components of thermal grids, such as central or building-/neighborhood-level heat pumps, are high, while space is scarce in urban areas. Regarding storage, participants' assessment of the competitiveness with established technologies diverged: on one hand, some participants noted that building a new (thermochemical) storage represented additional work compared to enlarging an already existing storage (e.g., boreholes). On the other hand, others pointed out the low investment cost of thermochemical storage, which may make it worthwhile despite transaction costs. In summary, this discussion suggested that TCN may represent an interesting alternative to hydronic thermal grids in dense, urban areas. In this case, potential investors would likely be (public and/or commercial) thermal grid operators.

As discussed above, there may be a clear reason for companies with excess heat to invest in TCN if it is more advantageous than alternatives for cooling. However, the economics of TCN are still uncertain, so that a positive business case is not always given. Furthermore, firms are sometimes reluctant to invest in external waste heat recuperation solutions despite potential financial benefits, due to lacking capabilities and capabilities and/or high transaction costs. Since the potential benefits of TCN align with several aspects of current national, cantonal and municipal energy policy, it was suggested that the public sector may act as an investor (and indirectly as an operator, through an integrated municipal utility, in municipalities where this governance arrangement is in place). Furthermore, firms with excess heat may not have the capabilities to identify their heating and cooling requirements and/or potentials. While this is commonly done at the feasibility stage of a project, a central inventory of these potentials, as done in municipal energy planning, is an important resource to facilitate the initiation of new projects. In summary, participants see a central role of the public sector in the future application of TCN in districts.

To conclude, the discussion has identified three classes of potential investors for future TCN applications: industrial companies with cooling needs, commercial and/or public operators of thermal grids, as well as the public sector (depending on the municipal governance arrangement, the two latter classes are overlapping).

For the next part of the discussion, an analogous visualization of business model variants was prepared for the demand-side, focusing first on small-scale customers such as residential buildings (Figure 41). As a further simplification, no distinction was made between customers and end users, although these roles may be filled by distinct actors with potentially diverging interests (e.g., building owners and tenants). The two options, which were already discussed in the first milestone report, mirror the two configurations encountered in low-temperature grids: in the first case, the role of the TCN operator on the demand-side is restricted to transporting the energy potential (concentrated TCF) to the end user. It is the user who is responsible for the operation of demand-side appliances. A low-temperature grid analogue for this configuration would be Anergienetz Visp-West, where the grid operator supplies water to customers, which are responsible for the installation and operation of the building-level heat pumps required for heating and cooling[3]. In the second configuration, the TCN operator also operates the demand-side appliances and is responsible for maintaining an adequate

[3] https://vispinfra.ch/reglemente-tarife/

indoor condition (through heating, cooling, dehumidification, etc.). Here, an analogue would be the grids operated by ewl in Lucerne and Horw, which use lake water as an energy source: in this case, the decentralized heat pumps (supplying buildings or groups of buildings) as well as the substations are owned and operated by the grid operator, whereas only the secondary-side installations are under the responsibility of the customer[4].

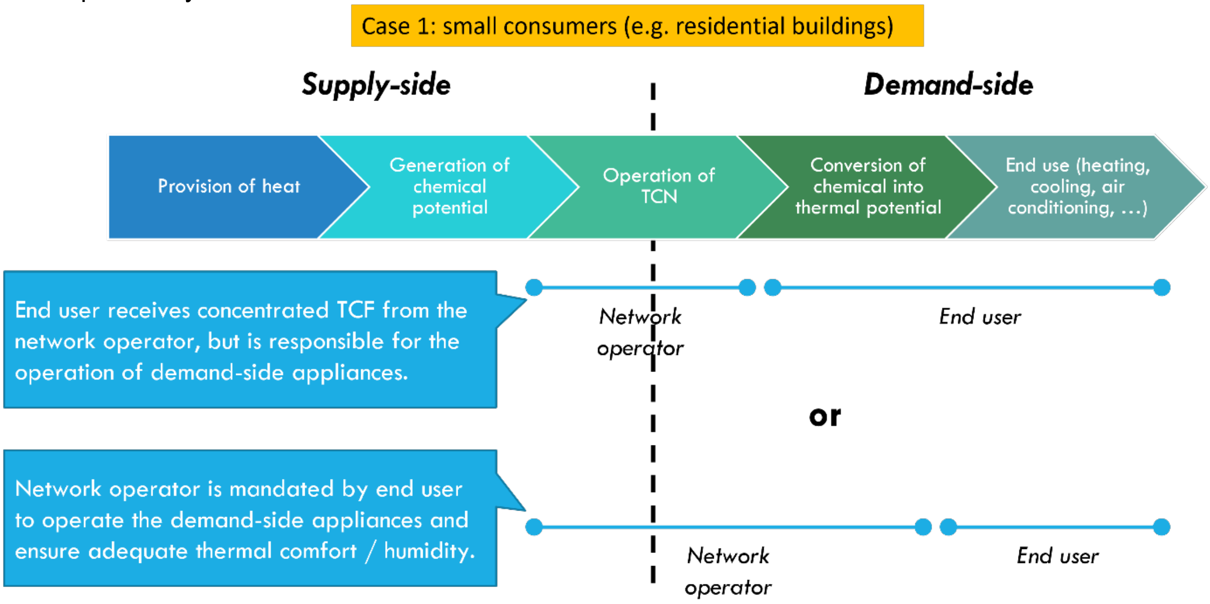

Figure 41. Possible demand-side business model variants, focusing on small-scale consumers (input to the workshop)

Participants pointed out that the latter case was clearly more advantageous for the TCN operator, as it allows them to optimize grid use under consideration of temporal differences in customers' thermal load. In their experience, this allows a reduction of up to 50% of subscribed power. The temporal control of domestic hot water provision was highlighted in this context. Participants expected this to be similar in TCN. On the customer side, a distinction was made between customer groups: whereas residential customers tend to appreciate the lower effort associated with the latter case, customers from industry or hospitals have more specific requirements, so that they need more control over their energy supply.

To conclude the first part of the discussion, a visualization of two demand-side variants in the case of large-scale consumers (e.g., industrial plants) was shown (Figure 42). Here, the case where the TCN operator also controls demand-side appliances was assumed to be less adequate (an assumption corroborated by the comment above). This case was therefore replaced by the situation where the users themselves operate the TCN. This is analogous to the internal heat distribution grid in an industrial plant, although it is not excluded that external suppliers and/or users are connected as well. This figure prompted no further discussion, other than a brief confirmation that it was plausible.

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[4]https://www.ewl-luzern.ch/files/ewl/Dokumente/AGBs_etc/Regeln_Netzanschluss_See-Energie_Seenergy_Luzern_AG_HorwKriens_20230627.pdf

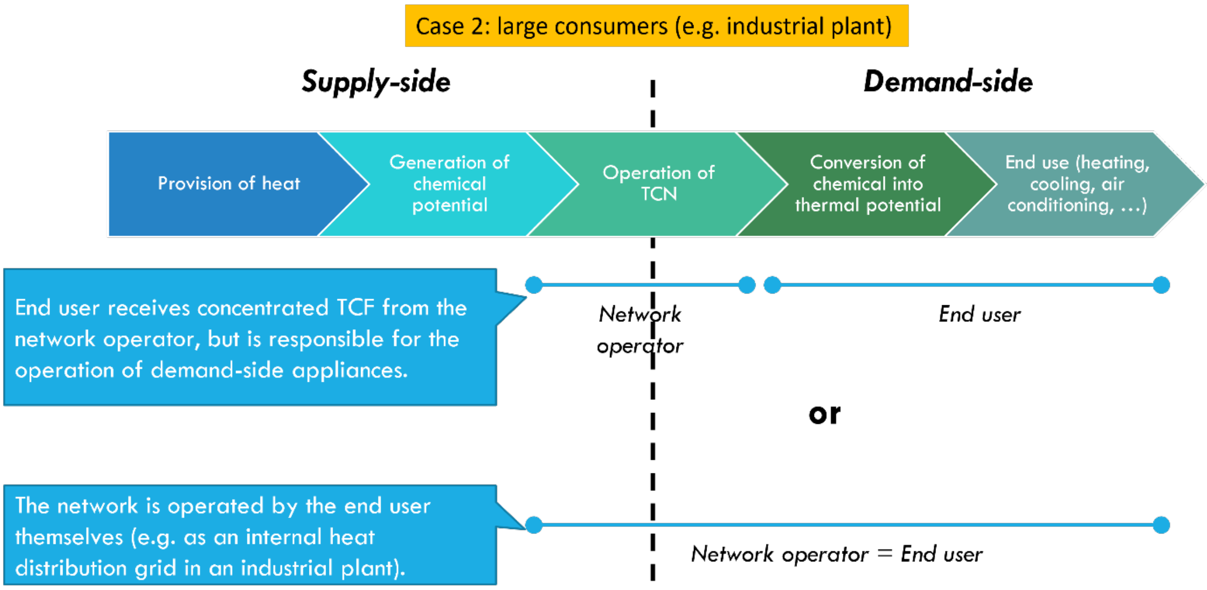

Figure 42. Possible demand-side business model variants, focusing on large-scale consumers (input to the workshop)

2.1.5.2 SWOT Analysis for the further development of TCN technology

The second part of the discussion was focused on a SWOT analysis for the further development and commercialization of the technology. Although a SWOT analysis is typically conducted at the level of an organization, it was used here in a broader sense: while helpful and harmful factors are generally categorized by whether they are internal or external to the organization, the boundaries were set here to the research and industry partners that have been involved in the development of TCN technology so far and are interested in its further development. Positive and negative characteristics of the technology itself were also within the scope of the analysis, as they translate into potential competitive advantages or further R&D needs, or influence the perception of the technology by stakeholders. This scope was clarified at the beginning of the discussion.

	Helpful	*Harmful*
Within the control of the value network	**Strengths** • Low space requirements as a clear advantage of the technology. • Strong research partners. • Ïndustry partners interested in the technology. • Ongoing research and development projects.	**Weaknesses** • Costs hard to estimate. • No norms / standards yet (e.g., standard materials). • Interoperability with existing equipment / processes is not yet given. • Few manufacturers of key components (e.g., armatures): possible price increases. • Lack of automation so far. • No implementation partner yet.
Outside the control of the value network	**Opportunities** • Political priorities: security of supply & GHG emission reductions. • Net-zero targets in public policy and industry. • Willingness of customers to pay more for new and environmentally benign technologies. • Changes in frame conditions make excess heat more valuable. • Large potential of so far uninvolved companies / industries.	**Threats** • Costs are still decisive for most customers. • Competitive decentralized solutions. • Difficult permitting process / negative perception of novel substances by environmental authorities. • Perceived low reliability. • Perception of TCF as dangerous by the public. • Space requirements on the demand-side. • Risk of shifting political priorities • Increasing complexity of interfaces (e.g., with industrial processes).

Figure 43. Results of the SWOT analysis

As already discussed before, the low space requirements of TCN pipes and storage elements are seen as a key advantage of the technology compared to existing thermal grids. Another strength pertains to the organizations so far involved in the development of TCN, both on the side of research (the HSLU was cited in regard to HVAC systems) and of the industry members involved in R&D so far. Ongoing R&D activities involving research and practice, such as the newly launched Innosuisse Flagship project 107.395 FS-EE, were cited as positive.

Some of the key weaknesses identified were related to the lack of maturity of the technology and pointed towards concrete R&D needs: for example, a key weakness is the fact that costs for TCN are still difficult to estimate or have not been properly estimated so far. Indeed, from the perspective of potential users, “not knowing the costs is worse than knowing that it is expensive”. Also, research on automation of TCN is at a very early stage. Another key weakness is the current lack of norms and standards: standardized materials were cited as an example. As another example, the interoperability with existing processes is not yet given (the increasing complexity of such interfaces was mentioned as a threat). Where specific components are needed (e.g., armatures that are resistant to corrosion), the low number of manufacturers was seen as a weakness, potentially leading to high prices.

Regarding opportunities, some of the factors mentioned were generic to technologies enabling an efficient use of energy and the integration of renewable energy sources: current political priorities place high value on GHG emission reduction and security of supply, which encourages the integration of local and low-carbon energy sources. This creates concrete incentives to explore technological options enabling this: for example, under current net-zero goals, the current administration and utilities have a mandate to decarbonize the building sector, and industrial companies need to strongly reduce their emissions. On the customer side, it has been documented multiple times (and confirmed by participants) that customers are willing to accept a somewhat higher price for energy if innovative and environmentally benign technologies are implemented. This seems to be connected with the trend towards decarbonization: in one participant’s recent experience, customers of a planned renewables-

based thermal grid were willing to accept prices of 20 Rp./kWh, which, according to this participant, would have been unthinkable a few years ago. These developments favor the implementation of technologies such as TCN, even if they turn out not to be fully cost-competitive. Another, linked development is that the frame conditions may make the sale of excess heat more attractive, thus improving the business case for TCN in such applications. Finally, it has been mentioned that the circle of organizations involved in the development of TCN so far has been relatively small, leaving a potential network of partners with complementary capabilities.
While the current political priorities were mentioned as an opportunity, it has been pointed out that this may always change, so that political shifts and accompanying policy shifts, such as the roll-back of current taxes and subsidies, represent a threat to the further integration of renewable energy sources. Also, despite a willingness of customers to accept somewhat higher prices, it was pointed out that costs are still the decisive factor for most customers. This may represent a threat if TCN turns out not to be cost-competitive (e.g., against decentral solutions). A more practical threat is the space requirement of demand-side appliances (e.g., compared to the substations of a thermal grid), which may reduce customer acceptance. Other identified threats relate to the perception of the technology by the public and by key stakeholders: For example, new technologies are often perceived as unreliable by users (one participant made the analogy to the “range anxiety” related to electric vehicles). Also, the use of materials unfamiliar to the public, or in a new setting, may generate resistance: participants noted the resistance in environmental authorities against a water-ethanol-mixture used in thermal grids, and expected a similar resistance towards TCF. Also, it has been mentioned that terms such as “Natronlauge” (sodium hydroxide), or even “Salzlösung” (brine) may be associated to danger by the general public.

2.2 Conclusions of WP1

From a socio-technical perspective, insights from the project can be summarized as follows:

- For the case that represented the focus of the TCology project (TCN for heating and cooling), the characteristics of TCN that were deemed particularly valuable were the low space requirements for pipes and storage elements, the associated lower investment costs, as well as the ability to provide cooling at low temperatures.
- The advantages of TCN may translate into benefits for several actor groups, which each might have an interest in investing into TCN projects. Three concrete investor groups were mentioned: industrial companies with cooling needs, current developers and operators of thermal grids, as well as the public sector (e.g., municipalities).
- The public sector may also play an important facilitating and coordinating role by considering TCN in municipal energy planning. Indeed, municipalities have an interest in enabling an efficient use of local heat and cold sources.
- The lack of a “price tag” for TCN hampers the technology’s perceived legitimacy in the eyes of potential investors and customers. Further research may focus on elaborating blueprints for viable multi-actor business models, based on a combination of techno-economic and qualitative research. This would enable to map the costs and benefits (including potential non-monetary aspects) for each actor group, to define possible exchange modalities for energy potential, and to estimate a price range for end customers in various cases.
- In the medium-term, some developments at the industry level were pointed out as important for the commercialization and scaling of TCN: elaborating norms and standards, ensuring interoperability with existing equipment and processes, enlarging and diversifying the set of involved organizations (with associated transaction costs related to communication), etc. A

roadmap might help the development of such an industry, based on an innovation ecosystem perspective (Adner & Kapoor, 2010; Speich & Ulli-Beer, 2023).

3 WP2 – Case study definition

To identify the potential of the TCN, quantify its performance, and compare it to classical hydronic DHN, a set of scenarios/synthetic case studies are defined. This section describes the methodology and criteria to conceptualize the scenarios and the corresponding benchmarks.

3.1 Overview of Swiss thermal networks

The Swiss Federal Office of Energy (SFOE) has made available a database with the district heating networks currently operating in Switzerland [19], which identifies the energy source, rated power, number of buildings connected to the network, the net length of the network, and its location. Figure 44 shows a screenshot of the existing thermal networks and their location.

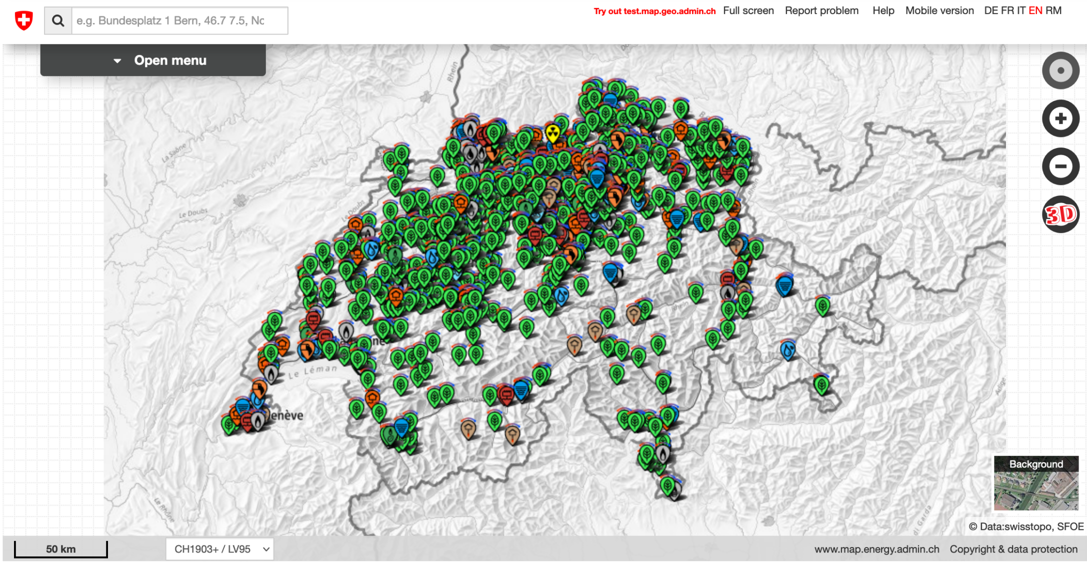

Figure 44. Screenshot with geodata of Swiss thermal Networks (from [19])

The database contains 1077 thermal networks with a thermal power ranging from 24kW to 457MW. Figure 45 shows the power distribution where it is observed that 10% of the networks have a power lower than 10MW. Whereof, most networks are relatively small, i.e., ~260 networks with less than 0.5MW.

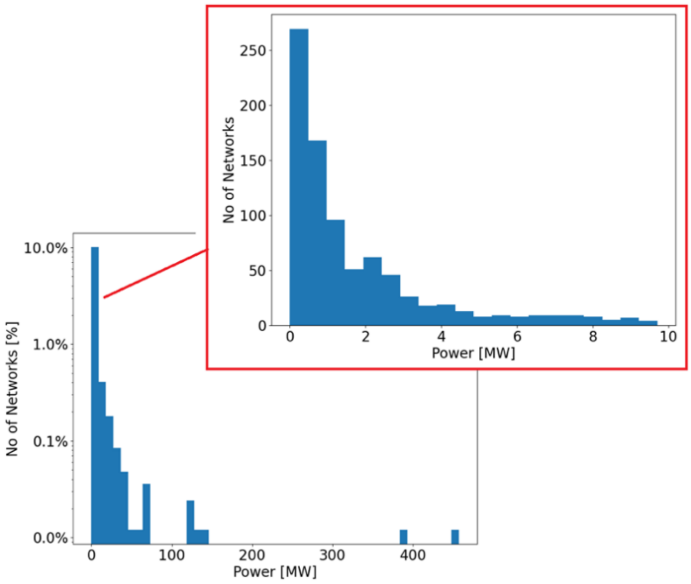

Figure 45. Thermal networks' power distribution

Regarding the energy supply (see Figure 46), the most common is wood chips, accounting for 677 networks, i.e., ~62.8%. Additional sources include other types of biomass i.e., pellets ~4.7%, logs ~0.3%; waste heat recovery from municipal incinerators ~3.1%, industrial and commercial waste heat ~2.5%, from nuclear power plants ~0.9%, and tunnel waste heat ~0.3%; heat extracted with HP from groundwater 4.2%, wastewater 3.8%, geothermal heat 3.6%, lake and river water 2.7%, and air 1.0%; natural gas 3.8%, natural gas cogeneration plant 2.9%, biogas 0.5%, biogas cogeneration plant 0.4%, and heating oil 2.4%.

