Peak shaving district heating system for daily and seasonal demand (**Heat-land**)

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Nomenclature

BTES	Borehole thermal energy storage
CAPEX	Capital expenditures
CEPCI	Chemical Engineering Plant Cost Index
CHP	Co-generation Power Plant
DHs	District heating systems
E-boiler	Electrical boiler
HP	Heat pumps
HW	Hot water
LCOH	Levelized cost of heat
LCOS	Levelized cost of storage
OPEX	Operating expenditures
SOC	State of charge
RES	Regional Energy Strategy
TCES	Thermochemical energy storage
TES	Thermal energy storage
TCM	Thermochemical material
PCM	Phase change material
P2H	Power-to-Heat

T_{11}	Primary supply line temperature
T_{1}	Primary return line temperature
T_{21}	Secondary supply line temperature
T_{22}	Secondary return line temperature

Chapter 1

Introduction

The Climate Act sets ambitious climate targets for the Netherlands. By 2050, the goal is to reduce greenhouse gas emissions by 95% from the 1990 levels. In order to achieve that goal it is the intention of the government that, by 2030, the Netherlands will reduce greenhouse gas emissions by 55% compared to 1990 and that electricity production will be completely CO_2-neutral by 2050. The government is taking steps to decarbonize the thermal energy sector, which includes implementing measures to reduce emissions in district heating systems (DHs).

DHs are centralized heating networks that utilize multiple heat sources to generate energy to heat up a fluid, usually hot water flow, which is efficiently distributed through pipelines to residential, commercial, and industrial consumers.

There are two main heat sources utilized in the DH system in the Enschede area: a cogeneration power plant (CHP) and a natural gas-fired boiler. An efficient CHP plant is used as the DH system's base load heat source, while a natural gas-fired boiler is used to supplement the heat supply for peak load. The usage of peak-load heat sources is linked to natural gas consumption, and efforts are being directed towards their reduction. This will lead to a consequent decrease in carbon emissions related to natural gas consumption. This objective can be realized through the implementation of thermal storage systems.

Thermal energy storage (TES) technology offers a solution to the energy generation-demand mismatch by storing excess thermal energy for later use. TES can lower the operating costs of DHs by reducing the need for less efficient and expensive energy sources during peak-load periods, while efficient heat sources like CHP can be utilized. This study is focused on DHs analysis and thermal storage system design in the Enschede region to improve the energy efficiency of DHs by reducing peak-load heat source usage.

1.1 HeatLand Project Introduction

The HeatLand project focuses on several key areas of research, including the implementation of the thermal storage system in DHs in general and thermochemical energy storage (TCES) in particular as well as the use of residual heat from industries. This project explores the development of TCES systems as a potential solution for DHs to support peak-load demand and provide extra buffer storage capacity for the utilization of residual heat from industries. Thus, the dependence on fossil fuels in heat generation for peak load can be reduced, and the sustainability of DHs can be improved.

The University of Twente (UT) works with several industry partners to develop TCES systems in the Enschede area. While TCES is still a relatively new and emerging technology, the HeatLand project is helping to advance its development and application in DHs. This project involves designing TCES systems and evaluating their feasibility in both the 3rd and 4th generation of DHs.

Twence B.V. is a leading company in the fields of waste management and energy production. It is committed to contributing to a more sustainable future by turning waste into valuable resources. Twence B.V. uses waste heat from its waste-to-energy plants to generate steam, which is then used for DHs as an efficient heat source. By using waste heat to provide DHs, Twence B.V. can reduce the use of fossil fuels that would otherwise be needed to provide heat to these buildings.

Ennatuurlijk B.V. operates several DH networks in the Netherlands to supply heat to thousands of customers in urban areas, reducing their reliance on fossil fuels and contributing to a more sustainable energy system. The network in the Enschede area uses residual heat from a waste-to-energy plant owned by Twence. Ennatuurlijk also implemented hot water storage as part of its DHs to improve the flexibility of its operations. This helps Ennatuurlijk reduce its reliance on natural gas and optimize its use of efficient energy sources.

1.2 Problem statement and design goal

The existing DHs require long-term TES to deal with weekly and monthly peak load demand, ensuring sustainable utilization of heat sources and further reducing their dependence on peak-load heat sources. However, the current thermal storage infrastructure is designed for short-term use, resulting in high heat losses. Moreover, the expansion of storage capacity for short-term TES is limited by the available space in urban areas. To address this issue, the use of TCES technology has shown promise due to its low heat loss over a long period of time and small footprint requirements for large storage capacity. Nevertheless, compared with sensible thermal storage technology, implementing TCES in DHs poses challenges due to its low response time, low thermal power output, and requirement of specific operating conditions. Therefore, there is a need to develop a methodology to analyze the feasibility of TCES in a specific condition of DHs.

The design goal of this project is to develop a comprehensive methodology that assesses the feasibility of integrating TCES technology into DHs in the Enschede area. This methodology should consider the unique challenges posed by TCES, such as its low response time and specific operating conditions. Additionally, the design aims to explore efficient coordination between heat production and storage to improve peak load management within the DHs. Ultimately, a thermal storage system is designed that can eliminate the reliance on natural gas-fired boilers, thus achieving a more sustainable utilization of heat sources for DHs in the Enschede area. To study TCES implementation in DHs, the following design questions will be addressed:

i: What is the key to the coordination between the heat source and thermal storage, and how does it correlate to the reduction of peak load generation within DHs?

ii: How does long-term TES accommodate sustainable heat source utilization? And what are the key challenges associated with implementing long-term TES technology (focusing on TCES in this study) in DHs?

iii: What is a suitable methodology to be developed to analyze the feasibility of integrating TCES technology into DHs, taking into account its unique challenges?

iv: What is the economic performance of a TCES system in DHS, and which design parameters and cost components in a TCES system have a significant impact on the economic performance?

1.3 Outline of report

The design project starts with the identification of design goals, considering stakeholder perspectives. In Chapter 2, an analysis of stakeholder needs across three hierarchical levels—government, municipality, and utility—is presented. This is followed by a literature review and benchmarking in Chapter 3. Furthermore, an assessment of the current operational status and condition of targeted DHs is conducted to establish a baseline. Simultaneously, an exploration of potential thermal storage technologies aligned with the design goals is undertaken. Chapter 4 focuses on the model-based analysis approach, serving as the main methodology. The section elaborates on the development of a model for the selected technology.

Chapter 2

Stakeholders need analysis

It's crucial to identify the needs and desires of stakeholders to provide practical design solutions. This study examines the broad scope and narrow focus of the need for two stakeholders, Twence (heat supplier) and Ennatuurlijk (DHs operator). The stakeholder's needs and wishes are analyzed from three hierarchical levels. Based on these findings, design requirements can be established, thus a design concept is proposed to overcome any obstacles.