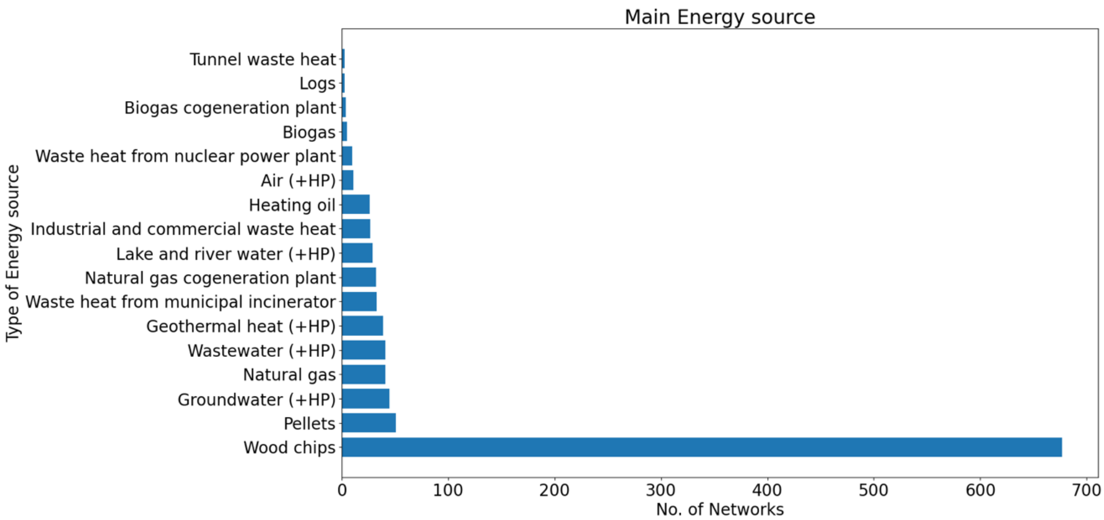

Figure 46. Thermal networks' main energy source

From an energy perspective, the distribution of the most important energy sources looks quite different. The biggest contribution comes from waste incineration, followed by wood and natural gas (see Figure 47).

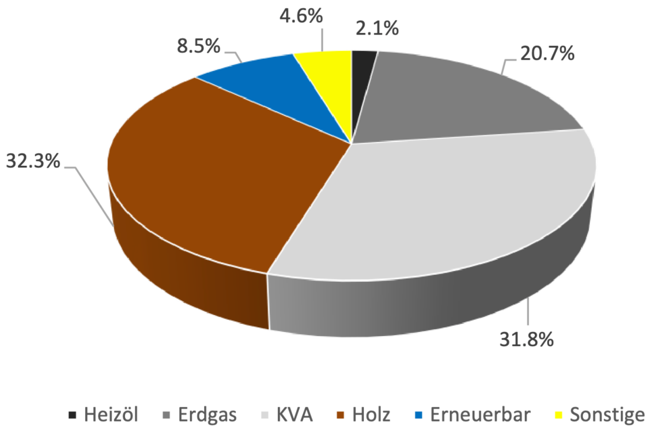

Figure 47: Distribution of heat generated by different energy sources for all district heating networks in Switzerland in the year 2020 [20].

Further, the database shows 396 (i.e., ~36.7%) thermal networks equipped with a secondary energy source to cover the peak loads. The most common secondary energy sources are heating oil, i.e., 43.6%, and natural gas, i.e., 30.5%. Figure 48 shows the number of thermal networks using natural gas or heating oil as a secondary energy source. Among these networks using a secondary energy source, candidates using wood chips as the primary energy source are the most common.

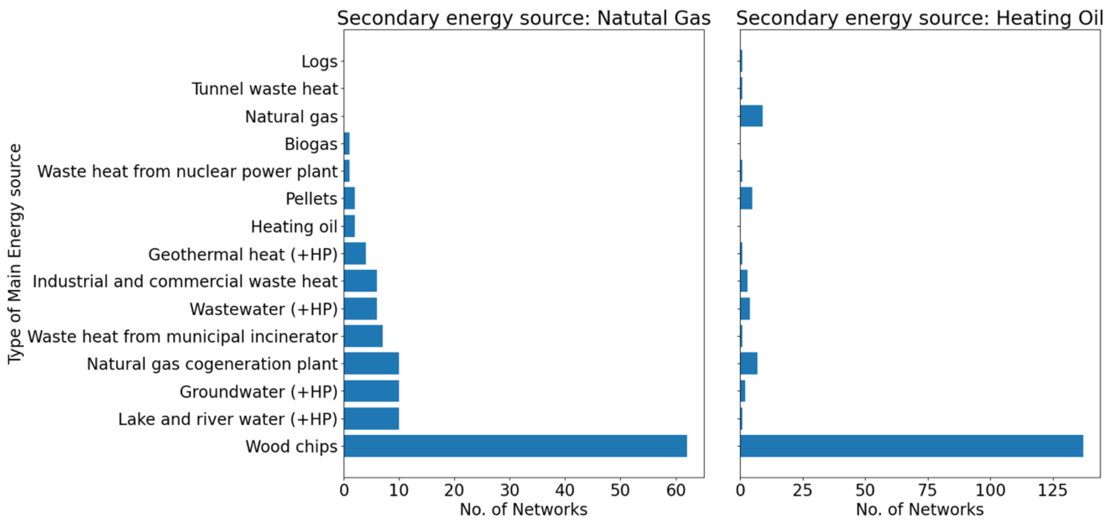

Figure 48. No. of thermal networks considering the secondary energy source

Beyond the mere energy distribution, TCNs have a great potential for shaving peak loads, especially during winter. Since there are virtually no losses when storing energy using TCFs, seasonal storage could replace (or reduce the need) for secondary energy sources such as natural gas and heating oil. In this case, excess energy generated during summer can be stored and released during winter. To this end, thermal networks with HP as their primary energy source are of particular interest because, the HP electricity demand can be replaced by the TCN and liquid sorption processes working as chemical HP. In this way, it can be stored and exploited the chemical potential to upgrade low-temperature, environmental and waste heat, to meet heating demand requirements.

Currently, one of the barriers to exploiting waste heat in remote locations is the distance between the energy source and the end-users. This is because of the large losses exhibited when transporting sensible heat using water or steam. TCNs have the potential to overcome this barrier since there is virtually no heat lost while transporting TCFs. As a result, this project's case studies will consider the network's length and the matching of energy supply and demand as essential parameters to assess the potential of TCNs.

3.2 Heat demand and supply

The literature was reviewed to identify available data and models to generate synthetic heat supply and demand profiles that will enable the numerical modeling of thermochemical networks (see Table 3). The review is focused on the terminal applications (open and closed sorption processes for drying, heating/cooling, full climate control, and thermal energy storage) discussed in WP1 (refer to Section 2.1). Further, it focuses on databases and model outputs suitable to the Swiss context.

Table 3. Reviewed load supply and demand models and datasets

Reference	Country	Approach	Supply	Demand	Resolution	Observations
Nielsen et al. [21]	Germany Spain France	Analytical	• Data-center cooling • Metro Ventilation • Wastewater treatment • Cooling – Service sector		Hourly	Based on a reference scenario 2015 and projections for 2050
Jesper et al. [22]	Germany	Data-driven		Commercial Industrial Public Residential	Daily	Heat load profiles based on 797 measured natural gas consumption profiles
Schneider et al. [23]	Switzerland	Data-driven		Commercial Industrial Public Residential	Hourly Yearly	Statistical regression bottom-up model Geo-located
Kannan et al. [24]	Switzerland	Data-driven	Residential: including type of energy source	Commercial Industrial Residential	Hourly	Based on heating demand patterns from Germany and calibrated to the Swiss context using heating degree days (STEM Model, JASM)
Pfenninger et al. [25]	Europe	Data-driven	PV potential		Hourly	The simulation code and the hourly simulations for all European countries are available freely via a web platform: www.renewables.ninja

Reference	Country	Approach	Supply	Demand	Resolution	Observations
Staffell et al. [26]	Europe	Data-driven	Wind farm potential		Hourly	The simulation code and the hourly simulations for all European countries are available freely via a web platform: www.renewables.ninja
Mazza et al. [27]	Europe	Analytical		Commercial Industrial Residential	Hourly	Analytical model for space heating and hot water demand validated with data from Finland
Iturralde et al. [28]	Switzerland	Stochastic		Residential	Hourly	Hourly space heating demand profiles for residential buildings in Switzerland. Includes single-family buildings old and new, and multi-family buildings old and new.
Murray et al. [29]	Switzerland	Bottom-up		Commercial Industrial Residential	Hourly	Hourly space and water heating, cooling and electricity demand profiles for a selected set of archetype buildings in Switzerland, under 2 envelope retrofit scenarios; includes single-family residential, multi-family residential, Office, School, Shop, Restaurant and Hospital; based on results from simulations with the CESAR model

One of the most relevant sources of information identified for the Swiss context stems from the SCCER Joint Activity Scenarios and Modelling (JASM) data platform [30]. It includes a detailed building stock analysis of the residential sector that defines building archetypes considering building age, type, location (i.e., Canton), heated reference floor area, and specific space heating demand [31]; the Swiss TIMES energy system model (STEM) model [24] represents the entire energy system of Switzerland with a high level of technical detail, a long-time horizon, and a high time resolution covering seasonal/diurnal variations in energy demand and supply. It estimates different typical hourly heat demand profiles derived for the Swiss context, such as residential space heating and hot water demand, service and industrial sector heat demand (i.e., aggregating space heating and hot water). Further, the profiles are generated for typical days in winter, summer, and intermediate seasons as well as weekdays and weekends. Alternatively, Iturralde et al. [28] have developed detailed residential annual heating demand profiles with hourly resolution. The profiles are developed for old and new, single- and multi-family buildings. The advantage of using these heat demand curves is that they are developed for the Swiss context (i.e., reference case located in Zürich) considering stochastic occupant behavior and using dynamic energy models hence, quantifying the uncertainty due to occupancy and occupants' activities and its impact on the heating demand calculation. Further, increasing the modeling level of complexity from [24], where typical days are considered to [28] where the annual profiles are given, allows for a more detailed analysis that captures the trends across the year as well as the stochastic nature of the occupant behavior; Additionally, Murray et al. [29] derived annual space heating, space cooling, and hot water demand profiles at hourly resolution using the CESAR-P model [32]. The model advances the building archetypes by considering the construction age period rather than the general classification of old and new. Furthermore, it includes the residential sector (i.e., single- and multi-family houses) and the commercial sector (i.e., offices, schools, shops, restaurants, and hospital buildings). Occupant-related inputs are considered deterministic; hence, these profiles don’t capture the stochastic variability of the occupant behavior.

All the described sources focus on sensible load profile estimation without providing any information on latent heat loads and/or potential supply and return temperatures of the heating system. The former is dependent on the type of use of the building or the specific industrial process, and the latter is dependent on the envelope quality of the system and a selected heat emission system. For studying the applicability of sorption processes, this information needs to be complemented, asking for additional data sources or separate simulations to be run for different building types.

3.3 Synthetic case studies

Synthetic case studies are envisioned to be dynamically and numerically simulated to evaluate the potential of TCNs and compare their performance against traditional DHNs. The information presented previously defines the main components and boundary conditions. First, district heating networks in Switzerland are being further analyzed in WP3 (Task 3.1) of the SFOE SWEET project DeCarbCH, to define network archetypes and representative cases. From a high-level perspective, parameters such as thermal power, network length, and the number of users connected to the network are used to classify the DHN.

Table 4 presents the main features of three generic DHNs defined considering the primary energy source and capacity. The **small network** is served by biomass to generate a peak power of up to 0.9 MW and supply 1.5 GWh of thermal energy. It connects 21 users with a 1.3 km network; the **medium network** scenario exploits low-temperature heat from lake water to produce 3.7 MW of peak power and 7.2 GWh thermal energy using an HP. It connects 32 users with a 2.6 km network; the **large network** recovers heat from a waste incineration plant to produce 23.3 MW of peak power and 47.6 GWh of thermal energy, serving 573 users with a 19.8 km network. Furthermore, the table presents typical supply and return temperature values, which are particularly important in TC processes.

Table 4. Generic thermal networks (Adapted from DeCarb-CH Workshop on generic and representative case studies)

Size	Primary energy source	Power [MW]	Energy demand [GWh]	Network length [km]	No. Users	Supply temperature [°C]	Return temperature [°C]
Small	Biomass	0.9	1.5	1.3	21	80	50
Medium	HP	3.7	7.2	2.6	32	70	40
Large	Waste incineration	23.3	47.6	19.8	573	110	55

Regarding the demand side, the review presented in section 3.2 identifies different load profiles that could be used as inputs in this analysis. Yet, it is essential to consider the required mass flow rate, temperature supply, and return to assess the performance of the sorption reactor. To this end, detailed building performance simulations are integrated using the SFH from the simulation reference framework presented in [33].

Following this logic, three case studies are defined to test and integrate the different applications progressively, and thus, the models developed (see Section 4.3). In brief, case study 1 (Section 3.3.3) is designed to test the key features of a DHN considering the aggregated SH demand, using an ideal and simplified closed sorption model, and virtually simulating the TCF. Case study 2 advances the study by modifying the operation of the SH systems to be more suitable for the TC process, adding the DHW demand, and improving the level of detail of the thermochemical reactor and fluid models (Section 3.3.4). Case study 3 focuses on the TCN level, including the discharging process of TCF for SH, DHW, and industrial drying, along with the regeneration of TCF using a solar collector plant (Section 3.3.5).

3.3.1 Key characteristics of TCN and the comparison to hydronic DHN

When comparing TCN to DHN one needs to be aware of the basic characteristics of TCN and sorption processes and in how far they differ from their hydronic counterparts.

TCNs are transporting salt solutions that carry a chemical potential. This potential can be used to upgrade low-temperature, environmental heat to utilizable heat. The underlying process is the one of a chemical (or thermal) heat pump where the thermochemical fluid replaces the electric compressor of an electric heat pump. Consequently, in a TCN, the energy required at the building-level for space heating and domestic water is not transported but only the chemical potential to locally produce this heat using an environmental heat source such as ambient air or ground heat. In that sense, TCN most closely compares to a 5th generation, ultra-low temperature DHN with local heat generation using electrical heat pumps. One major benefit of TCNs is that in winter-time when little renewable electricity is available to operate electrical heat pumps, it operates exploiting its chemical potential. A second benefit is that the chemical potential of the TCF can be stored lossless from summer to winter, thus allowing for seasonal load shifting and exploitation of summer renewables.

Based on the above characterization, TCNs represent (thermochemical) a grid-connected but decentraliced, heat generation solution while appart from the 5th generation DHN, 1st-4th generation DHN represent a centralized heat generation and distribution solution. For the comparison of TCN with DHN in the frame of this project a 4th generation DHN is chosen. Mainly because this type of network is currently the most representative in Switzerland and brings the advantage that little local equipment is required at the building level. Another reason is the possibility of long-term thermal energy storage at utilization temperature level and its comparability to sorption storage.

3.3.2 Terminal applications

This project integrates three terminal applications into the DHN/TCN: space heating, domestic hot water, and industrial drying. This section describes the process to estimate the demand profiles.

Residential Heat Demand

The SFH of the simulation framework presented in [33] is simulated using EnergyPlus and Cesar-P. This is a two-floor building with a total conditioned area of 140m^2. This building has an annual space heating intensity of 45 kWh/(m2*a). In this case, space heating is provided by a floor heating system with a variable mass flow. The supply temperature is fixed at 30°C and the return temperature at 22°C; the resulting mass flow rate follows the heating requirements considering the ambient temperature. The mass flow rate is scaled to represent the aggregate demand of multiple buildings (i.e., 190 SFH), thus representing a small thermal network (see Table 4). Further, the domestic hot water demand is integrated using a virtual tank that shifts the daily demand from the Standard SIA schedule [34] to the period where the SH requirements are minimal, i.e., reducing the peak load.

Figure 49 presents the estimated demand for DHW (Top) and SH (Bottom). The DHW tank is charged daily at 30-minute intervals between 9:00 and 19:00. In this way, the operation of a double-stage closed-sorption reactor to provide SH and DHW can be optimised (see Section 3.3.4). Regarding the

SH, the heating period starts at the end of October and ends in early April, with the highest requirement occurring in December and January. This is estimated using a constant heating setpoint of 21°C and the TMY weather file of Zurich [35].

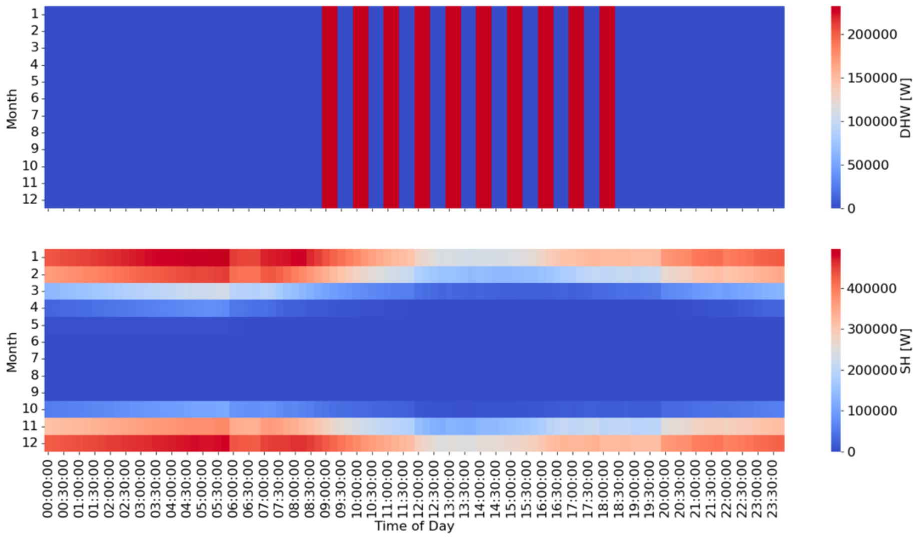

Figure 49. Heatmap – SH (Top) and DHW (Bottom) demand

Figure 50 presents the yearly residential heat demand, i.e., aggregated demand for 190 SFH. The DHW has a peak power of 0.23MW, accounting for an annual energy consumption of 0.45GWh. The SH has a peak power of 0.75MW, corresponding to a yearly energy consumption of 1.08GWh. This results in a heat demand of 1.53GWh per year with a peak power of 0.92MW, thereby simulating the demand of a small DHN (see Table 4).