DH is recognized as playing a crucial role in Europe's successful energy system transition. In the Netherlands, the energy system transition in DHs involves participation from various roles across three hierarchical levels: government, municipalities, and utilities. At the government level, the Dutch Climate Policy proposed the National Climate Agreement as the central goal to reduce greenhouse gas emissions by 49% by 2030, compared to 1990 levels. Additionally, it aims to increase the share of renewable energy by at least 32% and to enhance energy efficiency by at least 32.5% by 2030 compared to the 1990 data. At the municipality level, the Regional Energy Strategy (RES) [1] was then developed to provide an optimal approach to align the climate goals for each region while considering regional plans and development. At the utility level, the municipalities in the region collectively collaborate to establish a joint ambition with local utilities for their regional energy transition plan [2].

2.1 Government level - Energy transition in the thermal sector via District heating system

The energy consumption of low- and medium-temperature heating demand was 43% of the national total energy demand, as indicated in Figure 2.1. For older buildings, traditional natural gas central heating boilers were still the primary heat source. However, new regulations have been put in place so that small-consumer buildings that apply for environmental permits after 2018, such as households or apartments, cannot be connected to natural gas networks in areas where alternative energy infrastructure is available, such as DHs (RVO, 2018)., unfolding the rapid growth on DHs.

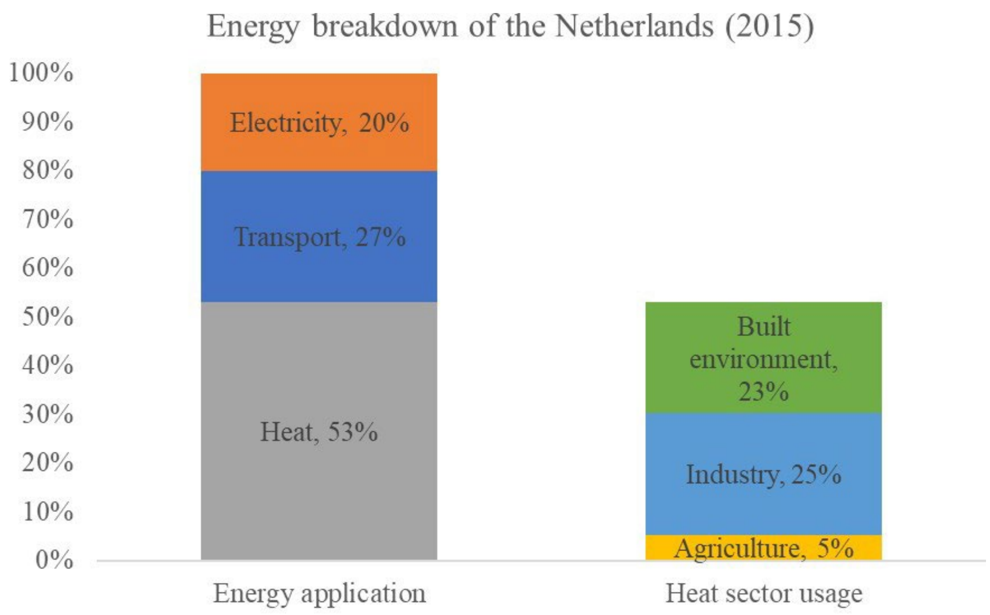

Figure 2.1: Energy breakdown of the Netherlands in 2015 (based on data from CBS, 2015).

Based on the projected increase in DH connections in the Netherlands, it is expected that the heating demand will reach 40 PJ by 2030. Heat suppliers of DHs are aiming to achieve an average reduction of 70% in carbon emissions by 2030, in comparison to current natural gas central heating boilers. This will result in a reduction of carbon dioxide intensity of the heat supplied by district heating grids to 18.9 kg of CO_2/GJ . To accommodate the increased heat demand from consumers in DHs, there is a need to enhance energy source sustainability and improve system flexibility.

2.2 Municipality level - Decarbonization of district heating network

The Regional Energy Strategy (RES) outlines the shared ambition of decarbonization among municipalities for regional energy transition, containing the supply of electricity, gas, and heat up to 2030. In RES Twente 1.0, the primary objectives are focused on the development of green electricity and the establishment of a regional heat network in urban areas. The preferred technologies for sustainable electricity generation are wind power and solar power for the Twente region. Figure 2.2 and Table 2.1 illustrate the collective aim of generating green electricity from the region (30 RES) and the local city of Enschede, respectively.

There are currently 280,000 homes in Twente heated with natural gas. Figure 2.3 shows the current and future ambition of the DHs network. It is expected to connect 100,000 homes to the heat network. Enschede’s Transition Vision outlines a goal to remove natural gas from all districts by 2050, resulting in a significant reduction in CO2 emissions.

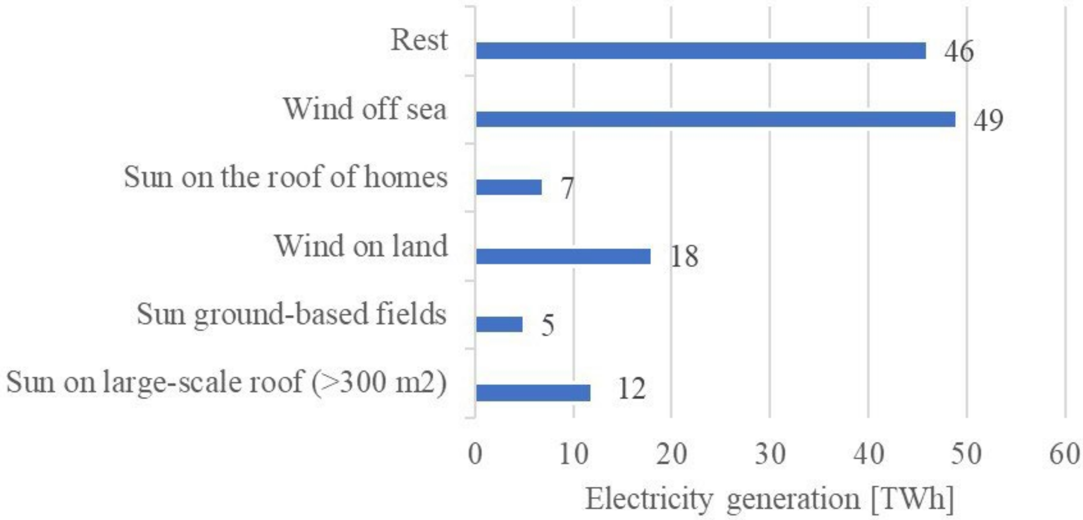

Figure 2.2: The goal of electricity generation contributed from all 30 RES in the Netherlands, including 12 TWh from the sun on the roof (> 300 m^2), 18 TWh from the wind on land, $5\,TWh$ from the sun on the ground fields, 7 TWh from the sun on the roof of homes, 49 TWh from the wind off the sea, and the rest of 46 TWh (Adopted from RES Twente 1.0).