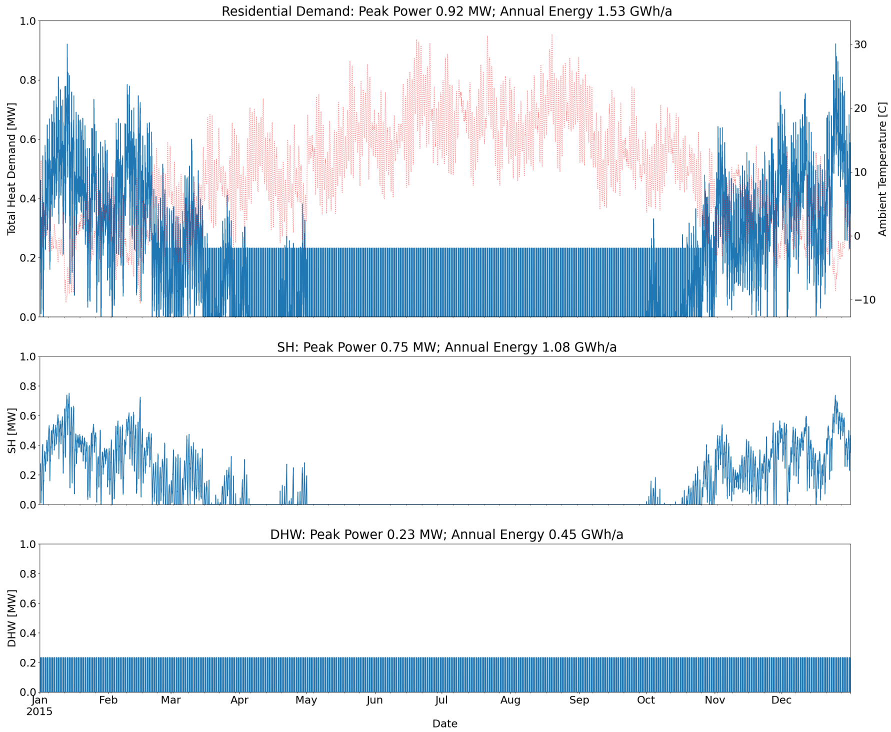

Figure 50. Residential Heat Demand for 190 SFH

Industrial Drying

The work within the project SONITRO [36] is used to integrate an industrial drying process into the DHN. SONITRO focused on developing and testing an open-sorption, low-temperature drying system for herbs and spice plants. The primary objective is to use caustic soda as a working medium in a pilot scale system to prove its technical feasibility and the required product quality. This process becomes relevant since its application is not limited to agricultural facilities but can also be used for many other industrial drying processes.

Figure 51 presents the drying program integrated into the DHN and TCN of Case Study 3 (see Section 3.3.5). The moist product has a humidity content of 84%, i.e., 5.1kg of water / 1kg of herbs. The drying process aims to achieve a humidity level of 12%, i.e., 0.12kg of water / 1kg of herbs.

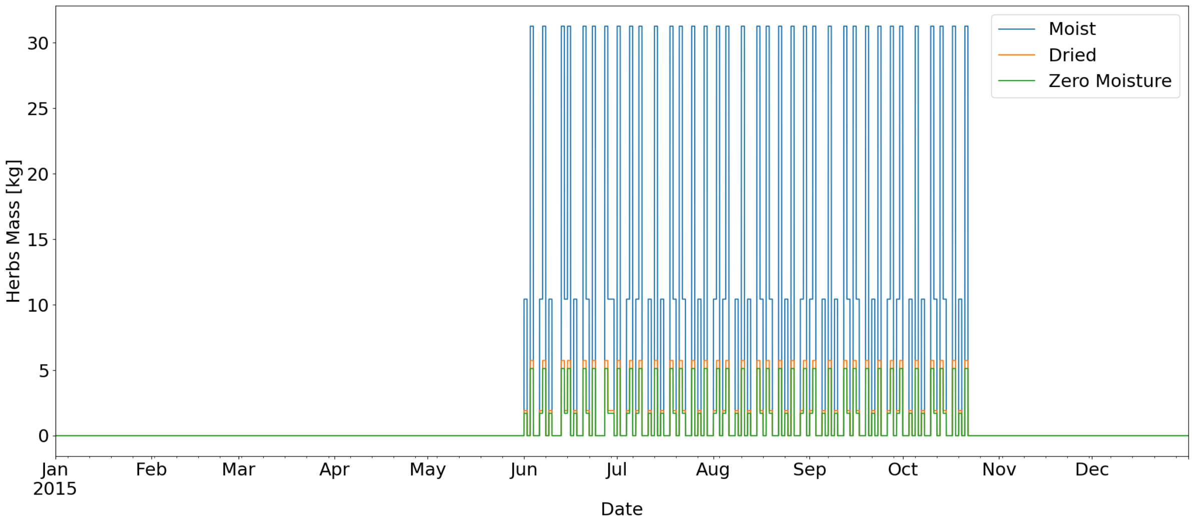

Figure 51. Yearly profile of drying program (Adapted from [36]).

3.3.3 Case Study 1

The first case study is used to capture and evaluate the key factors influencing the performance of TCN. This high-level analysis involves aggregated space heating demand (see Figure 50) and centralized heat supply covering only the winter period, i.e., only the discharging operation is evaluated.

As shown in Figure 52, the distribution network transports a TCF instead of water. Only the winter period is considered; thus, the generation is virtualized. It would represent any possible waste heat source or renewable heat generation units, such as solar collectors or electric heat pumps operated with PV to regenerate the thermochemical fluid during summer. Consequently, a regenerated, i.e., concentrated TC solution with a fixed concentration, is available to be discharged during winter. This concentration needs to be chosen considering the soil temperature to prevent solidification of the TCF. Further, a closed-sorption reactor exploits the low-temperature heat from a borehole to supply the required heat to the buildings.

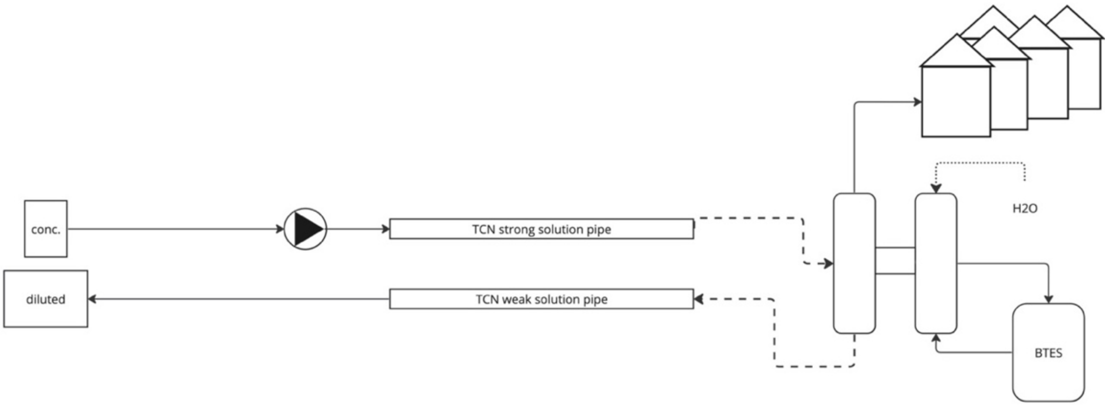

Figure 52. TCN with sorbent tanks, sorbent solution distribution network and ground-source coupled sorption reactor at the load side.

3.3.4 Case Study 2

The network implemented in this case serves SH and DHW demand (see Figure 50). Compared to Case Study 1, this adds complexity, given the different supply temperatures required for each system. Further, the reactor model used in this scenario corresponds to the detailed model developed (see Section 4.3.3).

As shown in Figure 53, a water buffer tank is integrated to operate the close-sorption reactor in a sequential 2-stage configuration. In the first stage, the ground heat exchanger provides low-temperature heat to the reactor to charge the buffer tank at the temperature required by the SH. In the second stage, the reactor exploits the heat stored in the buffer tank to provide DHW.

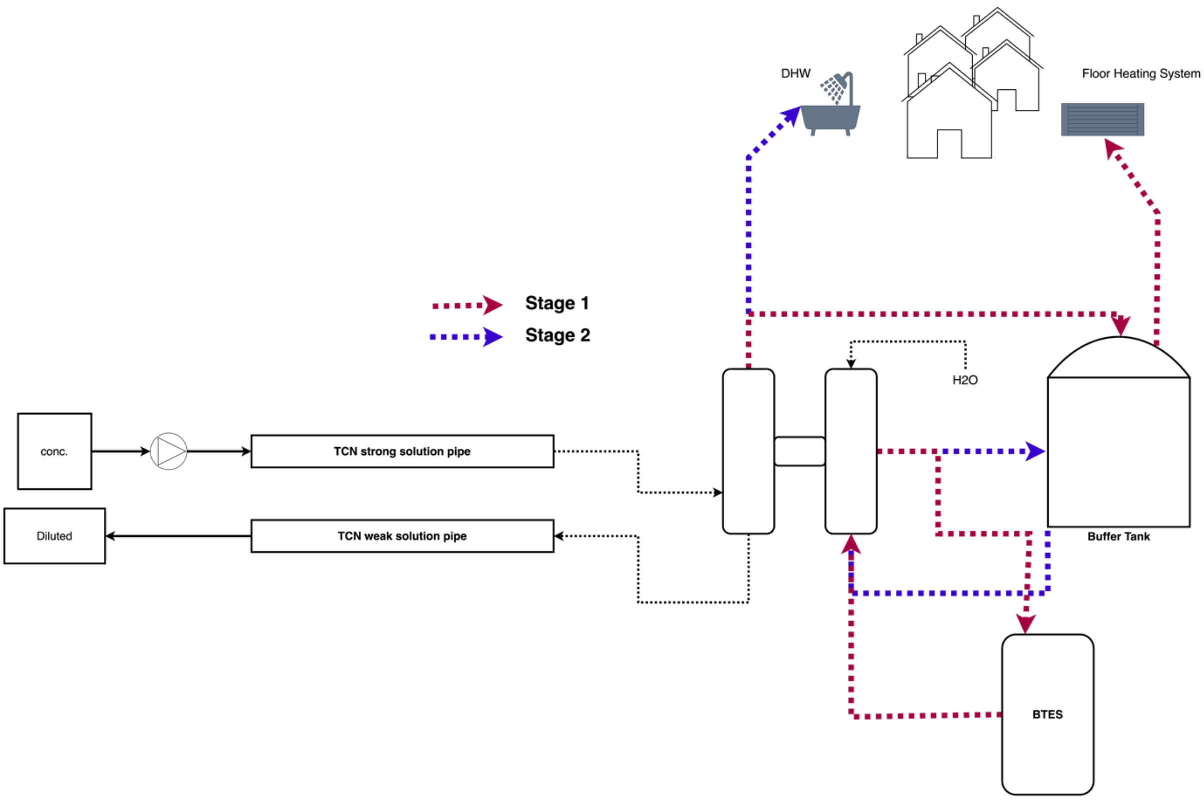

Figure 53. Case study 2: TCN with sorbent tanks, sorbent solution distribution network and two-stage sorption reactor at the load side coupled to a ground-source and a water buffer tank.

3.3.5 Case Study 3

Case Study 3 displays all the elements this project defines as a TCN ecology. Contrary to the previous scenarios where the availability of the concentrated solution is assumed, this case study integrates the regeneration cycle of the TCF. Heat from a solar collector plant provides the heat required in the regeneration process, and an air cooler is integrated to dissipate the excess heat. Further, on the demand side, the two-stage closed sorption reactor provides heat for the residential SH and DHW demand, while an open-sorption reactor serves an industrial drying process. Figure 54 shows a schematic of the TCN.

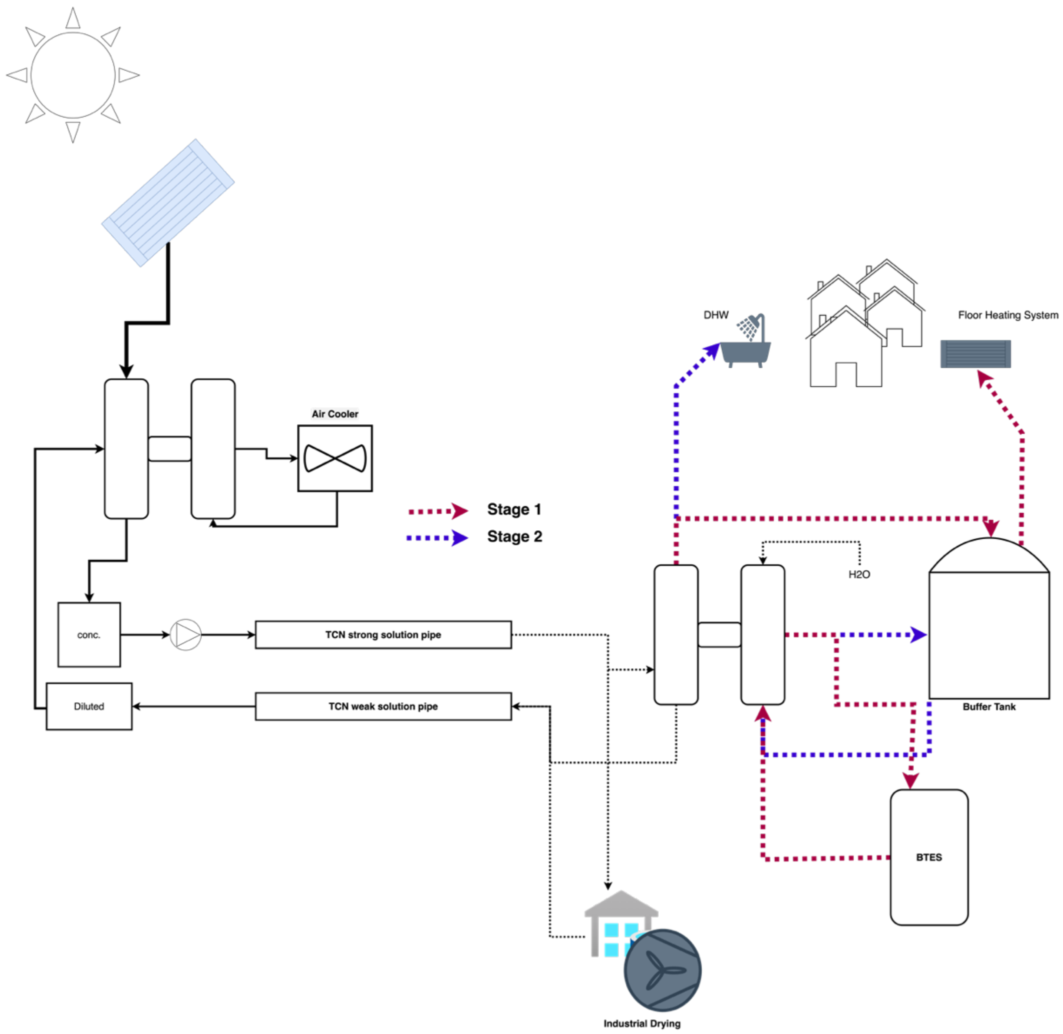

Figure 54. TCN with, at the supply side, sorbent tanks, sorbent solution distribution network, and a sorption reactor coupled to a solar collector plant to regenerate the sorbent solution; at the load side, and two-stage sorption reactor coupled to a ground-source and a water buffer tank to provide SH and DHW, and an open-sorption reactor for the industrial drying process.

3.3.6 Benchmark (DHN)

Figure 55 presents the hydronic DHN. This network is used to benchmark the performance of the TCN. It is based on the general characteristics of the small network presented in Table 4. Here, the heat supply is provided by a ground-source HP assumed to have a fixed source temperature on the evaporator side and a fixed sink temperature for heat rejection to the DHN. The supply temperature is fixed in each Case Study depending on the demand requirements, i.e., temperature for SH, DHW, or industrial drying. The HP is controlled to cover demand loads and the thermal losses across buried dual pipes. The DHN pipe diameter is selected so that the pressure drop is within a range of 150-250 Pa/m for the given mass flow, as recommended in [37]. The mass flow in the DHN is fixed, and the return temperature of the network is calculated based on the demand requirements and a defined supply temperature. The distance between the HP and the load is assumed to be the same as in the TCN, allowing for a reasonable comparison.

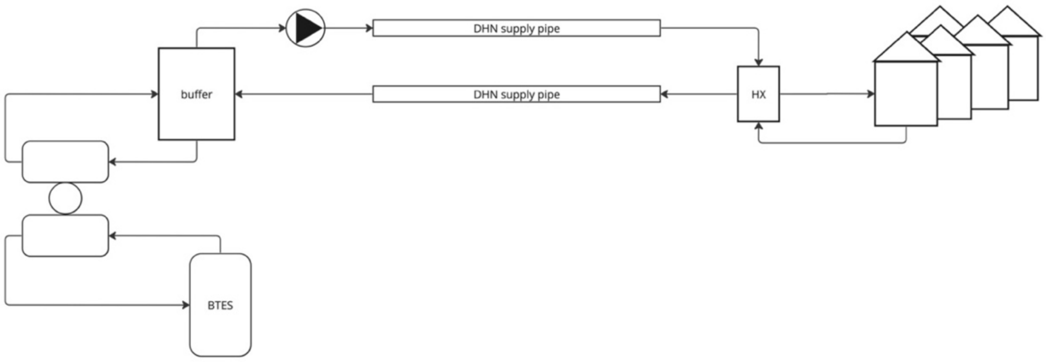

Figure 55. Classical, hydronic DHN with ground-source heat pump, distribution network and heat exchanger at the load side.

4 WP3 – Performance Analysis

4.1 State-of-the-art

4.1.1 Modeling thermal networks

The literature shows different modeling strategies for quantifying the performance of thermal networks. DHN can be modeled using black and physical white box models [38]. In the former, the network is considered a package where individual components within the system are disregarded. The DHN is modeled as a black box using transfer functions or artificial neural networks (ANN). In the latter, each network component is described by a set of physical equations, and thermo-hydraulic models are used to describe the performance of the whole network. Due to the nature of the black box models, they are primarily used for optimizing the design, operation, and performance of a defined network [39]. Physical modeling, instead, becomes relevant for sizing and analyzing the performance of individual components and the whole network. Accordingly, in this project, the development/implementation of physical models is followed, considering specific thermochemical components and their interaction with DHN networks, thus defining the TCN ecology.

In this regard, a variety of mathematical models have been presented in [40,41] including heat balance (heat supply, demand and heat losses within the distribution network); continuity of mass (i.e., 1st Kirchoff law: sum of mass flow rate in each node of the network equal zero); pressure loss i.e., due to friction along the pipelines; electric system model; hydraulic model. Due to the higher number of elements and physical processes involved, numerical methods are implemented to solve the system of equations e.g., Hardy-Cross, Newton-Raphson, and linear theory methods [38,41]. There are several tools available dealing with the complex issues of solving a numerical problem and facilitating the modelling of (not only) thermal networks. MODELICA programing language (and simulation environments such as Dymola and OpenModelica), TRNSYS, IDA-ICE are widely used by the research community [41,42]. TRNSYS is being extensively applied as an energy system modelling tool, especially when including seasonal thermal storage. Besides, it displays strengths when modelling solar systems and borehole thermal energy storage [43].

Considering MODELICA, several advances have been made and are available as open-source libraries driven by international efforts such as the International Energy Agency (IEA) Energy in Buildings and Community (EBC) Annex 60 focusing on the development of new generation computational tools for building and community energy systems [44]. Accordingly, the Annex 60 Library [45] was developed as the core of specialized libraries (i.e., to allow their interconnection) such as the AixLib [46] focusing on dynamic simulations of buildings, HVAC systems, distribution networks, and enabling integrated analysis at building and city district scales; the Buildings Library [47,48] focusing on simulations of building energy and control systems; the Ideas Library and the OpenIdeas framework [49] focusing on integrated district energy system simulations. Further, Wangda et al. [50] developed district cooling models featuring plant models and realistic mechanical systems and controls, and Bachmann et al. [51] developed the DisHeatLib Library to model complex district heating and cooling networks within a multi-level network structure, including bidirectional networks of production and consumption, or combined heating and cooling systems. Finally, Mans et al. [52] developed a framework for the automated model generation of DHC networks using Modelica. It aims at simplifying the process of performing parametric studies, especially for large, complex thermal networks.

4.1.2 Modeling TC components

Table 5 summarizes the main findings of the literature review performed to understand modelling alternatives of TCNs and processes. Here, experimental studies are presented that can be used to define inputs e.g., correlations for heat and mass transfer of LiBr and LiCl [53,54]; boundary conditions e.g., temperature and dehumidification levels of terminal applications [55]; validate simulation results [55]. Further, different modelling strategies are presented for closed and open sorption processes. Mathematical modelling based on the thermodynamic analysis [56–58] of the solution has been deployed to calculate the state i.e., temperature and concentration at the inlet and outlet of the reactor where the absorption and desorption process takes place. Accordingly, the thermophysical correlations of the solution are interpolated at each time step assuming thermodynamic equilibrium. Alternatively, physical modelling considering the governing equations of heat and mass transfer has been used to model the thermochemical reactor [59–63]. In this case, numerical methods such as the finite element method are used to solve the complex system of equations.

Table 5. The literature reviewed on thermochemical components and networks

Reference	Scope	Modelling Strategy	Highlights
Critoph et al. [56]	Investigation of thermochemical transmission systems based on liquid–gas (several working pairs modelled) absorption intended for application in urban district heating networks.	Mathematical modelling: Thermodynamic analysis	• Absorbent-refrigerant pairs are modelled using water, methanol and acetone as absorbates • Thermophysical properties from the literature are presented in the appendix • Closed-sorption processes

Reference	Scope	Modelling Strategy	Highlights
Giampieri et al. [55]	Experimental study of a thermochemical network and smart control strategies to assess their potential of integrating in thermal networks	N/A	• This reference presents typical temperature and dehumidification levels for different terminal applications as well as possible smart thermochemical network configurations. • Indicative reference for defining modelling boundary conditions and for validating results • Describes the effect of steady and variable heat sources on TCF regeneration performance
Delwati et al. [59,60]	Design and simulation approach for a thermochemical-district-heating-cooling-network and its components.	Physical modelling (Numerical simulation)	• Model developed/implemented in Modelica using the standard library and the IDEAS Library • Working pairs tested: MgCl2-H2O and LiCl-H2O • Absorber/desorber model based on work of [64]
Giampieri et al. [53]	Develop correlations for predicting moisture and enthalpy effectiveness of the liquid desiccant dehumidification and regeneration process	N/A	• Based on published experimental data with different system dimensions, liquid desiccant solutions (LiBr and LiCl), geometry and size of the packing and flow configuration (counter- and cross-flow) • Correlations developed for the mass flow rates of air and desiccant solution, the inlet temperature of the air and the desiccant solution, the moisture content and enthalpy of the inlet air, the moisture content and enthalpy of air at an equilibrium state with the inlet desiccant solution, the geometry, dimensions and wetting of the packing and the contact time between air and desiccant solution
Coronas et al. [61]	Experimentally validated, dynamic model of a hybrid liquid desiccant system.	Physical modelling (Numerical simulation)	• New components (i.e., non-adiabatic falling-film type with horizontal tubes and the solution tanks) developed in FORTRAN and implemented in TRNSYS. • Physical equations given for the air-solution contactor (Absorber/desorber component) • Sensitivity analysis at different operational conditions: inlet water temperatures in the air-solution contactors and the LiCl mass fraction

Reference	Scope	Modelling Strategy	Highlights
Delwati et al. [62]	Description of a Modelica Library components developed to model thermochemical networks	Physical modelling (Numerical simulation)	• Absorber model developed by [64] using heat and mass transfer correlations for LiCL-H2O working pair. • The building, heat exchanger, tank storage, heat pump, fan, pump, and evaporator models are adjusted from the Modelica IDEAS and BUILDINGS libraries
Muthukumar et al. [63]	Experimental investigations, numerical predictions, developed experimental correlations and Derringer's desirability-based optimization approach on liquid desiccant reactor	Experimental / Physical modelling	• Two-dimensional thermal model for the liquid desiccant reactor for determining the energy and mass exchange rates occurring along the packed tower (dehumidifier/re-generator). • Finite difference method to solve the system of equations implemented in Matlab
Han et al. [57]	Design and simulation of a hybrid photovoltaic/thermal and liquid desiccant system for deep dehumidification	Mathematical modelling: Thermodynamic analysis	• Numerical fitting equations adopted to calculate the thermophysical properties of LiCl solution
Tang et al. [54]	Mass transfer performance of the LiCl solution dehumidification process	Experimental	• The isothermal and non-isothermal equilibrium curves under some thermal conditions are calculated and could be used as reference.
Baldini et al. [58]	Simulation of a liquid sorption storage combined with a compression heat pump to provide space heating and estimate energy flexibility	Mathematical modelling: Simplified thermodynamic analysis	• Closed-sorption process • Monthly resolution • Sorption process modelled using Absorber/desorber represented by a heat and mass exchange using thermodynamic properties of NaOH – H2O solution
Tzinnis et al. [4]	Numerical study on the building integration of a liquid sorption storage combined with an air-source electric heat pump	Physical modelling (grey box numerical model)	• Modelling of the reactor is a 1D, steady-state, equilibrium model, based on mass end energy balance formulations discretized in space • Experimental data use to fit the model

4.2 Fundamental principles

4.2.1 Thermochemical fluid

Section 2.1.3 presents different thermochemical fluids, i.e., calcium chloride, calcium nitrate, lithium bromide, lithium chloride, magnesium chloride, and sodium hydroxide, and discusses their suitability for different terminal applications, i.e., temperature lift and heating, dehumidification in industrial drying and climatization, and energy storage. The sodium hydroxide aqueous solution displays several advantages to be used in a TCN serving different terminal applications, e.g., the minimum system temperature to prevent crystallization is 5°C considering a concentrated solution of 45% NaOH/Solution; it has the largest temperature lift potential thus it reduces the number of stages required; it has the minimum possible relative humidity that can be reached in open sorption processes; it has the highest exergy density. Accordingly, the sodium hydroxide aqueous solutions is selected to be implemented in the scenarios proposed in Section 3.3.

4.2.2 Thermochemical reactor: Closed sorption

As described in [58], the closed sorption reactor implemented in this project has two interconnected chambers (see Figure 56). The first works as an absorber and desorber (Chamber 1), and the second is a condenser and evaporator (Chamber 2). During charging operation, in Chamber 1, a heat source, e.g., HP or solar heat, provides the heat necessary to remove water from diluted sorbent, i.e., sodium hydroxide aqueous solution. In this process, evaporated water is transported to Chamber 2, condensed, and heat is released to a sink. During the discharging phase, water is evaporated in Chamber 2 and transported to Chamber 1, where concentrated sorbent absorbs the vapor water, releasing useful heat, e.g., for space heating applications.

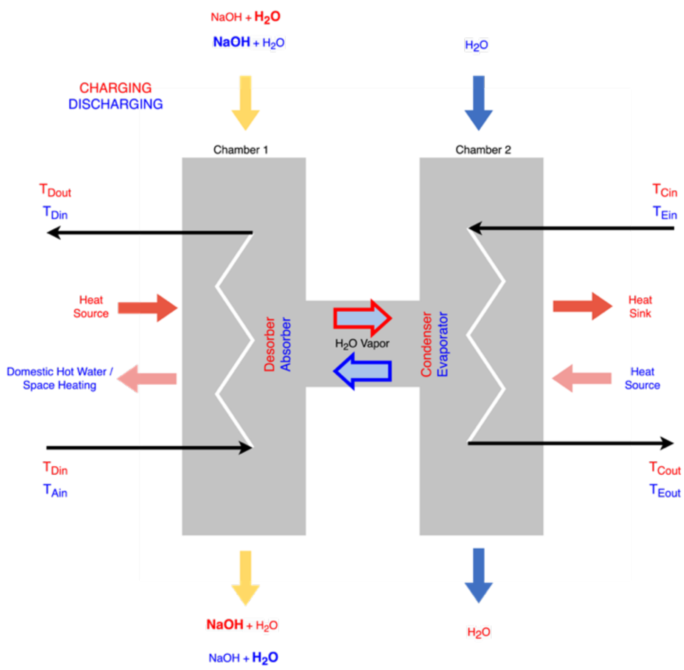

Figure 56. Reactor - Closed sorption (adapted from [58])

The model is developed assuming the solution is in equilibrium at each point of the system, the condensed water and the generated water vapor are saturated, and the system has no thermal losses to the environment. To this end, the mass and energy balance equations are implemented as in [65]. During the charging operation, the sorption reactor is composed of a desorber and a condenser. In the desorber, a heat source is used to evaporate water from the solution using a heat transfer fluid (HTF). The amount of heat transferred $\dot{Q}_{D,in}$ is described by:

$$\dot{Q}_{D,in} = \dot{m}_{D,htf} C_{p,D,htf} \left(T_{D,in} - T_{D,out} \right)$$

Equation 1

Where $\dot{m}_{D,htf}$ and $C_{p,D,htf}$ are the mass flow rate and specific heat of the heat transfer fluid, $T_{D,in}$ and $T_{D,out}$ are the desorber inlet and outlet temperature. In this case, an ideal reactor is modelled which means that the heat supplied by the HTF ($\dot{Q}_{D,in}$) and the heat gained by the sorbent solution $\dot{Q}_{Des}$ are equal. The former can be expressed by:

$$\dot{Q}_{Des} = \dot{m}_{D,H_2O,(g)} h_{H_2O,(g)} + \dot{m}_{s,w_{sh}} h_{s,w_{sh}} - \dot{m}_{s,w_{sl}} h_{s,w_{sl}}$$

Equation 2

Where $\dot{m}_{D,H_2O,(g)}$ and $h_{H_2O,(g)}$ are the mass flow rate and specific enthalpy of the water evaporated from the sorbent solution, $\dot{m}_{s,w_{sh}}$ and $h_{s,w_{sh}}$ are the mass flow rate and specific enthalpy of the concentrated solution leaving the desorber, and $\dot{m}_{s,w_{sl}}$ and $h_{s,w_{sl}}$ are the mass flow rate and specific enthalpy of the diluted solution entering the desorber. Further, using the mass conservation principle it can be derived the mass flow rate of the evaporated water for a desired concentration lift:

$$\dot{m}_{s,w_{sh}} w_{sh} = \dot{m}_{s,w_{sl}} w_{sl}$$

Equation 3

$$\dot{m}_{D,H_2O,(g)} = \dot{m}_{s,w_{sl}} - \dot{m}_{s,w_{sh}}$$

Equation 4

The desorber is operated assuming a saturation pressure given by the inlet temperature at the condenser ($T_{C,in}$) thus, the condensation heat $\dot{Q}_{Con}$ can be described by:

$$\dot{Q}_{Con} = \dot{m}_{D,H_2O,(g)} \Delta h_{fg} \left(p_{sat}(T_{C,in}) \right)$$

Equation 5

Where $\Delta h_{fg} \left(p_{sat}(T_{C,in}) \right)$ is the enthalpy of condensation of the water at the saturation pressure. Assuming an ideal process, the heat released to environment by the htf $\dot{Q}_{C,out}$ is equal to the condensation heat and can be expressed by:

$$\dot{Q}_{C,out} = \dot{m}_{C,htf} C_{p,C,htf} (T_{C,in} - T_{C,out})$$

Equation 6

Where $\dot{m}_{C,htf}$ and $C_{p,C,htf}$ are the mass flow rate and specific heat of the heat transfer fluid, $T_{D,in}$ and $T_{D,out}$ are the desorber inlet and outlet temperatures.

During the discharge phase, the sorption reactor consists in an absorber and an evaporator. In this scenario, concentrated sorbent solution absorbs evaporated water; hence, it releases the heat of solution and heat of evaporation. This heat is transferred to a HTF ($\dot{Q}_{A,out}$) to be utilized in a terminal application (e.g., space heating), and it can be expressed as:

$$\dot{Q}_{A,out} = \dot{m}_{A,htf} C_{p,A,htf} (T_{A,in} - T_{A,out})$$

Equation 7

Where $\dot{m}_{A,htf}$ and $C_{p,A,htf}$ are the mass flow rate and specific heat of the heat transfer fluid, $T_{A,in}$ and $T_{A,out}$ are the absorber inlet and outlet temperatures. Assuming an ideal process, the heat produced in the absorber ($\dot{Q}_{Abs}$) and the heat transfer to the htf ($\dot{Q}_{A,out}$) are equal. The latter can be described by:

$$\dot{Q}_{Abs} = \dot{m}_{s,w_{sl}} h_{s,w_{sl}} - \left[\dot{m}_{A,H_2O,(g)} h_{H_2O,(g)} + \dot{m}_{s,w_{sh}} h_{s,w_{sh}} \right]$$

Equation 8

The mass balance in the absorber is expressed as in the desorber using Equation 3 and Equation 4. Futher, the saturation pressure is given by the temperature at the evaporator outlet ($T_{E,out}$). Here, the minimum heat required to evaporate ($\dot{Q}_{Evap}$) the required water vapor mass is defined by:

$$\dot{Q}_{Evap} = \dot{m}_{A,H_2O,(g)} \Delta h_{gf} \left(p_{sat}(T_{E,out}) \right)$$

Equation 9

Where $\Delta h_{gf} \left(p_{sat}(T_{E,out}) \right)$ is the enthalpy of vaporization of the water at the saturation pressure. Assuming an ideal process, the heat required to evaporate the water ($\dot{Q}_{Evap}$) is equal to the heat provided by a low-temperature source ($\dot{Q}_{E,in}$) using a htf, and can be expressed by:

$$\dot{Q}_{E,in} = \dot{m}_{E,htf} C_{p,E,htf} (T_{E,in} - T_{E,out})$$

Equation 10

4.3 Model implementation

Based on the review presented in Section 4.1, combining different tools and models, a simulation framework is established and implemented in Modelica (using the Dymola 2023) to assess the performance of a TCN under different scenarios (see 3.3).

4.3.1 Media model

Based on the correlations developed by Olsson et al. [66] to model the thermophysical properties of sodium hydroxide aqueous solutions, two media models have been implemented in Modelica. The first only solves the thermophysical properties at specific nodes of the system. This means the fluid flow is solved in a post-processing stage, in this case, using the thermodynamic states calculated by the simplified model of the closed-sorption reactor (see 4.3.2). The second model implements a media model extended from the Modelica package *Modelica.Media.Interfaces.PartialCondensingGases*. Specifically, the temperature, concentration and pressure of the solution are defined as base variables, which are used to compute states defined by the density, enthalpy, energy, and saturation properties i.e., saturation concentration, temperature, and pressure. This implementation allows solving the fluid flow using interconnected components such as pipes, pumps, etc.

4.3.2 Closed-sorption Reactor – Simplified Model

A simplified closed-sorption reactor is implemented extending the model *PartialFourPortInterface* from the Modelica Buildings Library (v10.0.0) [47,48]. It includes two ideal heater/cooler representing the HTF side (i.e., water) of the absorber/desorber and the evaporator/condenser, while the TCF sides are described by the mass, species, and heat balance equations presented in Section 4.2.2. The model couples these elements to calculate the required TCF inlet mass flow rate to supply a prescribed heat flow in discharging mode or the TCF mass flow rate that can be regenerated in charging mode, using as inputs the mass flow rate and enthalpy of the heat transfer fluid in the absorber/desorber and evaporator/condenser. Figure 57 shows the graphical representation of the model.

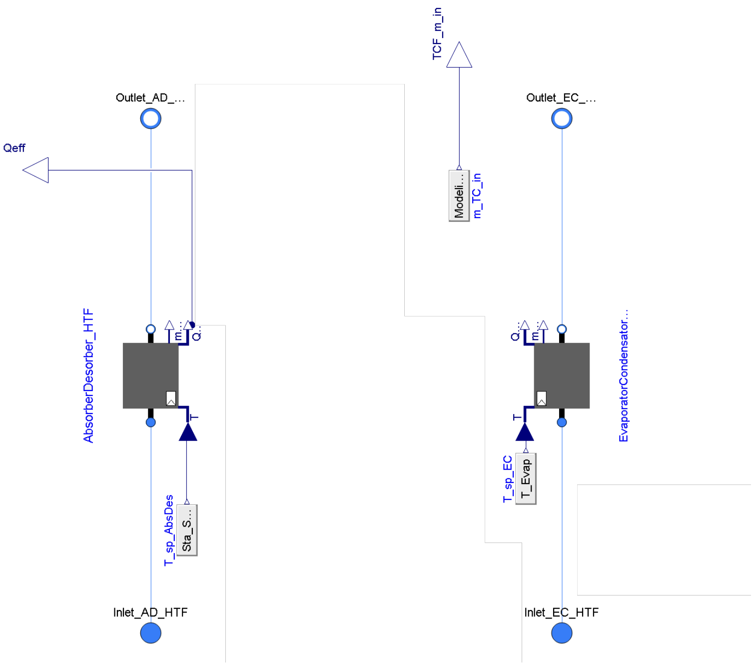

Figure 57. Simplified closed-sorption reactor - Modelica Implementation

It is essential to highlight that in this model the pressure and heat losses are neglected, and the inlet TCF is assumed to be at saturated conditions. Finally, this model captures the key performance aspects in Case Study 1 (see Section 3.3.3 and Section 4.5.1).

4.3.3 Reactor – Detailed model

4.3.3.1. Closed-sorption reactor model: Discharging mode

The model presented in Section 4.3.2 is advanced to capture with more detail the physical phenomena and improve the overall operation of the reactor:

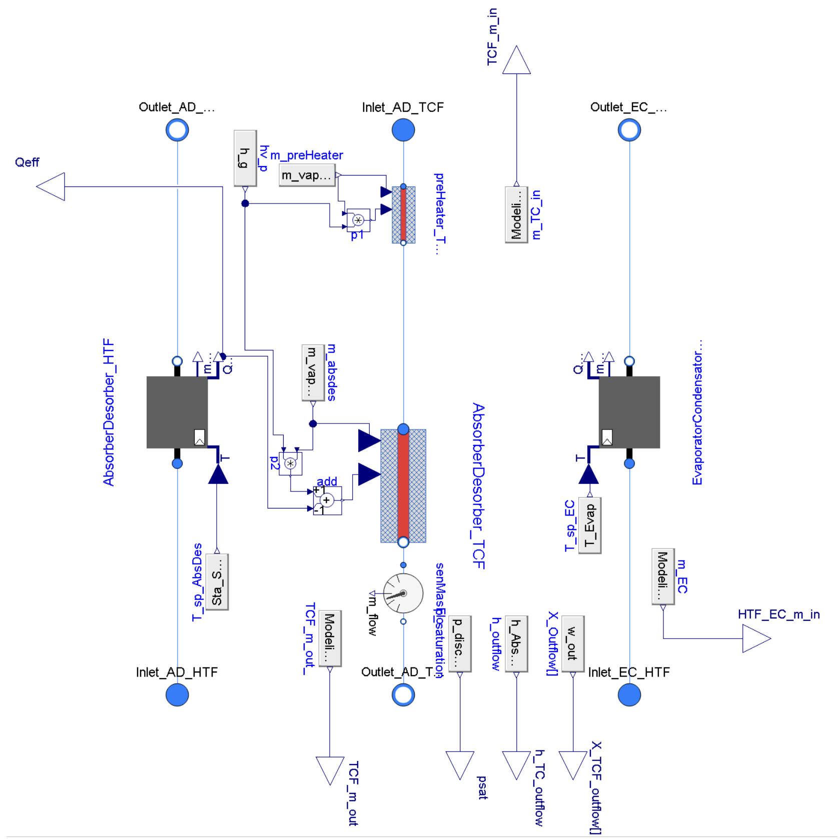

Figure 58. Detailed closed-sorption reactor - Modelica Implementation

- It includes an additional two-port interface to solve the TCF flow, allowing the integration of this model into a TCN.
- It adds a preheating section in the TCF side of the absorber/desorber, i.e., for any TCF inlet condition, the reactor preheats the fluid to reach saturation state.
- It adds two mass and heat transfer components extended from the model *TwoPortHeatMassExchanger* (Buildings Library) to represent the TCF preheating and absorber/desorber side.
- Calculates the inlet mass flow rate of the heat transfer fluid at the evaporator/condenser side to improve the control of the saturation pressure in the system and thus, the outlet TCF concentration.