Table 2.1: The ambition of Enschede to generate a total of 193 GWh of sustainable electricity

Provision of electricity via	Units	Electricity
PV on the roof	59 hectare	62 GWh
PV on fields	128 hectare	93 GWh
Wind turbine	3 pieces	38 GWh

2.3 Utility level - Robustness of heat supply and peak load management

Twence is the heat supplier for the DHs in the Twente area. The principal wishes and needs for Twence are ensuring the security of the heat supply and a transition to sustainable heat generation. As DH network is expected to expand following the municipality's heat transition plan (RES Twente 1.0), Twence's wishes include fulfilling the increasing scale of DHs in the Twente area. However, the scaling up of DHs may deteriorate the mismatch between heat generation and demand, and the current DHs pipeline network's transport capacity may limit

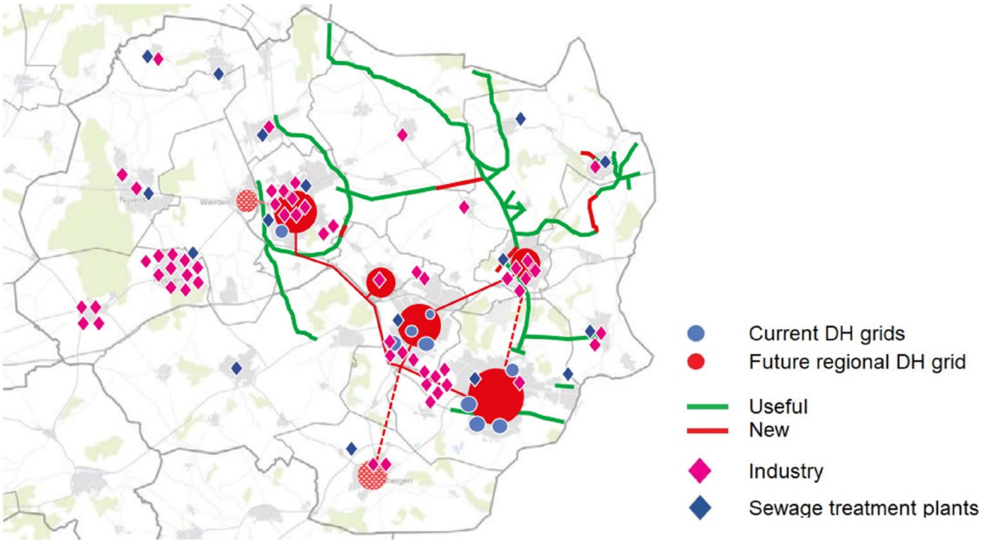

Figure 2.3: Twente future regional district heat network. Adapted from RES Twente 1.0 [1].

the amount of heat transferable at the same time. To address this issue, a promising solution is the implementation of thermal storage in the DHs, which can reduce the mismatch and prevent high thermal power loading during peak times. While this solution is currently being applied in the Enschede area, further research is required to comprehensively advance its effectiveness and potential impact.

Another approach that can be taken is using sustainable and cheap heat sources. There are several sustainable energy sources available, such as heat recovery from industrial processes, and power-to-heat from green electricity, which can be harnessed for heating purposes. The greater interconnectivity of DHs among heat consumers and heat suppliers catalyzes the adoption of sustainable heat sources. This is facilitated by the well-developed infrastructure such as underground pipe networks situated near factories or industrial sites. This configuration proves advantageous for promoting sustainability, benefiting not only heat consumers but also contributing positively to the industries involved.

Ennatuurlijk, like many other utility companies, faces the challenge of peak load management. Twence provides the baseload demand, and when there is a peak load, Ennatuurlijk's backup peak load boiler compensates for the gap in heat demand. Currently, natural gas-fired boilers are used for peak load generation, which is expensive and emits high levels of greenhouse gases. Ennatuurlijk has expressed a desire to phase out the use of these gas-fired boilers. To achieve this goal, the operation hours of the boilers can be reduced by utilizing thermal storage. The excess heat is stored in thermal storage when the demand is low so that the peak load demand can be met using the stored heat. The coordination between Twence's baseload heat supply and Ennatuurlijk's thermal storage management has been established and in operation for years. However, simply reducing the operation hours of the boilers is not enough to meet the goal of emission. Ennatuurlijk must also improve peak load management via various thermal storage technologies.

2.4 Case study of DHs in Enschede area

In this Section, the current status of DH operation in the Enschede area is presented.

Domestic heat demand profile

The target consumers of DHs in this work are domestic houses and buildings. The composition of domestic heat demands mainly comes from space heating and hot water. The demand profile is different in location, weather, and human behaviors. To specify the local condition, the heat demand profile analyzed in this work is derived from raw data obtained from a heat substation in the Enschede area. The raw data was measured in 2019 and consists of the hot water flow rate and the temperature difference between the inflow and outflow of the substation. This data set is correlated with the environmental temperature in the same period to obtain the heat demand profile for the simulation purpose. For instance, the nominal peak demand is 1800 kW when the outdoor temperature is at -3 °C. The results of the heat demand profile are 5159 MWh annual accumulative heat demand out of 458 buildings with an average of 120 m^3 of living space.

Heat generation for baseload

Twence b.v aims to utilize the heat produced from a cogeneration heat and power plant (CHP) to directly meet the heat demand in the DHs. The heat supply to DHs is based on the agreement with Ennatuurlijk, who estimates the heat demand in advance and requests the desired power from Twence. The CHP owned by Twence serves as the baseload heat source. For simulation purposes, the heat generation schedule profile for CHP is predicted by assuming the average heat demand within each month, as indicated in Table 2.2.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Power [kW]	1136	1065	923	426	355	107	107	107	284	604	852	1136

Table 2.2: Monthly variation of heat generation schedule profile for CHP

Peak load demand management

Currently in the DHs, when the heat demand exceeds the baseload from CHP, natural gas-fired boilers operated by Ennatuurlijk are used. Ennatuurlijk’s primary challenge is phasing out this gas-fired heat source for peak demand. To facilitate the peak load demand, a hot water storage tank with 200 m^3 of water, equivalent to 6000 kWh capacity, was installed in one of the substations in the Roombeek community. During periods of surplus heat in the DHs, such as at night, the heat energy is stored in the hot water storage. The stored heat can then be used during peak load times, such as in the morning or evening. However, it is observed that boiler generation will be needed again when the storage has been fully depleted. This observation highlights the impact of the storage system operation and the selection of storage capacity, which is a challenge in peak load management.