- In discharging mode, it is possible to fixed a target minimum outlet TCF concentration.
- While the model could be used in charging or discharging mode, the discharging mode is preferred. For the charging mode, additional parameters have been implemented (see Section 4.3.3.1)

4.3.3.1. Closed-sorption reactor model: Charging mode

In charging mode, the model presented in Section 4.3.3.1 is extended as shown in Figure 59.

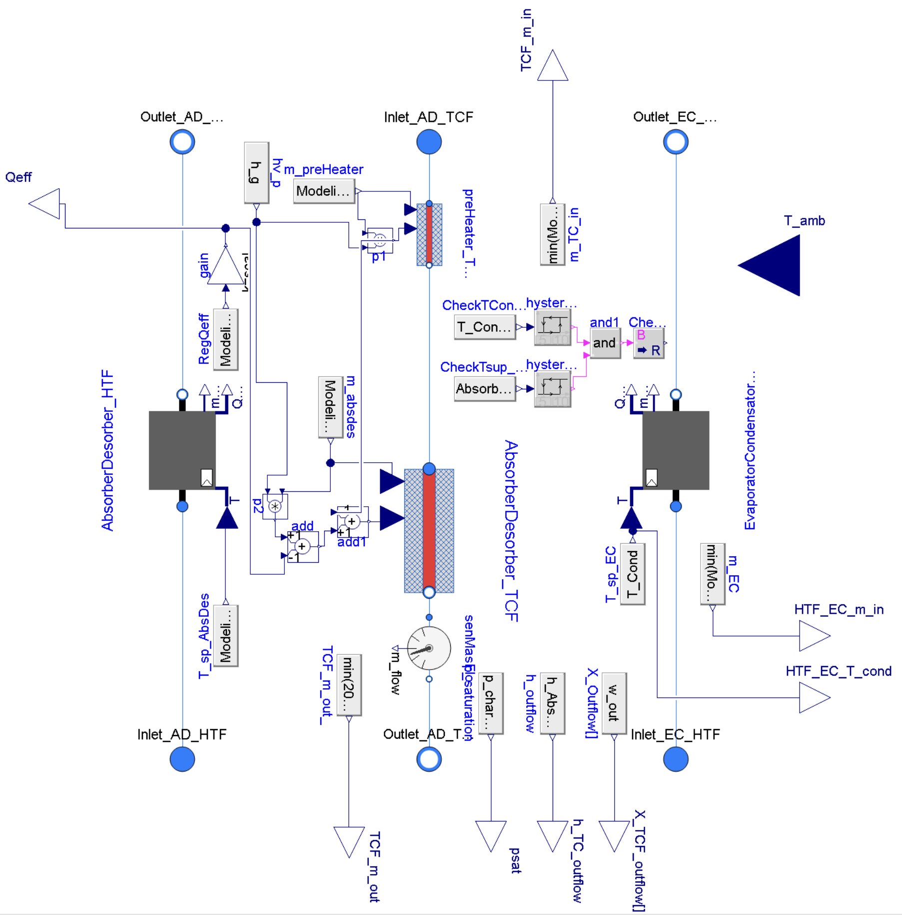

Figure 59. Detailed closed-sorption reactor (Charging mode) - Modelica Implementation

It includes the following improvements:

- The target TCF outlet concentration as an input parameter.
- A scaling factor is introduced to simulate multiple systems coupled in parallel to the HTF side of the desorber.
- A control loop that checks suitability of the temperature levels of the HTF at the desorber and condenser to charge the TCF:

- The HTF inlet temperature in the desorber is higher than the diluted TCF saturation temperature.
- The HTF inlet temperature in the condenser is lower than the condensation temperature.

4.3.3.2. Closed-sorption, double-stage operation

During a discharging process, the maximum temperature that can be reached is constrained by the evaporation temperature and the inlet TCF concentration. As explained in Section 2.1.3, the heating process could be performed in multiple stages to overcome this limitation. In this case, while the temperature required by the SH (i.e., ~ 30°C) could be achieved in a single stage, the temperature lift to provide DHW (i.e., water from the city network at 12°C to DHW at ~ 55°C) calls for a multiple stage configuration. A two-stage operation could be achieved by running two sorption reactors simultaneously in-series. Alternatively, a sequential operation of a single reactor in combination with a water buffer tank could be used. This project focuses on the latter configuration as presented in Figure 60 to operate a closed-sorption reactor in a two-stage heating process for serving the residential SH and the DHW.

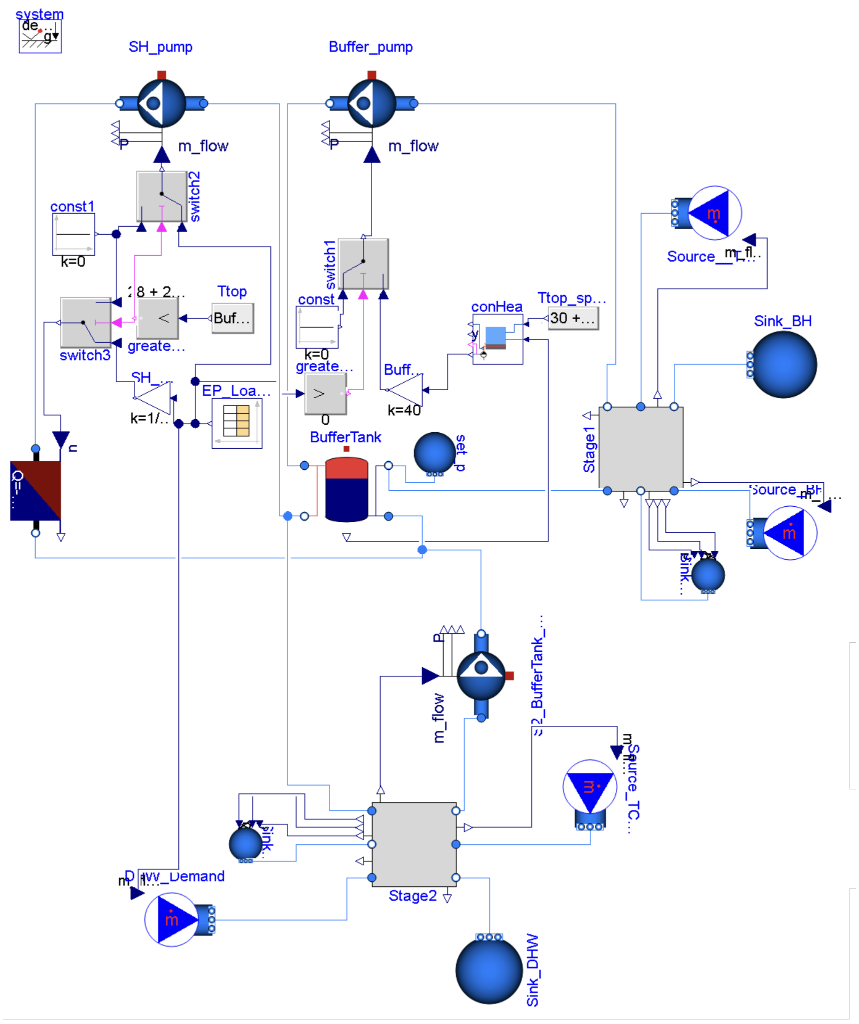

Figure 60. Detailed closed-sorption reactor: Double-stage operation – Discharging mode

The model uses as input a heat load profile with the mass flow rate and power required for the SH and DHW systems (see 3.3.2). The stage 1 operation of the reactor exploits the heat from a ground-source heat exchanger represented by an ideal HTF source and sink. Similarly, an ideal source and sink of TCF is connected to the reactor to complete the TCF loop. The HTF is circulated from a buffer tank (modelled with the storage tank model of the DisHeatLib Modelica Library [51]) to the absorber lifting the temperature to the SH level, hence, charging the storage tank. The stage 2 operation exploits the heat stored in the buffer tank to evaporate the water needed to discharge the concentrated solution. The higher evaporation temperature translates into a higher saturation pressure, and depending on the available concentration of the TCF, it is possible to reach the temperature lift required by the DHW.

A single reactor and a hydraulic circuit would be needed to reproduce the double-stage operation. For simplicity, in this implementation, two reactors are used, and a control logic is defined so that they cannot operate simultaneously:

1. stage 1 charges the storage tank if the temperature at the top is lower than 30°C and there is no DHW demand.

2. stage 2 operates whenever there is DHW demand.

3. The SH can operate only if the temperature at the top of the storage tank is higher than 28°C

Following this control logic, the size of the storage tank becomes critical to ensure there is available heat stored when there are DHW and SH demands simultaneously. It is important to highlight that in a real system, the buildings and building systems have a thermal inertia that is not considered here because of the representation of the heat demand through a load profile. This means larger tanks are required to meet the instantaneous demand. To compensate for this effect, lower supply temperatures are accepted for small periods, i.e., 28°C instead of 30°C for the SH.

4.3.4 Open-sorption model

While in this project, the modeling efforts focused on developing the media model and closed-sorption reactor, the open-sorption model is integrated from the work performed in the project SONITRO [36], where an open-sorption drying device was developed, tested, and simulated. In this view, given the drying profile presented in Figure 51 (Section 3.3.2), a conversion factor is applied to estimate the concentrated and diluted TCF mass flow rates. Specifically, in [36] was established that 1.65kg of sodium hydroxide is required to dry 1kg of wet material, considering a TCF inlet and outlet concentration of 45% and 30%, correspondingly, and temperatures varying between 34°C and 40°C. This information is used to translate the drying profile into TCF profiles integrated into the TCN simulation of Case Study 3. Furthermore, it is established that 1.2MJ/kg of herbs is consumed by the fan in this open sorption process.

Likewise, in SONITRO, a conventional dryer was studied to benchmark the sorption dryer's operation. Here, the specific energy of the conventional fan is 3.4 MJ/kg. In addition, to integrate the process to the DHN, it is assumed the latent heat of evaporation required to reduce the moisture content from 84% to 12%, is extracted from the DHN.

4.3.5 Network model

Case Studies 1 and 2 focus on the discharging operation to fulfill a heating demand and capture key and high-level aspects of the TCN. Case Study 3 explores the so-called TCN ecology in depth. To this end, a TCN model is implemented considering the different terminal applications on the demand side and integrates the charging loop required to regenerate the TCF.

4.3.5.1. Charging-loop

The detailed closed-sorption reactor described in Section 4.3.3.1 is coupled to an ASHRAE93 solar collector model (Buildings Library v10.0.0) to regenerate the TCF. A pump controlled by the mass flow rate circulates the diluted TCF from a tank (OpenTank model from the Standard Modelica Library) through the reactor. Then it directs the resulting concentrated TCF into the concentrated TCF tank. A control strategy is established so that when the collector's heat gain per unit area is higher than a threshold, and there is enough diluted TCF to be charged, a pump circulates the HTF, i.e., water, to supply the charging heat from the collector to the reactor. Finally, the condensation heat is released through a virtual air cooler simulated by a HTF ideal source with a temperature that follows the ambient temperature with an offset to mimic a real heat exchanger. The TMY weather file for Zurich is integrated to estimate the collector's solar radiation and ambient temperature. Figure 61 shows a schematic of the TCN's charging loop.

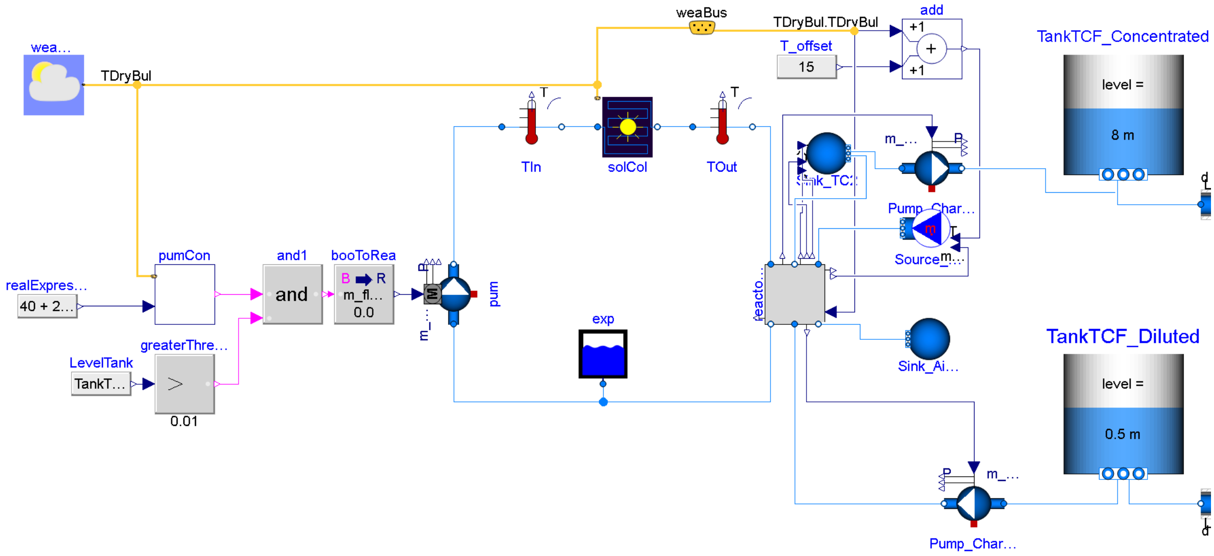

Figure 61. TCN model implementation: Charging loop.

4.3.5.1. Discharging-loop

Regarding the discharging loop, the terminal applications have been decoupled from the TCN simulations. This is necessary to reduce the complexity and computational cost of the simulation. This means that instead of plugging the discharging reactors into the network, from the simulations performed in Case Study 2, TCF profiles are extracted and integrated into the TCN simulation. To this end, ideal sinks and sources represent the inlet and outlet nodes of the discharging reactor using the recorded mass flow rates, concentration, temperature, and pressure. The concentrated and diluted TCF tanks are connected to the demand sources and sinks using the PlugFlowPipe and Junction models (Buildings Library v10.0.0). This allows for accounting for the hydraulic and heat losses in the TCN. Figure 62 presents a schematic of the model implemented.

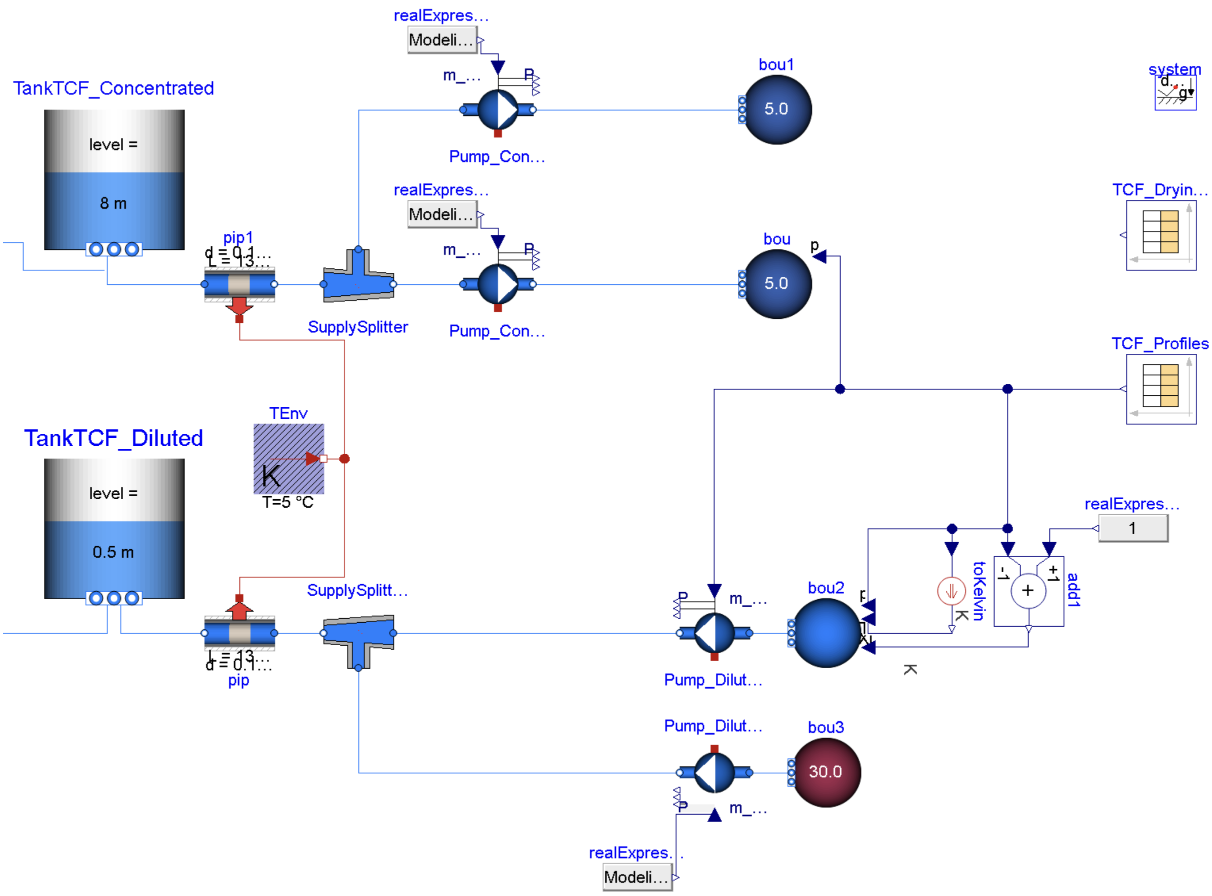

Figure 62. TCN model implementation: Discharging loop.

4.3.1 Benchmark – Hydronic DHN

Finally, a hydronic DHN is implemented to benchmark the performance of the TCN. As mentioned in Section 3.3.6, this network supplies the heat using an HP coupled to a ground-source heat exchanger. The HP is modeled with a prescribed condenser outlet temperature, i.e., the network fixed supply temperature (Buildings Library v10.0.0). The ground-source heat exchanger is simulated using an ideal source and sink. A pipe modeled with the PlugFlowPipe model (Buildings Library v10.0.0) accounts for the hydraulic and thermal losses in the network between the supply and demand, considering the same length as in the TCN scenarios. An ideal cooler simulates the heating demand, coupled with the load profiles extracted from EnergyPlus (section 3.3.2). Finally, the mass flow rate controls the pump circulating the fluid across the network. While in Case Study 1, this is a constant value across the year, in Case Studies 2 and 3, two values are imposed, one during the heating period and one for the rest of the year. Figure 63 shows the complete model implemented.