Thermal storage operation

Normally the heat demand fluctuates more than the heat generation schedule, and a mismatch between the two may occur, resulting in two situations: surplus heat generation during low demand and insufficient heat generation during high demand, called overgeneration and under generation, respectively. During an overgeneration situation, the surplus heat from CHP generation will be injected into the hot water tank to store the excess heat as long as there is sufficient space in the storage. Conversely, during under generation periods, the storage will discharge the stored hot water to support peak load and stop discharging when the peak demand period is ended or the water level in storage has been depleted. This observation highlights the significance of studying the connection between peak load management and storage system control, making it a worthwhile area of research.

To sum up, from the case study investigation, Twence is currently the only baseload heat supplier in the Enschede area. With more sustainable heat suppliers joining for baseload supply in the future, it can be beneficial for heat supply robustness and align with the government climate goal of the energy transition. The potential heat suppliers of sustainable heat sources is discussed in Section 3.1. The thermal storage system installed in the Ennatuurlijk-owned substation has helped to mitigate the peak load demand. Even though there have been efforts to address the issue of peak load demand, it is not feasible to only rely on single hot water storage to eliminate the peak generation. Our simulation results, presented in a later section (Section 4.1.2), support this conclusion. It highlights the importance of long-term storage implementation. which is discussed in Section 3.2

Chapter 3

Literature review - Design requirement and concept

To specify the design requirement, the challenge beyond the stakeholders' wishes has to be clarified first. Afterward, the wishes of stakeholders could be accurately translated into design requirements and indicators for feasibility analysis. The design concept of sustainable heat source utilization is researched in Section 3.1. The candidate of thermal storage technologies will be reviewed in Section 3.2.

3.1 Sustainable heat source in Enschede area

The motivation behind exploring sustainable heat sources in Enschede's DHs is driven by the urgent need to reduce peak generation, accelerate the energy system transition, and secure the heat supply. In our quest for these objectives, we explored four promising technologies: solar-thermal, hydrogen fuel, power-to-heat (P2H), and industrial heat recovery. The selection of candidates for sustainable heat implementation in the DHs is highly dependent on their characteristics and compatibility with other components in DHs. Solar-thermal faced challenges from the weather-dependent characteristic, while hydrogen demanded a vision for a future hydrogen-based energy system. P2H's easy implementation and versatility made it a standout. Industry heat recovery offered simplicity and direct use of existing heat sources, further enhancing our goal. Ultimately, P2H and industry Heat Recovery emerged as our final selections. The explanation is detailed in the following section.

Solar-thermal technology uses sunlight directly with solar collectors to generate heat, but the space for the installation of collectors and the need for significant energy storage capacity are limiting factors for economic viability [3]. Finding suitable sites for large-scale solar thermal projects in Enschede can be challenging, particularly considering competition from roof-mounted solar PV systems, as highlighted in the RES Twente document [1].

The intermittency and seasonal fluctuation of solar irradiance are the challenges for solar thermal systems. Although combining long-term TES with solar-thermal systems can facilitate such issues, an extra temperature boost technique might still be required to lift the temperature level of long-term TES to the desired level for DHs [4]. Moreover, integrating the dynamic variation of temperature in solar thermal systems, advanced control strategies, and the integration of different heat transfer components are needed since DHs operate relatively in constant and stable temperatures. Managing these temperature variations and meeting diverse heat demands efficiently is a complex task. In [5] it is stated that frequent on-off control of the solar circulation pump to manage the temperature level could significantly reduce the system's performance due to the high annual electricity consumption. Furthermore, situations characterized by relatively low solar fractions may acquire additional long-term storage installations, and this configuration is better suited for newly constructed energy-efficient residences [6].

Hydrogen fuel can be used as a clean energy carrier, where hydrogen is produced using renewable electricity. The green hydrogen can be utilized for heat demand in DHs, acting as a good alternative to natural gas for DHs [7]. One of the promising concepts is power-to-hydrogen in DHs to achieve energy integration among the power and thermal sectors [8]. For example, by using low-temperature electrolysis, high production, and cheap electricity in summer can be used to produce hydrogen. This system matches well with the goal the RES Twente 1.0 in increasing the share of green electricity production. The waste heat of hydrogen production can be recovered and supply the base load in DH. However, such a system is more suitable for future DHs in low-supply temperatures since the limitation of temperature levels from waste heat from hydrogen cells [9].

The implementation of hydrogen-based DHs requires the creation of a dedicated hydrogen infrastructure including production facilities, storage tanks (or underground storage), pipelines, and distribution networks. This infrastructure development comes with substantial costs and a prolonged timeline. A case study by [10] delves into underground hydrogen storage in the Netherlands, revealing that the most significant determinants affecting the Levelized Cost of Heat Supply (LCOHS) is the investment in cushion gas and electricity expenses. Notably, cushion gas investment stands out as the primary cost factor within the LCOHS, accounting for 76% of the total levelized cost in scenarios involving one complete cycle of injection and withdrawal per year. Another research [11] concluded that minimizing energy losses during hydrogen production, and distribution in the form of waste heat between 50 °C and 90 °C is crucial for achieving cost-effectiveness and sustainability

Power-to-heat (P2H) is a transformative energy process that involves converting surplus electricity, often from renewable sources, into heat energy. This concept enables the efficient utilization of excess power by directing it into heating systems, thereby promoting energy integration and grid stability [12] [13]. Applying P2H technologies, specifically heat pumps (HP) and electrical boilers (E-boiler), for DHs offers both potential and obstacles. When it comes to addressing peak load in DHs, E-boilers tend to be more promising than heat pumps. E-boilers offer immediate heat output and can quickly respond to changing heat demand. They provide reliable and precise control, making them suitable for managing peak load periods where high heat output is required promptly [14]. HP, although efficient during normal load conditions, may struggle to provide sufficient heat output during peak load situations due to its dependence on external heat sources for the evaporator and its slower response times. The uncertain supply of low-temperature heat sources for HP, for instance, if it is too cold or its temperature fluctuates significantly, will reduce the output temperature of the condenser thus limiting its thermal performance [15]. Moreover, the relatively low operational hours in peak-load make the heat pump not financially attractive. Instead, an HP is more suitable for baseload supply to avoid frequent ON/OFF switching [16]. Thus, the E-boiler is the optimal option for a sustainable heat supply, particularly for peak load periods.

Industrial heat recovery for DHs benefits from the presence of existing heat sources within industrial processes. By capturing and utilizing residual heat from industrial operations nearby, it becomes relatively straightforward to integrate this recovered heat into DHs. The adoption of residual heat in DHs is expected to expand significantly with the transition towards 4th generation DHs [17]. In 4th generation DHs, harnessing surplus heat at 55°C has the potential to effectively double the available excess heat resources for DHs. This opens up the opportunity for industrial facilities situated within approximately a few km of DH zones to actively contribute heat to the DHs, consequently enhancing the energy efficiency of the system for industries as well as the DHs.

The industrial residual heat is a predictable and reliable heat source that can be harnessed for DHs. Unlike renewable energy sources that depend on weather conditions, industrial residual heat can be utilized via on-site heat exchangers and lifting the heat to higher temperatures utilizing HP [18]. However, heat recovery from industries also presents certain challenges. The insufficient public information on the quality and quantity of the waste heat sources hinders its implementation in DHs [19]. The low willingness to participate in heat recovery measures in industries can be another challenge due to the concern of disruption to their primary processes or the possibility of compromising their operations.

3.1.1 Exploration of heat recovery from industries

To identify the potential residual heat from industrial processes, a method is used that primarily examines the flow conditions, including temperature and the type of thermal carrier being used. The low- and medium-temperature heat streams operating within or below the range of 100 °C are optimal for DHs due to the similarity with DHs supply temperature. Regarding the types of thermal carriers, both liquid and gaseous streams are preferable for matching the existing distribution system of DHs. Applying these criteria, four candidate companies/industries in the Enschede area have been identified: Thales, AkzoNobel, Vredestein, and local supermarkets. These companies have the potential to contribute to DHs through the recovery and utilization of residual heat from their industrial processes.

Thales is a technology company and its operations involve a wide range of industrial processes, such as manufacturing electronic components, and systems integration. These processes often involve machinery, electronics, and various thermal processes, which could potentially generate waste heat suitable for recovery. Moreover, Thales demonstrates a strong willingness to embrace heat recovery approaches in their operations. Since 2022, Thales has deployed an energy usage and efficiency plan [20]. Through ongoing projects in Toulouse and Blagnac, as well as in Elancourt, Thales aims to harness the waste heat generated by data centers to provide heating for all buildings on the site. By identifying specific heat streams within Thales' operations, it is possible to assess their temperature profiles and compatibility with DHs.

AkzoNobel is a multinational chemical company specializing in paints, coatings, and specialty chemicals. Their operations cover a diverse range of industrial processes, including production facilities for paints, coatings, and chemical intermediates. These processes often involve high-temperature reactions and heat-intensive operations, which may generate residual heat that can be recovered and utilized for DHs purposes. AkzoNobel demonstrates a strong commitment to sustainability through its emphasis on recycling and reusing processed water [21]. Cooling purposes account for approximately 78% of their water usage. To effectively manage wastewater, AkzoNobel employs on-site treatment plants. By implementing appropriate water treatment and adjusting formulations, they successfully reuse water within their plants. These efforts highlight the potential for AkzoNobel to explore and capitalize on residual heat recovery in their operations. However, finding adequate data sources can be challenging.

Vredestein is a tire manufacturing company known for its high-quality tires and rubber products. The tire manufacturing process involves various stages, including mixing, extrusion, curing, and finishing. These stages typically require significant energy inputs and generate heat as a byproduct. However, finding adequate data sources can be challenging.

The local supermarket represents a candidate for residual heat recovery due to its refrigeration and cooling systems. Supermarkets rely on refrigeration systems to maintain the freshness of perishable goods, such as fruits, vegetables, and dairy products. These cooling systems generate excess heat that can be captured and repurposed for DHs. The advantage of the local supermarket in residual heat recovery lies in its stable availability. Supermarkets operate consistently throughout the year, maintaining a continuous demand for refrigeration to preserve perishable goods. As a result, the excess heat generated from the supermarket's cooling processes is readily available consistently. This stable availability of residual heat ensures a reliable and consistent heat source for DHs, contributing to the overall efficiency and stability of the system. Another advantage of heat recovered from the supermarket is its minimal impact on the supermarket's original process. Heat recovery from refrigeration systems is typically achieved through the use of heat exchangers or heat pumps, which extract residual heat without interfering with the primary cooling function. This means that the supermarket's ability to maintain appropriate temperatures for its products remains unaffected, allowing the business to continue its operations without compromise.

By capitalizing on these advantages, the local supermarket becomes an attractive candidate for DH applications among all chosen candidates. Given its widespread presence in urban areas and similar cooling systems between supermarkets, accessing residual heat is straightforward, enabling both quantitative and qualitative identification of its potential. Moreover, the ease of duplicating and scaling up the residual heat recovery system in supermarkets further enhances their suitability as reliable heat sources for DH networks. According to RVO data collection [22] adopted in June of 2023, there is potential for residual heat from local supermarkets. The original refrigeration cooling process in supermarkets generates residual heat at temperatures ranging from 30 to 45 °C, amounting to 1.83 $TJ/year$ for a specific supermarket in the Enschede area. By employing a heat pump for temperature lifting, this heat source can be elevated to a suitable range of 60 to 80 °C, providing a total of 2.33 $TJ/year$. These temperature levels are ideal for DHs. To facilitate simulation, the yearly residual heat energy is translated into a daily profile, presenting as 110 kW during the daytime and 38 kW at night over a year. This profile serves as an external heat source for our DH models. Our focus is to assess the energy utilization of this residual heat through our designed storage system and evaluate its potential for reducing peak loads. However, during the economic analysis, it is important to consider the electricity requirements of the heat pump used for temperature lifting. Further details on the economic analysis can be found in Section 6.2.

3.2 Long-term TES implementation

3.2.1 Cooperation between long-term TES and other components

Thermal energy storage (TES) can be categorized into short-term TES and long-term TES based on the duration for which energy is stored. Short-term TES typically involves storing energy for relatively brief periods, often within the span of hours to a day, to address immediate demand fluctuations. In contrast, long-term TES stores energy over more extended periods, ranging from weeks to months, to accommodate seasonal variations. Long-term TES serves a crucial role in complementing the short-term TES's storage capabilities within DHs. While short-term TES addresses immediate peak demands and short-term heat surpluses, long-term TES is responsible for storing surplus heat over extended periods with low heat losses. Combining short-term TES and long-term TES can balance the energy supply and demand more effectively. However, coordinating these two different technologies in connection and control strategies poses a challenge. The main difficulty arises from their incompatible response time and nominal power. To address this issue, several studies have explored different system configurations. For instance, Sibbitt et al. (2012) [23] used hot water storage (function as short-term TES) and borehole (function as long-term TES) in solar DHs, transferring heat from borehole storage to hot water storage when needed, and using a gas boiler as a temperature booster. Similarly, Rosato et al. (2020) [24] charged borehole storage from hot water storage during low-demand periods and discharged it to maintain the temperature level of short-term TES. Renaldi et al. (2019) [25] used hot water storage as a hub to connect other systems, including solar collectors, long-term TES, and heat demand loops. The long-term TES serves as backup storage to ensure sufficient energy is available in the short-term TES, reducing the need to operate the backup boiler. These studies suggest that long-term TES can contribute to daily or weekly heat demand, not just function as seasonal storage, making it possible for short-term TES to select its storage capacity based on average heat load instead of peak load.