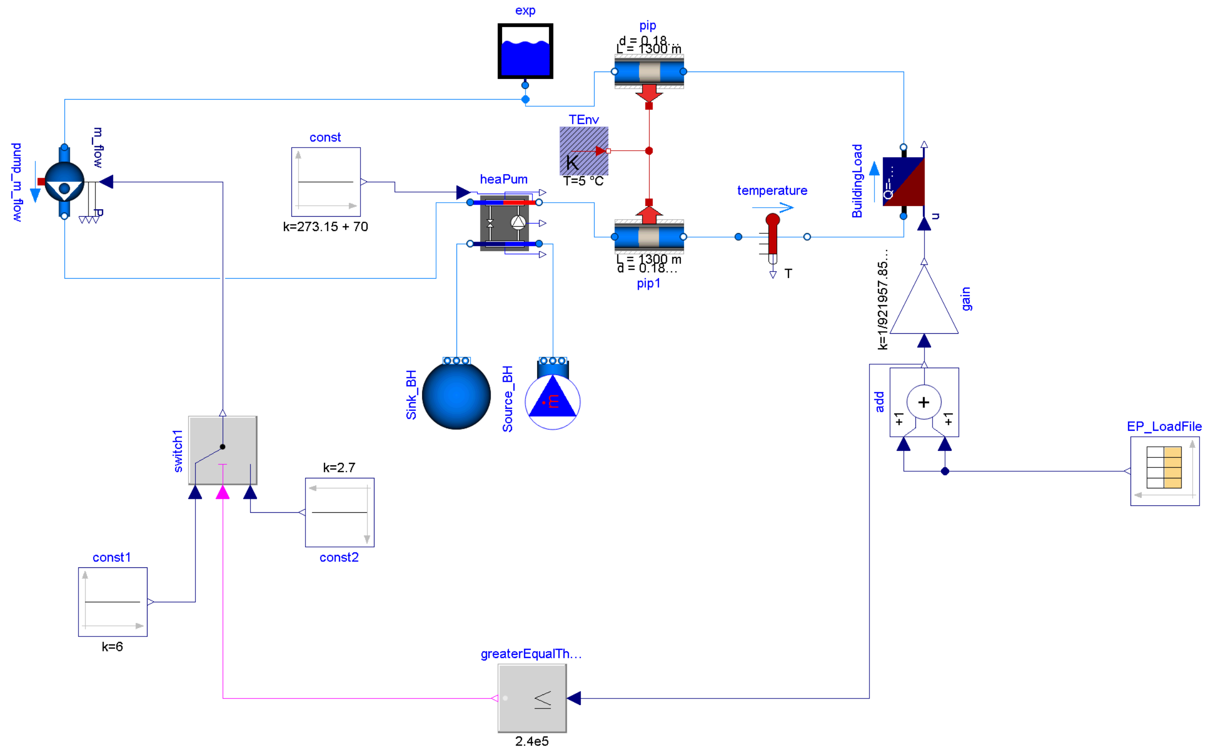

Figure 63. The hydronic DHN model implemented

4.4 Key Performance Indicators

A set of KPIs is defined to assess the performance of the TCN and benchmark its performance against a hydraulic DHN. For each scenario, the thermal energy efficiency (Equation 11), exergy efficiency (Equation 12), electric COP (Equation 13), and energy storage density (Equation 14 and Equation 15) are calculated considering the operation of each DHN during one year.

Thermal energy efficiency is defined as the ratio between the total annual heat demand and the total annual heat supply (Equation 11). In Case Study 1, the total heat supplied corresponds to the residential SH; the total heat supply corresponds to the heat generated by the TC reactor. In Case Study 2, the total heat demand corresponds to the sum of the residential SH and the DHW; the total heat supply is the total heat generated by the TC reactor (two-stage operation). In Case Study 3, the total heat supplied corresponds to the sum of the residential SH and DHW demand and the heat required by the industrial drying; the total heat supply is the sum of the total heat generated by the closed-sorption TC reactor, i.e., two-stage operation for SH and DHW), the open-sorption TC reactor, i.e., for the industrial drying process), and the closed-sorption reactor i.e., single-stage reactor to regenerate the TCF. Finally, in the benchmark simulations, the total heat supply equals the heat delivered by the HP.

$$\text{Thermal energy efficiency } = \frac{total\ heat\ demand}{total\ heat\ supplied} = \frac{\sum_1^i Q_{i,demand}}{\sum_1^j Q_{j,supply}}$$

Equation 11

Exergy efficiency is the ratio between annual exergy demand and supply (Equation 12). In each Case Study, the heat demand and supply considered for the thermal energy efficiency are multiplied by a Carnot factor $1 - \frac{T_0}{T}$ where T_0 is the ambient temperature and T is the temperature at which the heat is required (i.e., heat demand) or the temperature at which the heat is supplied (i.e., heat supply). In addition, the electric power $\sum_1^k E_{el}$ consumed by the DHN to deliver the heat is included in the total exergy supply. This is, for example, the electricity consumed by the circulation pumps, or the electric energy required to operate the HP.

$$\text{Exergy efficiency } = \frac{total\ exergy\ demand}{total\ exergy\ supplied} = \frac{\sum_1^i \left(1-\frac{T_0}{T_i}\right) Q_{i,demand}}{\sum_1^k E_{el} + \sum_1^j \left(1-\frac{T_0}{T_j}\right) Q_{j,supply}}$$

Equation 12

Electric COP is defined as the ratio between the total annual heat demand and the total electricity consumed by the network (Equation 13). The heat demand for each case is described in the energy efficiency calculation. The total electricity consumed by the TCN is primarily due to the electricity used by the pumps to circulate the TCF. Regarding the benchmark simulations, the electricity consumed by the HP is added to the total electricity consumed.

$$\text{Electric COP } = \frac{total\ heat\ demand}{total\ electricity\ supplied} = \frac{\sum_1^i Q_{i,demand}}{\sum_1^k E_{el}}$$

Equation 13

Finally, the energy storage density is defined as the ratio between the total heat demand and the volume of the energy carrier medium (Equation 14 and Equation 15). Regarding the TCNs, it is calculated considering the diluted TCF, whereas, for the hydronic DHN, it corresponds to the water, given a temperature difference.

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

Equation 14

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

Equation 15

4.5 Results & Discussion

4.5.1 Case Study 1

A yearly simulation is solved for the TCN described in Section 3.3.3 with the reactor model described in Section 4.3.2. Assuming that the TCF distribution pipes are buried, and the soil temperature is constant at 5°C, a maximum concentration of 45 wt.% is defined to avoid crystallization of the TCF, being aqueous sodium hydroxide solution. For other TCF, different temperature limits would hold. For comparison reasons, the same pipe diameter as in the hydronic DHN are implemented, i.e., DN80. The ground-heat exchanger is assumed to have a fixed return temperature of 5°C and a mass flow rate of 73 kg/s, which prevents the evaporation temperature going below 1 °C.

Figure 64 presents the main operation aspects of the closed-sorption reactor during the discharging operation to meet the SH demand. The concentrated TCF mass flow rate follows the heating demand with a maximum of ~1 kg/s. The saturation pressure is variable, between 7.5 mbar and 8.5 mbar, due to the fixed mass flow rate in the HTF side of the evaporator, i.e., 73 kg/s, which produces a variable evaporation temperature. Accordingly, the saturation temperature assumed at the inlet of the reactor varies between 35 °C and 36 °C. Instead, the outlet TCF temperature is constant at 22°C, i.e., following the SH return temperature, resulting in a variable diluted concentration between 34 wt.% and 36 wt. %.

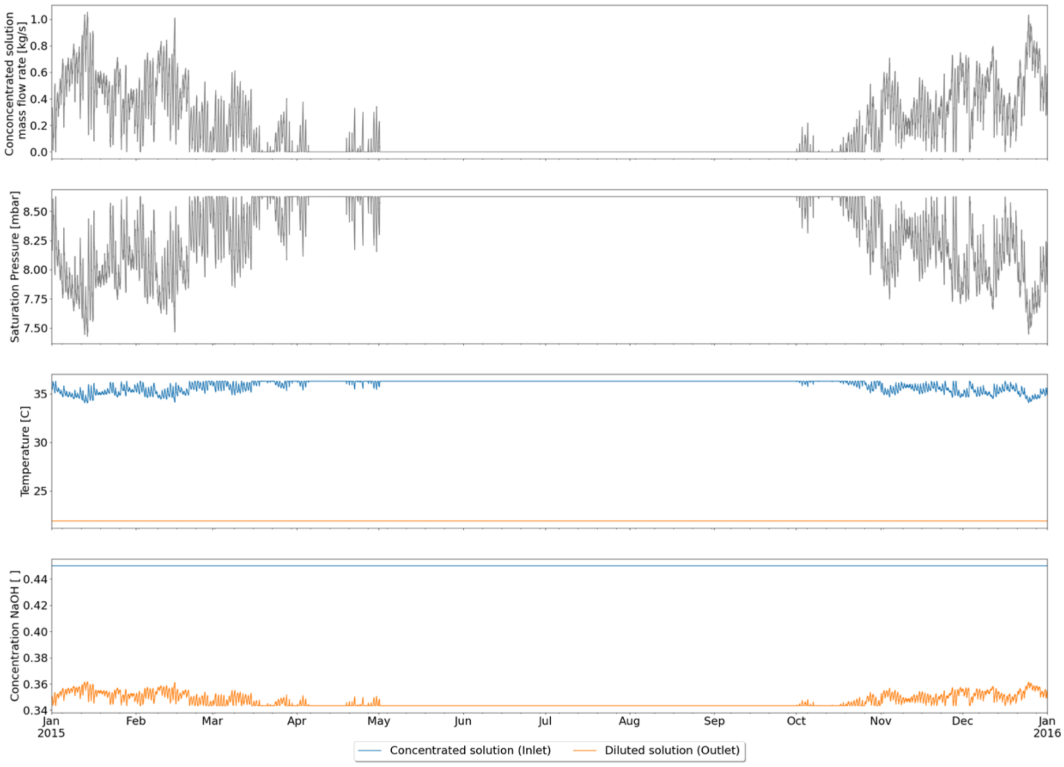

Figure 64. CS1 – Closed-sorption reactor operation

The estimated mass flow rate of the concentrated TCF required by the reactor, and the resulting diluted TCF are used to calculate the capacity and volume across the year of the concentrated and diluted TCF storage tanks. In this case, no continuous regeneration process is considered. Figure 65 shows that 3350 m^3 of concentrated and 5000 m^3 of diluted TCF tanks are required to fulfil the SH heating demand of 190 SFH under the given operation conditions.

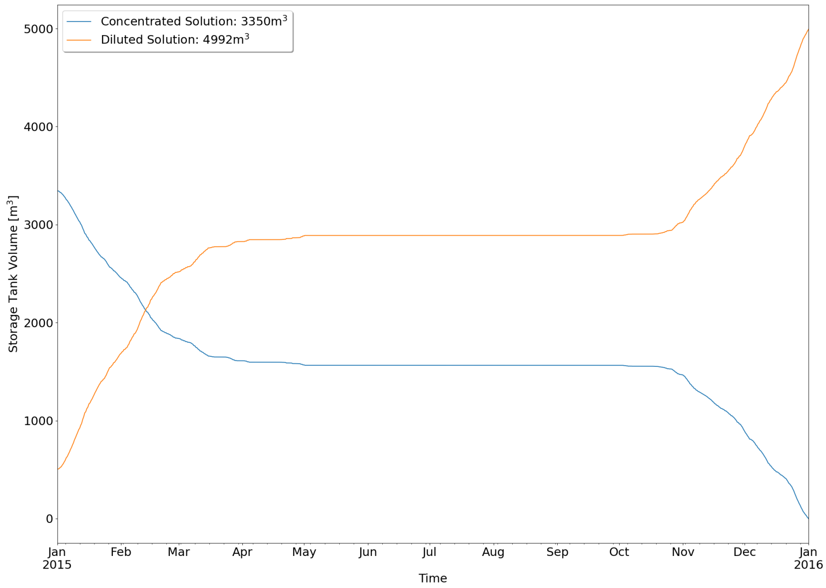

Figure 65. CS1 – TCF storage tank

The TCN is benchmarked against a hydronic DHN described in Section 3.3.6. In this case, the supply temperature of the DHN is set to 45 °C with a fixed mass flow rate of 8 kg/s. Heat is generated by a ground-source HP in which the return temperature of the ground heat exchanger is set to 5°C with a mass flow rate of 30 kg/s. Buried DN80 dual pipes of 1300 m connect the heat supply and demand, resulting in a pressure drop of 255 Pa/m.

Considering a yearly simulation, Table 6 presents the KPI estimated for both networks. It can be noted that (i) the TCN has a higher energy efficiency because the transport of sorbent solution does not involve any thermal losses, i.e., no heat is transported but only a chemical potential. Further, the heat losses of the absorber in discharging mode are neglected under the ideal modeling assumptions. (ii) A significant difference by a factor of ~5 can be recorded when comparing the exergy efficiency. This is mainly because the TCN does not show any significant electricity demand for circulation or heat generation assuming the same diameter for the piping. In this case, the TCF and the chemical potential it carries substitutes the electric energy needed by the compressor of the electric HP in the DHN case. (iii) While the electric COP for the DHN appears reasonable, the electric COP for the TCN is large. This can be explained by the low mass flow rate of the TCF solution needed to operate the sorption reactor, resulting in a pumping cost of 3.72 MWh/y., compared to 95MWh/y for the DHN. This explains the large difference of the COP. (iv) Looking at the volumetric energy storage density, in the simulated case, the density in the DHN case is low because of the small temperature difference between supply and return in the network of about 23K 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 216.33 kWh/m^3. This is higher by a factor of 8.06 or 3.70, respectively, compared to the sensible water storage.

Table 6. CS1: Summary KPI

	Hydronic DHN	TCN
Energy efficiency	0.87	1
Exergy efficiency	0.13	0.70
Electric COP	2.5	290.58
Storage density @ΔT=23K [kWh/m^3]	26.83	216.33
Storage density ratio @ΔT=23K	8.06	
Storage density @ΔT=50K [kWh/m^3]	58.33	216.33
Storage density ratio @ΔT=50K	3.70	

In this case study, the results are limited by assuming that the concentrated TCF is available at the saturation temperature. This will affect the exergy efficiency and storage density. Moreover, given the operation of the reactor implemented, the saturation pressure is not controlled, thus, the resulting diluted TCF concentration have significant fluctuations. This means that the TCF is mixed within the distribution network and the diluted tank, resulting in additional energy losses. These aspects are considered and advanced within Case Study 2.

4.5.2 Case Study 2

A yearly simulation is solved for the TCN described in Section 3.3.4 and the model presented in Section 4.3.3. This is a TCN where the heat required to meet the residential SH and DHW demand is generated by a double-stage closed-sorption reactor. In the stage 1, the reactor exploits the heat of evaporation from a ground heat exchanger with a return temperature of 5°C. Differently from Case Study 1 where the mass flow rate was fixed, in this case the closed-sorption reactor model calculates the mass flow rate so that the evaporation temperature is constant at 1°C and thus, a constant saturation pressure is set. Further, the reactor model implemented integrates a preheating section that brings the concentrated solution, assumed to be a 5°C, to a saturated state. The saturation temperature of the concentrated TCF defines the maximum temperature, which is the temperature at which stage 1 of the reactor charges the buffer tank. A mass flow rate of 40 kg/s is set for charging the tank to ensure there is available heat when it is required. Regarding the buffer tank, it has been sized so it can store the required heat to supply SH and DHW when they work simultaneously, i.e., 100 m3 with a height of 10m. The SH demand is met directly from the buffer tank. Finally, in stage 2, the reactor exploits the heat of evaporation from the buffer tank. The evaporation temperature is set to 24°C thus, with a 45 wt.% concentrated TCF, it is possible to lift the temperature of the water from the city network at 12°C to ~55°C, reaching the DHW requirements. With this temperature difference (55°C – 12°C) theoretically, it would be possible to fully dilute the TCF, which is however beyond what can be achieved in practice. Realistically, there is a limitation in the totally achieved concentration difference across the reactor as the driving force for water vapor absorption decays with lower sorbent concentrations. This leads to non-equilibrium conditions which are not accounted for in the mathematical model. Consequently, to account for this circumstance, the diluted concentration is artificially limited to 30 wt.%. **Error! Reference source not found.** presents the key parameters of each stage of the closed-sorption reactor.

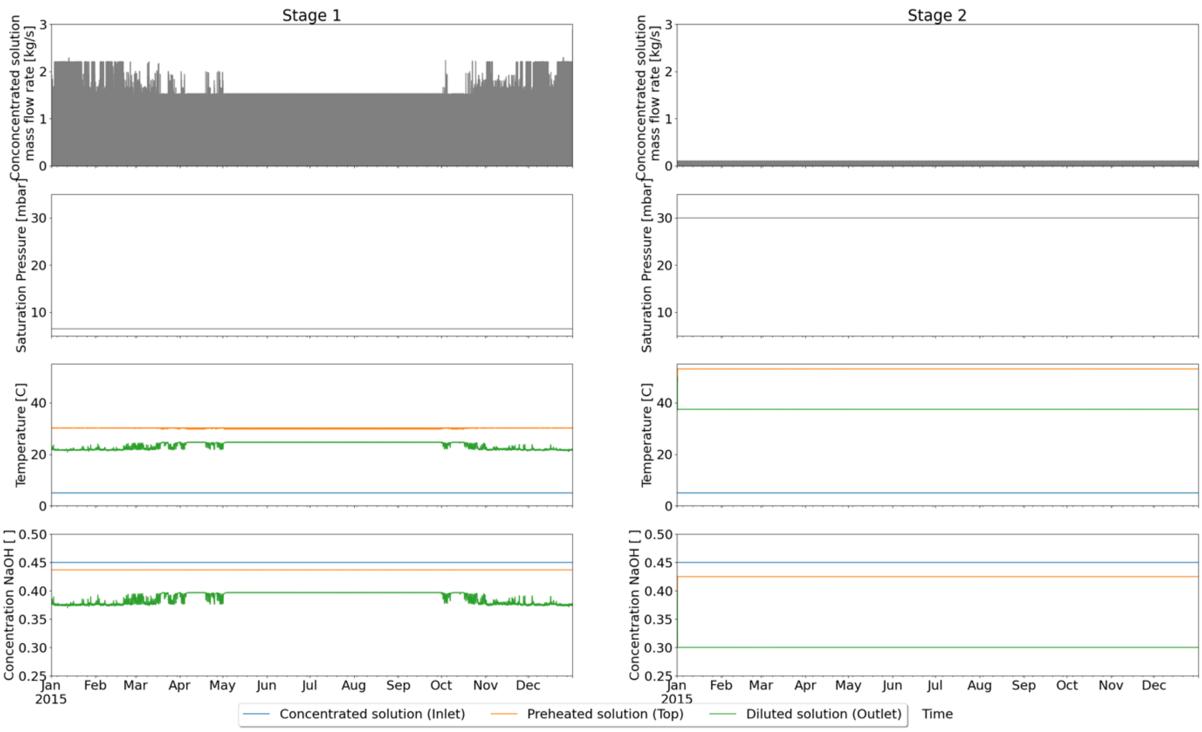

Figure 66. CS2. Closed-sorption reactor: stage 1 and stage 2 (Limited diluted concentration of stage 2 @30 wt.%)

In stage 1, the calculated mass flow rate of concentrated TCF reaches a maximum of 2.88 kg/s. This is with a constant saturation pressure of 6.5 mbar. Further, the concentrated solution enters the reactor at 5 °C and 45 wt.%, after the preheating section it is saturated at a temperature of 30.13 °C and a concentration of 43.6 wt.%. While during the SH period, the diluted TCF reaches a minimum concentration of 36.97 wt.% and temperature of 20.83 °C, when there are no SH requirements, it reaches a temperature of 24.9 °C and a concentration of 39.01 wt.%. This is a temperature difference of 9.3 °C and 5.23 °C, and a concentration difference of 8 wt.% and 6%, during and outside the SH period respectively. In this case, the diluted concentration varies between ~ 36 wt.% and 39 wt.% depending on the minimum temperature at the bottom of the buffer tank. In stage 2, the calculated mass flow rate of concentrate TCF is 0.1 kg/s. This is with a constant saturation pressure of 30 mbar. Under these conditions, the TCF enters at a temperature of 5°C with a concentration of 45 wt.%. After the preheating section, it is saturated at a temperature of 53.16°C and a concentration of 42 wt.%. The resulting diluted TCF reaches a temperature of 37.47 °C and a concentration of 30 wt.%. This is a temperature difference of ~15 °C and a concentration difference of 15 wt.%.