The integration of long-term TES becomes even more significant when coupled with industrial heat recovery. A large storage capacity is essential for supporting the continuous availability of residual heat. By having a substantial storage capacity, excess heat recovered from the supermarket can be stored during periods of low heat demand and utilized during peak demand. This effectively maximizes the utilization of residual heat resources, optimizing energy efficiency and reducing potential heat wastage. This synergy between long-term thermal storage and industrial heat recovery allows for enhanced peak load management and optimized utilization of residual heat resources, supporting the sustainability and reliability of DH systems.

3.2.2 Selection of long-term TES for district heating application

Recognizing and differentiating the functions of long-term thermal storage is vital for the se- lection of suitable technology as it impacts energy allocation, control strategies, and design decision-making. The aforementioned functions for long-term TES include large storage capacity, low heat losses, and more critical, compatibility with the existing short-term TES (hot water storage) in DHs in our case. When comparing long-term thermal storage techniques for DH applications, several options stand out, including borehole thermal energy storage (BTES), phase change materials (PCMs), and thermochemical energy storage (TCES).

BTES is a mature technology that utilizes the thermal energy stored in the ground. It offers significant storage capacity but requires a large footprint, making it challenging to implement in urban areas where space is limited. Additionally, BTES systems have higher installation and maintenance costs, which can hinder their widespread adoption in DHs.

PCMs, on the other hand, provide an optimal option for long-term thermal storage. PCMs can store and release thermal energy during phase transitions, such as solid-to-liquid or liquid-to-gas transformations. This characteristic allows them to store energy over extended periods with low heat losses. They have the advantage of high energy density and can store and release heat at a specific phase change temperature. PCMs can be incorporated into compact and modular storage systems, for instance, shape-stabilized PCM (ssPCMs) [26], making them suitable for installation in various locations. The PCM storage system could integrate the hot water tanks and the solar collectors for domestic applications [27]. However, one limitation of PCMs is their relatively low thermal conductivity, which may affect the rate of heat transfer and, therefore, the system's responsiveness to varying heat demands.

TCES, a relatively newer approach, offers an interesting advantage over other techniques. It utilizes reversible chemical reactions to store and release heat, enabling longer-duration heat storage compared with BTES and PCMs. Besides, TCES offers higher energy density compared to PCMs (2-20 times higher) and BTES (3-30 times higher) [28], thus it can store a larger amount of energy within a smaller volume, allowing for more efficient use of available storage space in an urban area. Moreover, TCES has the advantage of being able to operate at a wider range of temperatures compared [29]. This flexibility enables TCES to adapt to different heat sources and heat sinks, enhancing its applicability in diverse DH scenarios, for example, adopting the transition from 3rd generation toward 4th generation of DHs, or seamless cooperation with other storage techniques. Lastly, TCES has the unique capability of not only providing heating but also cooling, making it versatile for both seasonal energy storage and cooling demands in DHs [30] [31].

Despite being a newer technology, TCES offers a promising solution for long-term thermal storage in DHs. Designing TCES systems introduces challenges that span various levels: system, component, and material [32]. At the system level, achieving optimal integration into existing DH systems while ensuring efficient energy conversion poses a significant challenge. The compatibility of the storage system with the overall energy network, including control strategies and load demands, requires careful consideration.

At the component level, the design must address the complex interaction of multiple components like reactors, heat exchangers, and evaporator/condenser. Designing the reactor and creating effective heat exchangers are important to achieve high heat storage capacity and efficient heat transfer to accommodate the low thermal conductivity of TCM [33]. Furthermore, careful attention needs to be paid to the inclusion of an external reservoir to provide the necessary water vapor for evaporation, such as a relatively lower temperature water container within the range of 10 to 20 °C [29].

At the material level, identifying suitable materials that exhibit high energy storage capacity, rapid reaction kinetics, and long-term stability under cyclic operation is challenging. Moreover, the materials must be cost-effective and environmentally friendly [34] [35].

Chapter 4

Design steps

4.1 Methodology

The methodology employed in this study consists of two main steps. Firstly, a DHs model was developed to simulate heat generation, demand, and storage (Section 4.1.1). Followed up by a simulation to find the relation between peak load generation and hot water storage capacity (Section 4.1.2). Subsequently, a TCES component model was created to enable adjustments to TCES's storage capacity and operating conditions during the design phase (Section 4.2.1). All models were developed using OpenModelica (version 4.0.0), an open-source model-based modeling environment. The components of the DHs models, including the CHP, heat exchangers, and pumps, were obtained from the Buildings libraries (version 9.0.0). the TCES component model was constructed using basic thermal components such as thermal capacitors, thermal resistors, and thermal conductors.

4.1.1 Construction of the DHs Model

The configuration of the DHs model in this study is based on the DHs system in the Enschede area. The DHs system operates with a supply line temperature of 75 °C and a return line temperature of 45-50 °C. The primary heat supply for the DH system comes from a CHP plant, with additional support provided by a natural gas-fired boiler. To enhance performance, a hot water storage system has been integrated into the DHs. Other descriptions of these focused DHs were mentioned in Section 2.4.

Primary and secondary network

The DHs model includes two heat networks, storage operation, and a control strategy for DHs. The DHs schematic in this study (shown in Figure 4.1) includes a closed loop of pipelines forming the primary network upstream of DHs, and a secondary network connected to the primary network through a heat substation. This configuration allows for separating the two networks, enabling separate control over their characteristics in terms of quality (temperature) and temporal variability (flow rate).

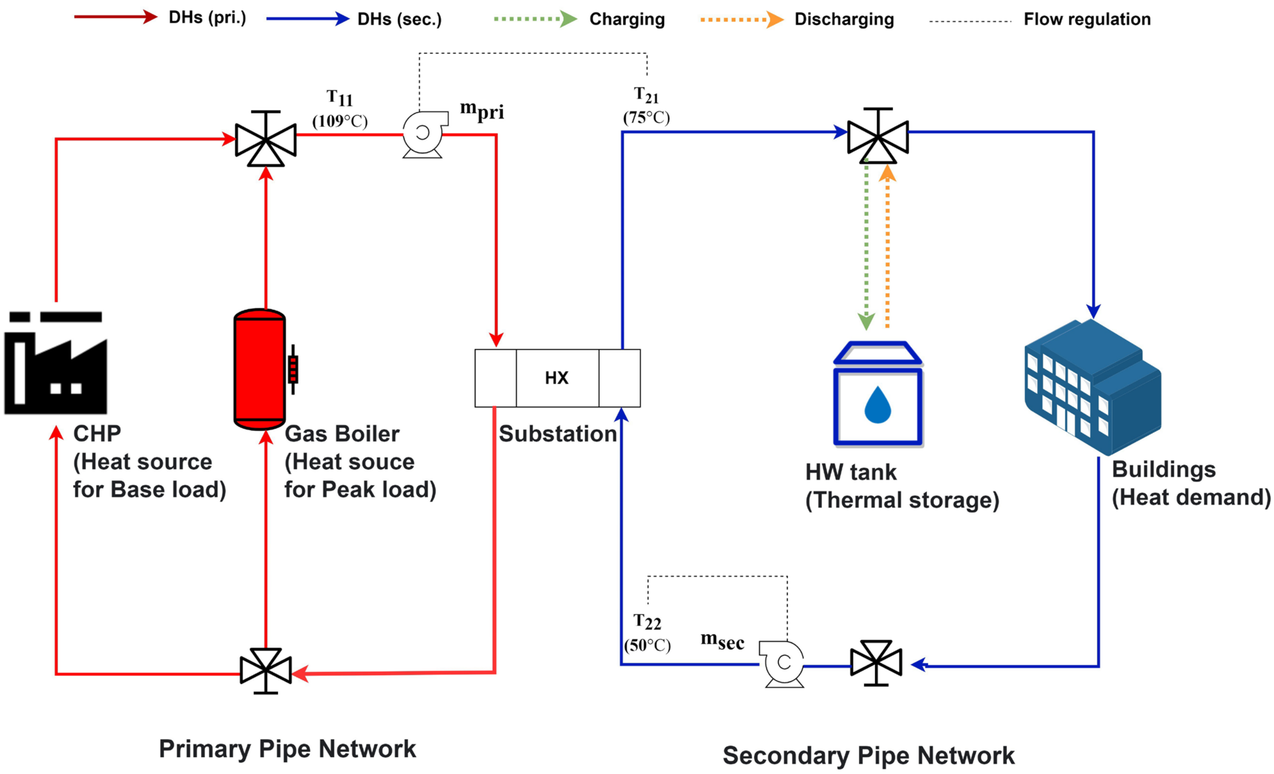

Figure 4.1: The schematic illustrates the DHs components, which consist of heat generation utilities like CHP and gas boiler, primary and secondary networks for heat distribution, heat consumers for load, and a hot water tank for thermal storage. The temperature control in DHs for T_{21} and T_{22} is achieved through flow rate regulation using pumps located in the primary and secondary networks.

The CHP unit in the primary network operates consistently at a stable power level. In contrast, the operational conditions in the secondary network are subject to greater fluctuations, as it is directly influenced by the heat demand of end-users, which exhibits daily and seasonal peak load demand. During peak load demand, a natural gas-fired boiler is utilized as it can quickly ramp up. Decentralized thermal storage is installed in the secondary network for peak load management, ensuring proximity to the consumer and requiring lower storage temperature levels. The heat demand profile is derived from raw data obtained from a heat substation in the Enschede area during 2019 and is correlated with the environmental temperature in the same period.

Baseload and peak load definition

The primary network relies on CHP as a baseload heat source, as illustrated by the monthly variation profile (see Table 2.2). This monthly generation profile can cause two types of supply-demand mismatch, namely overgeneration and undergeneration. Overgeneration could occur when the baseload produced by CHP exceeds the transient heat demand, resulting in excess heat that can either be stored or discarded. This amount is called redundant heat from CHP in this study. In contrast, overgeneration could occur when the CHP is insufficient to meet the heat demand, then the gas boiler is utilized to compensate. The requirement of peak load generation from the gas boiler is called peak load generation in this study.

Hot water storage charging and discharging

To minimize redundant heat from CHP and peak load generation, thermal storage installations can be utilized. This involves charging the storage during overgeneration periods and discharging it during undergeneration periods. As long as there is surplus heat from CHP generation and sufficient space in the storage during overgeneration periods, unused hot water will be injected into the water tank to store the excess heat. Conversely, during undergeneration periods, the storage will be discharged by removing the hot water to support the peak load and stop discharging when the peak demand period is over or the water level has been depleted. The control strategy implemented for the storage will impact its (dis)charging contributions, ultimately affecting the system's effectiveness in reducing redundant heat and peak load generation. Further details on storage control strategy are discussed in the later part of ”Temperature and flow rate regulation”.

This study simulates an indirect connection type of storage system, which separates the storage from the DHs and operates at atmospheric pressure. In this configuration, the charging (inflow) and discharging (outflow) are independently controlled using a pump and valve. Additionally, a pressure vessel with the same volume of water in the storage tank is necessary to maintain stable pressure in response to the changes in water flow into/from the storage.

Temperature and flow rate regulation

Temperature and flow regulation are distinguished from the flow transport temperature in the different generation DHs. In Section 4.2, our focus is on 3rd generation DHs with a supply temperature of 109 °C in the primary network, 75 °C for the supply line, and 50 °C for the return line in the secondary network. In 4th generation DHs, the temperature is decreased to 80 °C and 60 °C for supply temperature in the primary and secondary network, respectively. More discussion and results for the 4th generation DH are presented in Chapter 5.

The primary and secondary networks are both controlled by two pumps. The primary loop flow rate m_{pri} is regulated by a pump located in the primary network to maintain T_{21} at 75 °C in 3rd generation DH. The secondary network's flow regulation m_{sec} aims to achieve the desired return flow temperature (T_{22}) and is controlled by a pump located in the secondary network. Heat losses during transport in the secondary network are considered constant values and incorporated as part of the heat demand in this study.

Heat losses during transport in the secondary network are considered constant values and incorporated as part of the heat demand, thus the temperature drop along the transport path is not considered in this study. Failure to consider the transportation loss might have consequences, particularly in terms of component site selection and the potential need for additional booster substations along the path. However, this study focuses solely on the core components and their immediate performance in energy utilization and peak load management. Thus, the approach in this study neglects the transportation losses and views them as a systematic heat demand for the whole DHs.

4.1.2 Single storage system equipped with hot water storage

Figure 4.2 illustrates the improvement achieved in different storage capacities from the perspective of three performance indicators, the peak generation on the gas boiler, redundant heat on CHP, and the heat losses in storage. When the storage is full during charging periods, the rest of the available heat from CHP generation cannot be utilized and will be wasted. This amount of waste is called ”redundant heat” in this study. Moreover, the thermal storage system's heat loss during operation is another significant performance indicator. These heat losses result in a decrease in the temperature level of the storage system, reducing the quality of heat for discharging, and resulting in extra peak load gas boilers generation.

Without any storage unit, a 12.7% peak load demand requirement is evident, as shown in the same figure. Introducing a small storage volume of 50 m^3 significantly improved the performance. Peak load generation and redundant heat are reduced to half of the intrinsic value. This result implies that the storage system with a small capacity is already capable of fulfilling most of the daily charging and discharging demands. Increasing the storage water volume can further enhance the system's ability to improve the performance of these first two indicators. However, beyond a certain point, increasing the water volume does not lead to further improvement, as demonstrated by the peak load generation value plateauing at 2.7% for a 1200 m^3 water volume. This performance bottleneck is primarily due to heat losses in the storage. The heat loss value is approaching the value of peak generation at a case of 1200 m^3 water volume. Thus, a new storage system with minimal heat loss is required.