Important differences are noticed between the operation of each stage of the reactor. This is because in stage 1 the heat required to directly meet the SH heating demand is generated, indirectly supplying the evaporation heat to stage 2 for generation of DHW. In this course, some heat is lost from the buffer tank to the environment. The peak power of DHW demand accounts for approximately 30% of the SH. In stage 1, the absorber operates with a maximum temperature difference of 9 K and a maximum concentration difference of 8 wt.%, which is significantly smaller than the 15 K and 15 wt.% achieved in stage 2, pointing to a better exploitation of the chemical potential of the TCF in stage 2. All together this results in a higher demand of concentrated TCF in stage 1 than in stage 2.

Figure 67 presents and snapshot of the combined operation i.e., stage 1 and 2, of the closed-sorption reactor during a week in winter. It can be observed how the reactor shifts between the stages according to the demand requirements. A uniform periodic operation is observed while there is a DHW demand, following the charging pattern of the virtual, daily DHW tank.

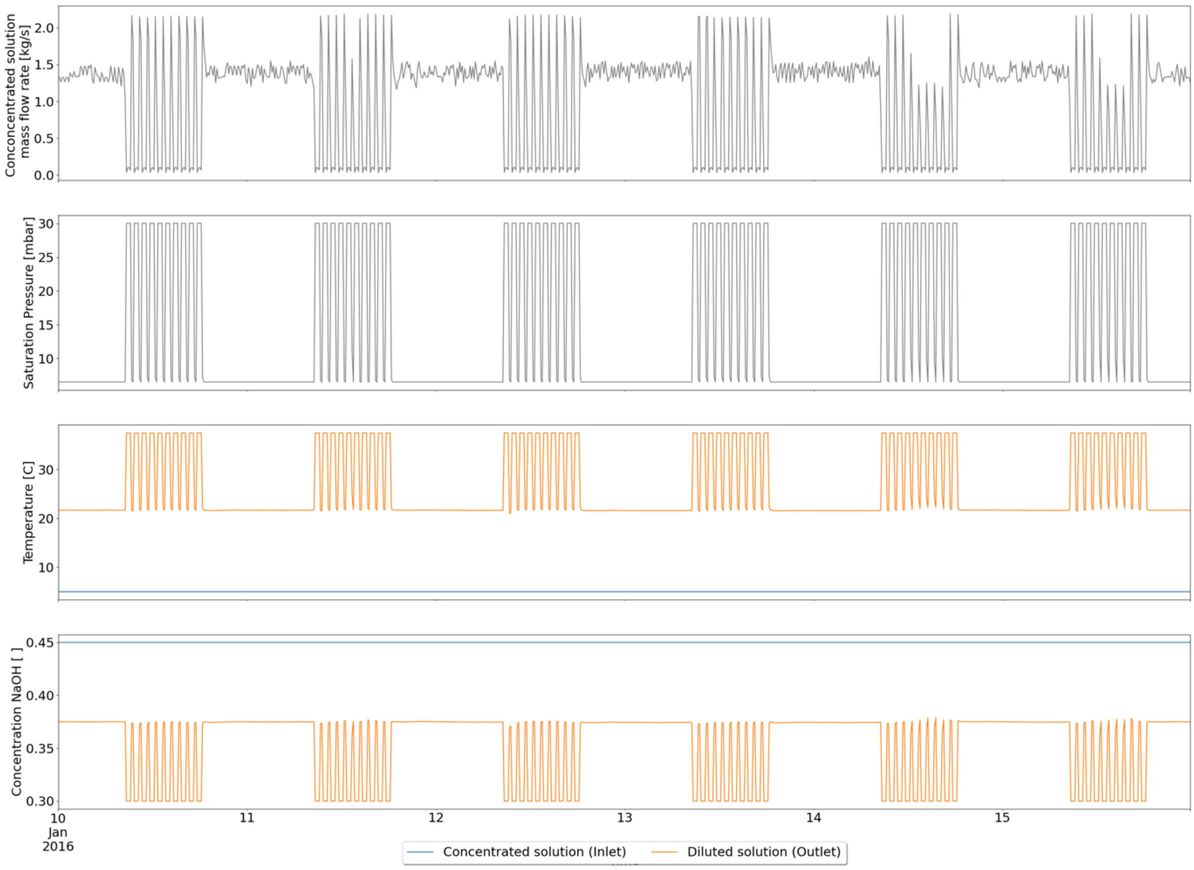

Figure 67. CS2: Closed-sorption reactor combined operation.

Figure 68 shows the temperature levels at the top and bottom of the buffer tank. During the heating period, the return temperature of the SH drives the temperature at the bottom of the tank, otherwise, its driver is the evaporation temperature in the stage 2. This is the temperature at the inlet of the HTF side of the absorber of stage 1, thus, it defines the minimum concentration of the diluted TCF. Despite the operation of the reactor has been improved to fix the saturation pressure at a constant value, the variation of the tank temperature at the bottom results in a variation of diluted concentration.

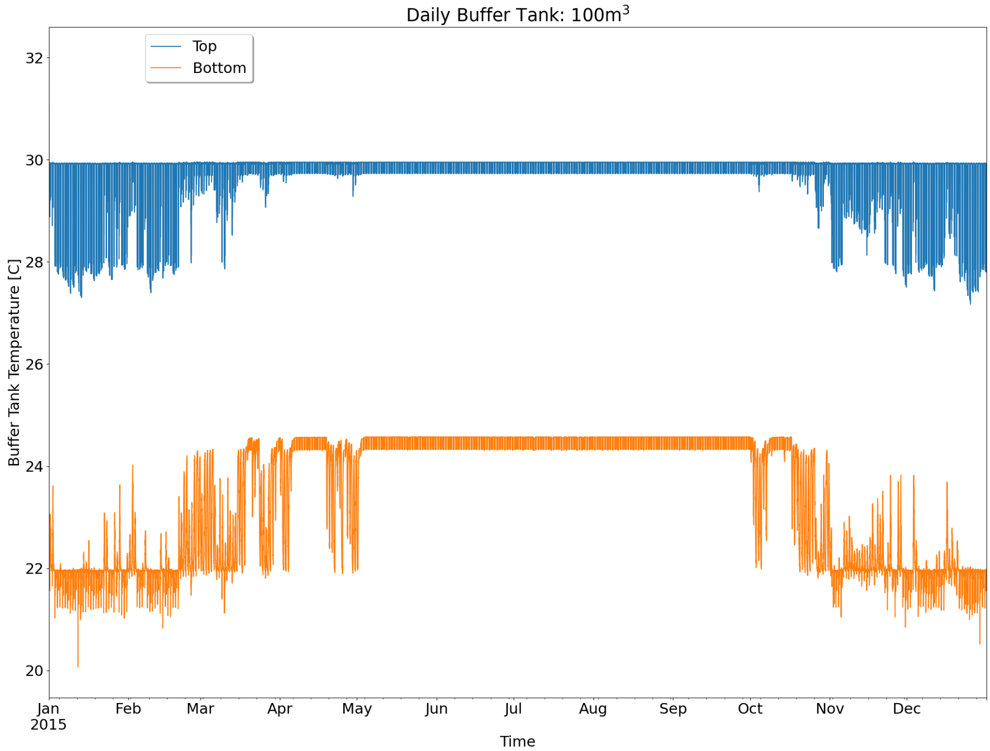

Figure 68. CS2: Buffer tank – Top and bottom temperature levels.

A second simulation is performed to see the impact of improving the control of the diluted TCF concentration. To this end, the diluted concentration of the stage 2 operation is limited to 39 wt.% to match with the terminal concentration of stage 1. Figure 69 shows the key operation parameters at each stage. In this case, while the diluted concentration is virtually constant and no additional TCF mixing will occur in the distribution network, the lower exploitation of chemical potential results in larger TCF demand. This can be seen in the increased maximum mass flow rate of concentrated TCF during stage 2, i.e., an increment of 430% compared to the previous case. Similarly, during the stage 1, there is an increment of 126% in the concentrated TCF mass flow rate due to the increment of heat of evaporation required by the stage 2.

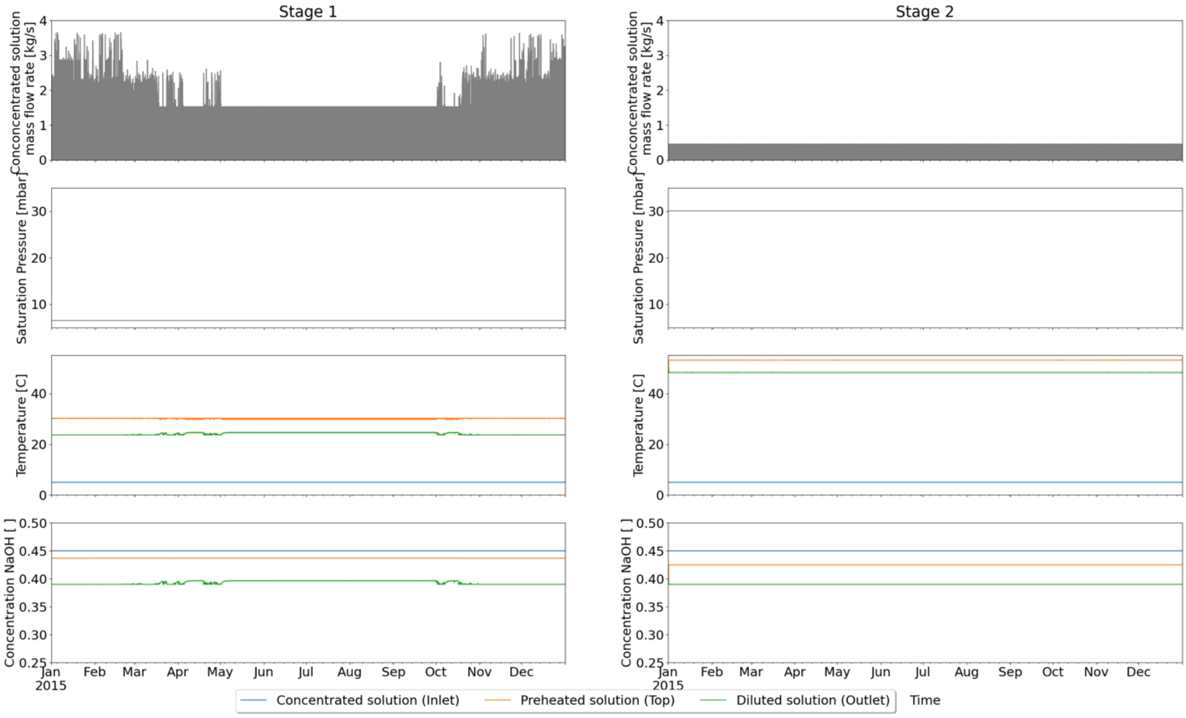

Figure 69. CS2. Closed-sorption reactor: stage 1 and stage 2 (Limited diluted concentration of stage 2 @39 wt.%)

Figure 70 shows the estimated capacity and volume across the year of the concentrated and diluted TCF tanks for each simulated case, i.e., limiting the concentration of the diluted TCF in the stage 2 operation of the reactor at 30 wt.% (Scenario A) and 39 wt.% (Scenario B). While in Scenario A, a total volume of ~10900 m^3 of concentrated TCF is required, in Scenario B an increment of 44% is perceived, i.e., ~15800 m^3. Likewise, while in Scenario A, it is required a ~14025 m^3 diluted TCF storage tank, in Scenario B, it is perceived an increment of 35%, i.e., ~19000 m^3.

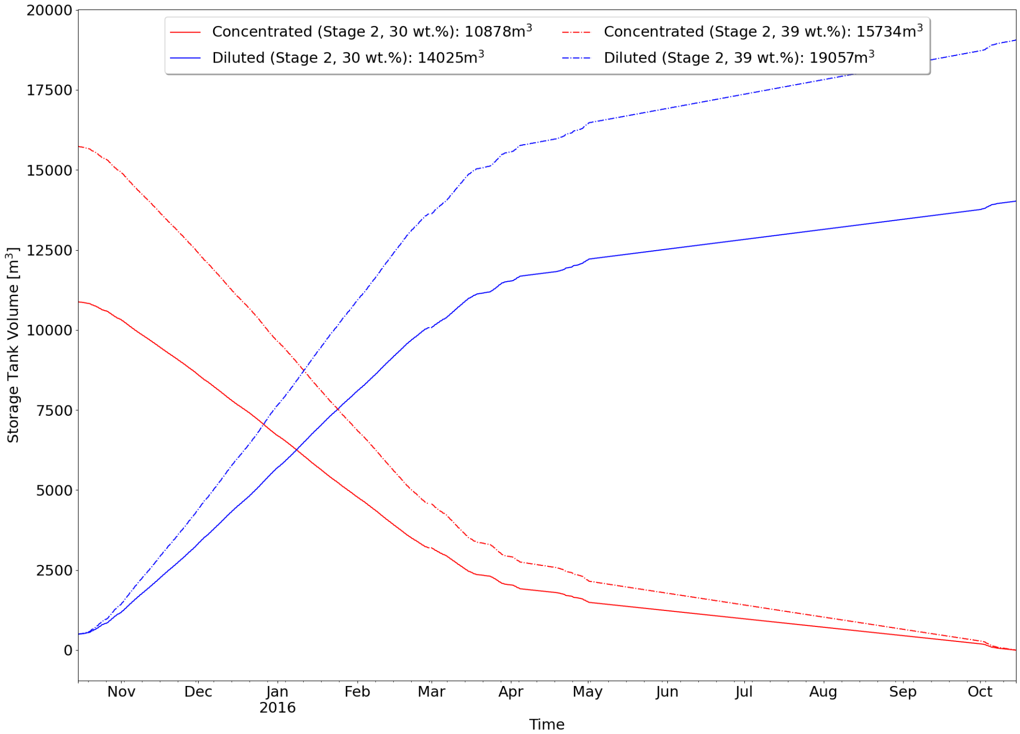

Figure 70. CS2: Concentrated and diluted TCF storage tanks.

The TCN is benchmarked against a hydronic DHN described in Section 3.3.6. In this case, the supply temperature of the DHN is set to 70 °C with a fixed mass flow rate of 6 kg/s during the heating period, and 3 kg/s outside the heating period. This heat is generated by a ground-source HP in which the return temperature of the ground heat exchanger is set to 5°C with a mass flow rate of 30 kg/s. Buried DN80 dual pipes of 1300 m connect the heat supply and demand.

Considering a yearly simulation, Table 7 presents the KPIs estimated for the hydronic DHN, and two scenarios for the TCN. Scenario A, where the diluted concentration of the reactor's Stage 2 operation is limited to 30 wt. %, thereby, an additional mixing occurs in the distribution network and storage tank; Scenario B, where it is limited to 39 wt.% to prevent mixing within the distribution network. The following observations can be made: (i) Thermal losses occurring in the daily buffer tank integrated to operate the reactor in two stages, together with the heat require to saturate the concentrated TCF results in an energy efficiency of 0.78 (Scenario A) and 0.72 (Scenario B). Since in Scenario B there is a higher TCF demand, the higher is the preheating energy and thus, the lower the efficiency. (ii) Regarding the exergy efficiency, a significant difference by a factor of ~9 can be recorded when comparing the exergy efficiency of TCN to the DHN. This is mainly because the TCN does not show any significant electricity demand for circulation or heat generation assuming the same diameter for the piping. In this case, the TCF and the chemical potential it carries substitutes the electric energy needed by the compressor of the electric HP in the DHN case. In addition, in the TCN the heat is supplied at lower temperatures than the DHN (70 °C), closer to the demand requirements, i.e., for the SH with a heating setpoint of 22°C, heat is supplied at ~30 °C, and for the DHW with a requirement of 55°C, the heat is supplied at ~53 °C. (iii) Regarding the COP, the large difference between the TCN and DHN is again due to the low electricity requirements for pumping the TCF and the replacement of the HP's compressor, in the DHN, by the chemical potential, in the TCN. (iv) Finally, regarding the volumetric energy storage density, the difference between the Scenario A and B can be explained by the reduction of the exploitation of chemical potential in Scenario B.

It is important to highlight that, in this case study, the sensible losses occurring in the TCN have no impact on the KPIs thus, limiting the diluted concentration and avoiding unnecessary TCF mixing in the distribution network is only reflected in the reduction of storage density and increment of pumping costs.

Table 7. CS2: Summary KPI

	Hydronic DHN	TCN (Scenario A)	TCN (Scenario B)
Energy efficiency	0.87	0.78	0.72
Exergy efficiency	0.12	0.63	0.56
Electric COP	2.11	60	34.86
Storage density @ΔT=30K [kWh/m^3]	38.5	109.81	79.26
Storage density ratio @ΔT=30K	-	2.85	2.05
Storage density @ΔT=50K [kWh/m^3]	58.33	109.81	79.26
Storage density ratio @ΔT=50K	-	1.88	1.35

4.5.3 Case Study 3

A yearly simulation is solved for the scenario described in Section 3.3.5, using the models described in Section 4.3.5. This is a TCN that serves the SH and DHW residential demand, and the industrial drying process. To this end, the TCF demand and return profiles calculated in Case Study 2, i.e. for SH and DHW, and using the model described in Section 4.3.4, i.e., for the industrial drying process, are integrated to a TCF network consisting in buried pipes of DN80 and 1300m length. A concentrated and a diluted TCF storage tank serve the network, and couple the charging loop i.e., to regenerate the diluted TCF. This loop consists in a charging reactor that exploits the heat generated by a solar collector plant and releases the excess heat to the ambient using an air cooler. Specifically, 4’500 flat plate solar collectors are connected in parallel to deliver the required heat, accounting for a total collector area of 13’500 m^2. This collector area is the minimum needed to allow for a continuous operation with a complete regeneration of the diluted TCF. The azimuth and tilt angles of the collectors are 0.3 and 0.7, respectively.

Figure 71 shows the supply temperature achieved by the solar collector plant across the year, with a maximum of 86 °C during summer. It is important to highlight that the pump of the collector plant is only activated when there is enough power over the collector (10 W/m^2), and the temperature levels in the reactor are suitable to regenerate the TCF (min. temperature difference between ambient and solar collector output temperature). While the simulation reports all the values across the year, when the system is not operating, the temperature follows the ambient temperature.

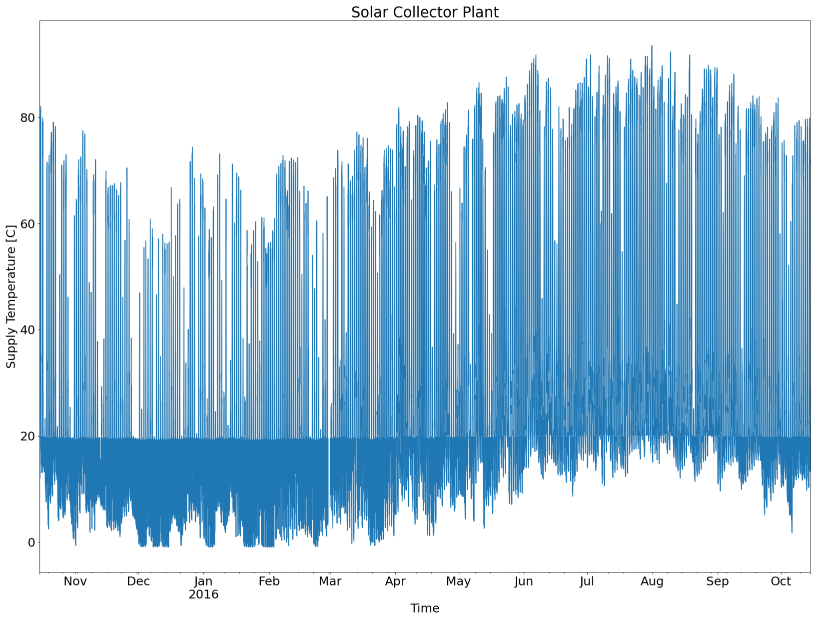

Figure 71. CS3. Solar collector plant: Supply temperature

With the charging conditions described, Figure 72 shows the main operation parameters of the reactor. The maximum mass flow rate that can be regenerated is ~11 kg/s. The charging process occurs continuously throughout the whole year when the solar plant produces enough heat, naturally, more frequently during the summer. The saturation pressure varies between a minimum of 30 mbar during winter, and 162 mbar during summer. Finally, the diluted TCF with a mean concentration of 37.8 wt.% is regenerated to a mean concentration of 44.76 wt. %.

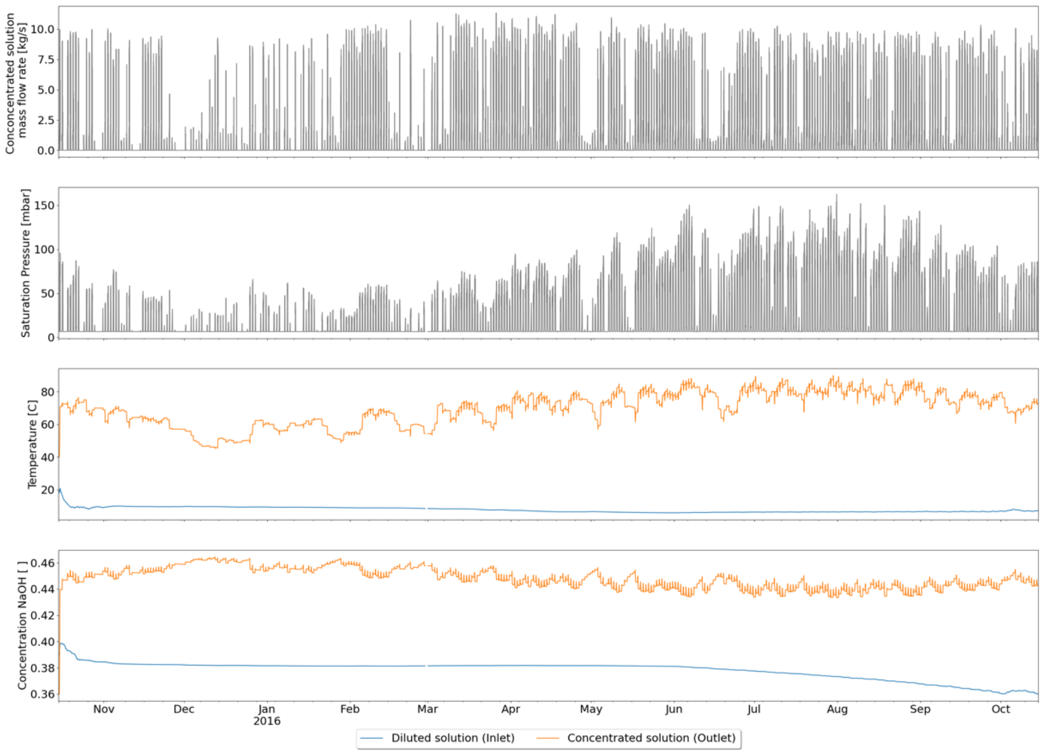

Figure 72. CS3. Charging reactor: key operation parameters

To compare the impact of the continuous charging (vs. intermittent charging) on the TCF storage capacity, the simulation is run with and without charging loop. Figure 73 shows that without regeneration, the concentrated and diluted tanks need to be ~11'500 m^3 and ~15'000 m^3, respectively. These volumes can be reduced by ~50 % when the continuous regeneration loop is integrated, i.e., a concentrated tank of ~5'400m^3 and a diluted tank of ~7'200m^3.

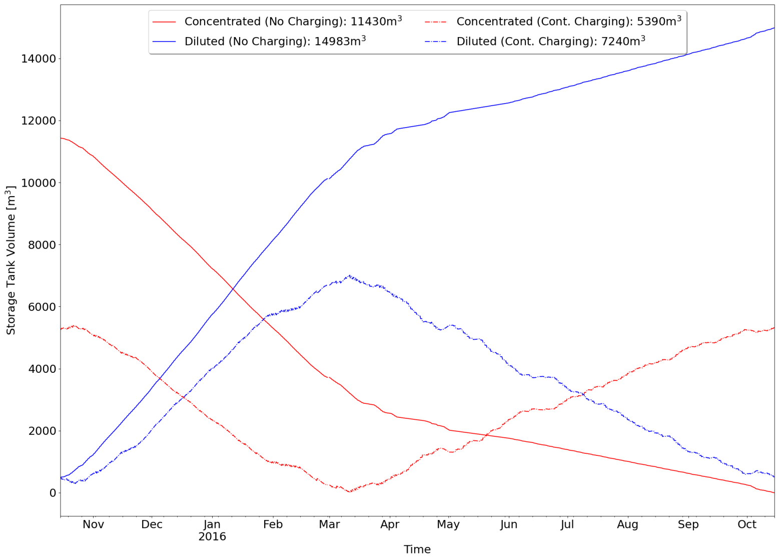

Figure 73. CS3: Concentrated and diluted storage tanks

Figure 74 presents the volume level of the TCF storage tanks across a period of two years. This is to verify that the initial conditions are not affecting the TCN simulation. As it can be seen, the maximum and minimum levels are consistent across the whole simulated period.

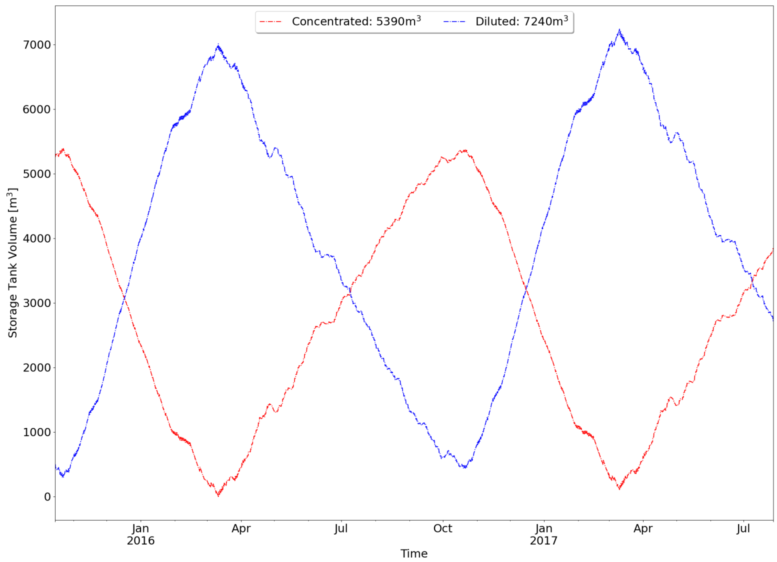

Figure 74. CS3: Two year simulation. Storage tanks state

The TCN case is benchmarked against a hydronic DHN as described in section 3.3.6. Here, the industrial process is assumed to be served by the DHN, delivering the heat required to evaporate the water content from the herbs. To this end, using the drying profile presented in Figure 51, and corresponding initial and target moisture levels, a load profile is estimated (see Figure 75).

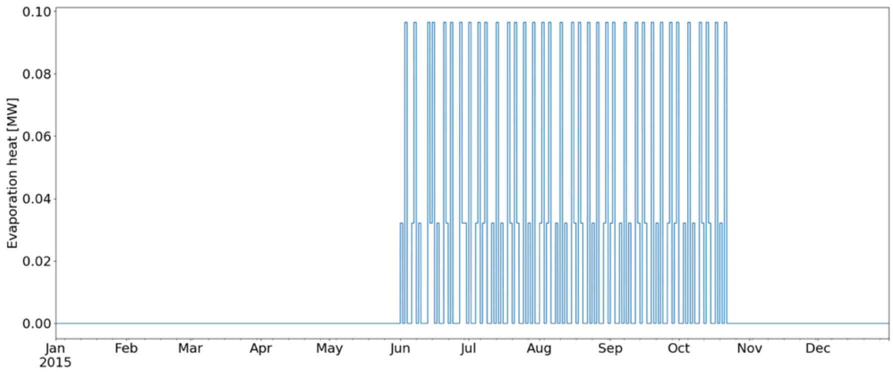

Figure 75. CS3: Heat of evaporation – Industrial drying process

Table 8 presents the summary with the KPIs estimated for each network. The most important difference in relation to Case Study 1 and 2, is the integration of the drying process along with the charging loop. Specifically, by continuously regenerating the diluted TCF, the capacity of the TCF storage tanks can be reduced and thus, the storage density increases. In this case, a ratio between the TCF and DHN storage density results in 3.61 when charging the water storage at 50 °C.
The KPIs in Case Study 3 is still only addressing the discharging part, leaving out the charging phase. This is for the sake of comparability with the classical DHN, where the driving force for the heat generation, i.e. the electricity driving the electric heat pump, is assumed to be received from the grid without any knowledge about its conditions of production. When comparing to Case Study 2, the TCN of Case Study 3 has the same energy efficiency given both cases have the same thermal losses, i.e., from the daily buffer tank to the environment within the double-stage operation to meet the SH and DHW demand. Regarding the COP for both networks, it decreases from 2.5 (DHN) and 290.58 (TCN) in CS1, to 1.99 (DHN) and 25.11 (TCN) in CS3. This can be explained by the increment in the heating demand in each case study, i.e., starting with the SH (CS1), and progressively adding the DHW (CS2), and Industrial Drying process (CS3), which results in an increment of mass flow rates and then pumping costs. (i.e., water for the DHN and TCF for the TCN). Consequently, this also affects the exergy efficiency slightly diminishing in the DHN from 0.13 in CS1 to 0.11 in CS3, and in the TCN from 0.7 in CS1 to 0.54 in CS3. The most important addition of Case Study 3, beyond the scope of the KPIs is the seasonal load shifting enabled through the TCF storage and the integration of local renewables for a regeneration of the TCF, allowing for a 100% renewable fraction of the heat supply.

Table 8. CS3: Summary - KPI

	Hydronic DHN	TCN
Energy efficiency	0.82	0.78
Exergy efficiency	0.11	0.54
Electric COP	1.99	25.11
Storage density @ΔT=30K [kWh/m^3]	38.5	102.70
Storage density ratio @ΔT=30K	2.66	
Storage density @ΔT=50K [kWh/m^3]	58.33	102.70
Storage density ratio @ΔT=50K	1.76	

4.6 Conclusions of WP2 and WP3

- For the analysis of TCN three case studies were defined ranging from a first ideal setup, only addressing space heating, to a more advanced one including space heating and domestic hot water demand, to a full network integration of domestic heat demand together with an industrial application of drying. This threefold analysis yielded valuable insights into possibilities for combining different applications and understanding the influence of the operating conditions on the performance of a TCN.
- The network chosen was based on statistical data for a “small” DHN. The size has little implication for the analysis of TCN and its performance such that it can be seen as representative also for larger networks.
- When comparing TCN to classical DHN, one needs to be aware of the conceptual differences. TCN transport the chemical potential that can be exploited for a local transformation of heat, in the sense of a decentralized heat pump. In contrast to state-of-the-art 5th generation, ultra-low-temperature DHN with electric heat pumps, TCNs feature a chemical heat pump process leading to a very low electricity demand in winter-time during heating.
- The comparison of TCN to DHN was done based on defined KPIs including energy and exergy efficiency, electrical coefficient of performance and volumetric energy storage density. The analysis showed, that generally speaking for TCN higher values for all the defined KPIs are recorded. This is because TCN allow for storage and distribution of a chemical potential that does not involve any thermal losses. Further, it allows for higher volumetric energy storage densities because of the chemical potential that can be used to upgrade environmental heat. With this, it does not act as a heat battery but as a thermal transformer. Because of the latter, much lower mass flows need to be circulated, leading to a significantly reduced pressure loss and pumping cost even at lower pipe diameters.
- The TCN analysis of case two, with space heating and domestic hot water combined, revealed a similarity to classical DHN in the sense that the different requirements lead to different supply and return temperatures (DHN) or concentrations (TCN) and hence a trade-off between exergy efficiency and energy storage density. While for DHN, the elevated supply temperature required by the DHW increases thermal losses and significantly lowers the exergy efficiency, the reduced return temperature from the DHW increases the energy transport capacity of the network and the energy storage density. For TCN, provision of DHW requires a 2-stage process that leads to additional thermal losses and the reduced return concentration leads to loss of chemical potential through mixing processes. When controlled to match return concentrations for both, SH and DHW provision, these losses can be avoided but energy storage density is reduced due to smaller concentration differences.
- For TCNs, the selection of the working fluid is decisive. This is strongly depending on the application and the process chosen, e.g. whether it is the main goal to achieve a high temperature lift in a closed process or to absorb humidity in an industrial drying process or to allow for effective cooling. Furthermore, selected working fluid and temperature boundary conditions are decisive for acceptable maximum concentrations. In case of TCN with NaOH as working fluid the assumed ground temperature of 5°C limited the maximum concentration to 45wt%, avoiding freezing of the working fluid. This concentration also limits the maximum temperature lift achieved in the thermochemical process along with the energy storage density.
- When studying the full network integration with both, discharging and solar charging, it can be observed that charging not only takes place in summer but also in the transitional seasons spring and fall. With this, the total storage volume required can be significantly reduced. For case 3 simulated, storage volume for concentrated/diluted solution is halved, when using continuous solar regeneration.

5 Over-all conclusions

- This project claimed the exploration of the **T**hermo**C**hemical network ec**ology** TCology which was done by means of identifying and analyzing different terminal applications based on thermochemical processes (WP1), evaluating the performance of individual thermochemical applications as well as for their integration in a thermochemical network (WP2, WP3) and understand its applicability by means of a stakeholder and value mapping followed by a SWOT analysis (WP1).
- Bottom line, TCNs offer an effective mean for long-term energy storage without self-discharge such that heat generation in winter is available with minimum electricity (exergy input) such that it can significantly contribute to seasonal load shifting and the overcoming of the renewable supply gap through integration of waste heat and solar energy.
- To the question of what major challenges are and where TCNs should they be applied, the following answers can be given:
    - One of the major challenges is seen in the nature of TCN, in that it is not a centralized, stand-alone solution but requires local equipment for heat generation. In that sense, it is very similar to 5th generation, ultra-low temperature DHN and does not allow for an equally effective roll-out like 1st to 4th generation DHNs. On the other hand, from a social acceptance perspective, the bottom-up approach with local equipment could even be favored over a top-down approach with centralized supply, especially in Switzerland.
    - Another potential drawback of TCNs is the fact that besides the local transformation equipment (chemical heat pump), an environmental heat source with high enough temperatures, such as boreholes, is needed. This generally leads to higher investment cost for the owner of the equipment.
    - A particular challenge for TCN is the limitation of the available temperature lift making the process more suitable for low-temperature applications and thus better performing for low-energy buildings. The possibility of multi-staging opens its applicability for higher temperature applications but with a penalty on the level of performance and investment cost. These limitations are similar for classical DHNs when electric heat pumps are being applied but more expressed for TCNs.
    - TCNs are an alternative solution to conventional DHNs with the above-mentioned benefits and challenges. An ideal implementation would be a combination of requirements on the demand side such that both, closed and open sorption processes could be leveraged. An example is given in case 3, where industrial drying is made more effective and efficient using a thermochemical process. In any case, TCN is interesting when emphasis is put on heat supply with high renewable fractions and low electric demand peaks in winter.
    - When looking at the cooling application in buildings there are some chances for the application of TCN. With closed sorption processes, space cooling can be provided with potential exploitation of generated heat for simultaneous DHW production. Open sorption process also allows for cooling with the additional possibility for humidity control. To this end, a combination of evaporative cooling is used together with an open absorption process.

- Further insights regarding requirements for applicability of TCN in practice were gained through a stakeholder workshop. There, the biggest advantages of TCN were seen by the reduced space requirements for the piping and the consequently reduced investment cost along with the ability to provide cooling at low temperatures. Potential investor groups identified include industrial companies with cooling needs, current thermal grid developers/operators, and the public sector (such as municipalities). The public sector's role is seen crucial in facilitating TCN adoption through municipal energy planning.

6 Outlook and next steps

This project was laying the corner stone for the exploration of TCN and to better understand its potential in combination with different terminal applications. Further, it presented clear performance comparison to classical DHN based on most relevant KPIs. Nevertheless, there are remaining open questions for further research and evaluation together with partners from practice. Remaining questions and potential next steps comprise:

- Extension of theoretical analysis based on synthetic cases to real network cases with measured demand data, featuring more detailed application clusters with specific requirements in terms of energy demand and supply and return temperatures.
- Extension of comparison of TCN to DHN including different network generations, i.e. 5th generation, ultra-low-temperature networks along with additional analysis of cooling application (space and commercial cooling).
- Based on specific use cases with potential grid operators and customers possible designs for TCNs would need to be defined for a subsequent analysis of the economic feasibility. The latter would have to include cost estimates for network, including fluid, piping, installation as well as the terminal application components. The reliability of cost estimates of novel terminal application components is challenging because of the rather low TRL. Also, there are some novel components that are not explored yet in detail, e.g. sorben circulation pumps, that are different to today available commercial pumps because of altered reuqirements. Here, more research will be needed.
- Future research should focus on developing viable multi-actor business models and industry standards to foster TCN commercialization.

7 National and international cooperation

During the duration of this project there was an ongoing colaboration with the SFOE SWEET research project DeCarbCH. This entailed the exchange with other research groups doing research on the level of DHNs. Among others, the definition of the network case considered here (case 1 to case 3) was moderated within the DeCarbCH consortium. As the SWEET project activities continue throughout 2028 the work done in this project will be used as a basis for further research therein.

Another related research project is the Innosuisse flagship project SwissSTES (2024-2027) with a focus on seasonal thermal energy storage. There, research on the level of TCN is being continued, partly carrying on the activity of this project.

8 Publications

Baldini, Luca; Zambrano, Juan Mahecha, 2023. Thermochemical storage networks for integration of renewable energy sources through seasonal load shifting. Journal of Physics: Conference Series. CISBAT International Conference, Lausanne, Switzerland, 13-15 September 2023. IOP Publishing. https://doi.org/10.1088/1742-6596/2600/4/042001

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