The power profile of peak load generation is further investigated. The study identified two conditions that can lead to peak load generation. The first condition occurs when the water level in the storage tank drops below 1% of its full capacity as shown in Figure 4.3 (a), (b), (c), and (d). While the second condition arises when the temperature of the discharging flow falls below 75 °C, resulting in an additional flow rate from the pump at the secondary network for flow compensation, which is indicated in Figure 4.3 (e).

An explanation of the second condition of peak load demonstrated in Figure 4.3 (e) is the temperature drop resulting from heat losses in storage. These losses cause a drop in temperature, resulting in a discharge temperature that is inadequate to the DH supply line temperature. When this discharge flow mixes with the DH supply line, the final temperature is lower than the desired temperature of the supply line. To offset this temperature difference, a higher flow rate is needed from the pump, which results in increased demand for peak generation. Nonetheless, the power of this peak demand is relatively small compared to the peak demand observed in the first condition of the peak load.

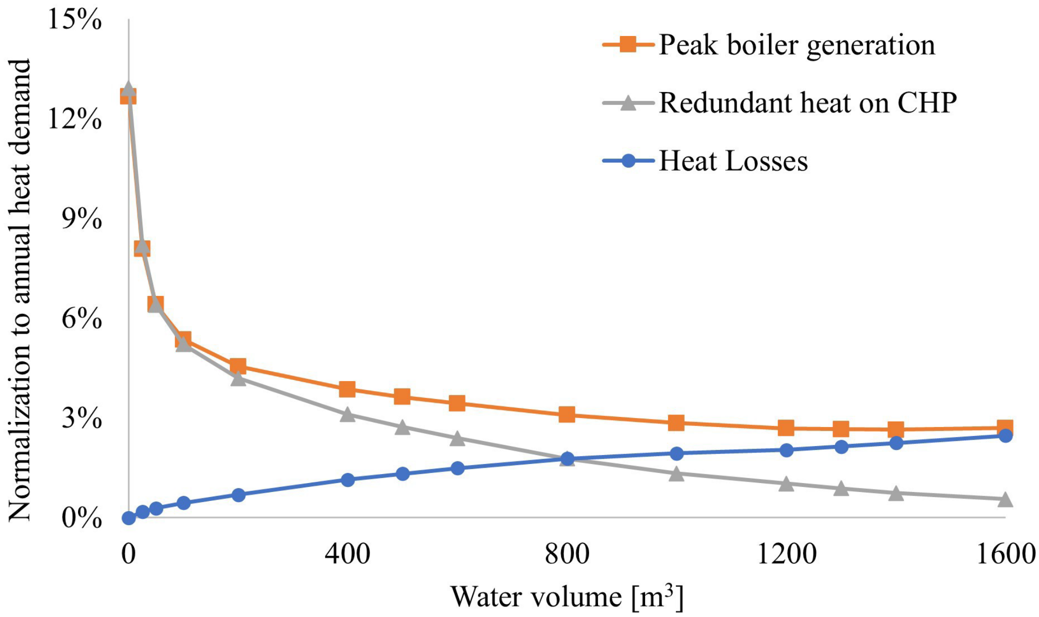

Figure 4.2: Annual peak load generation, redundant heat from CHP supply, and storage heat losses for various storage capacities of water volume in the single storage system. It was observed that peak load generation reaches a performance limitation at 2.7% regardless of the increase in water volume. Moreover, the redundant heat from the CHP is reduced as the water volume increases, meaning less energy is wasted. However, heat losses increase over water volumes as more hot water is stored in a hot water storage tank for a longer duration, resulting in more energy being dissipated to the environment.

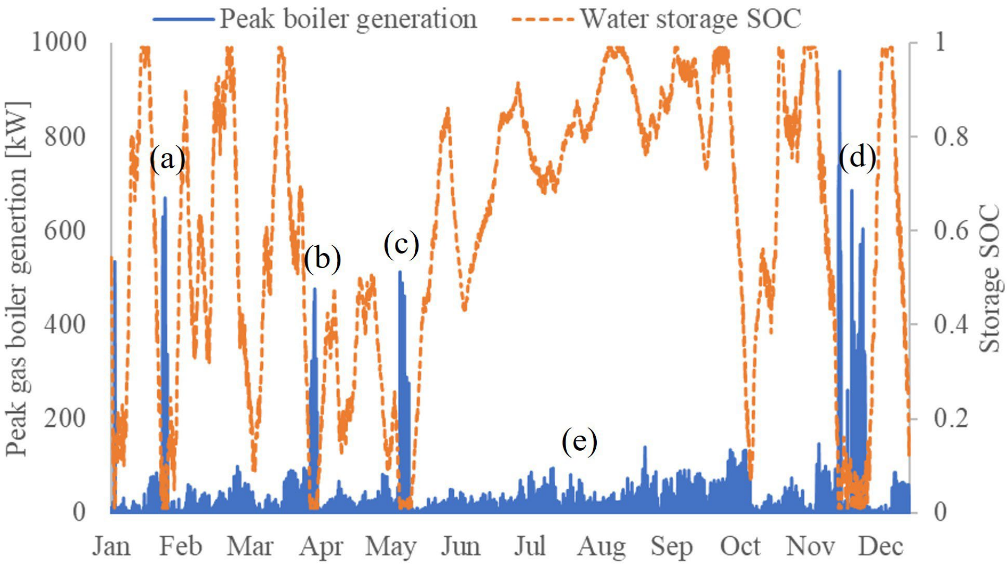

Figure 4.3: The power of the peak gas boiler generation and the normalized water level profile throughout a year in the case of a single storage of 800 m^3. During periods when the water tank approaches its minimum capacity indicated as (a), (b), (c), and (d), the peak gas boiler generation is employed to compensate for the deficit between heat demand and CHP, which is a higher value. In contrast, lower values in the profile, which is below 50 kW and indicated as (e), result from the flow compensation when the storage discharge temperature is below the supply line temperature.

4.2 Feasibility of TCES storage in 3rd generation DHs

TCES system is considered an optimal option for long-term thermal storage in DHs due to its operating temperature matching the heat demand temperature for domestic applications. However, its fitness varies based on the operating conditions of DHs. Therefore, a test was conducted to evaluate the integration of TCES in the 3rd generation DHs and assess its impact. The objective of the test was to analyze the compatibility of TCES within the system, understand its behavior, determine its contribution to peak load management, and compare it with the current district heating system in Enschede to study the feasibility of its implementation.

4.2.1 Development of TCES component model

The development of the TCES component model depends on the selection of the type of reactor. A closed system with a fixed-bed reactor was used to implement TCES in this study. Since heat transfer is the primary limitation in such systems, thermal behaviors play a dominant role in determining TCES's characteristics. Furthermore, since water vapor transportation is driven by the vapor pressure difference among the system components, it facilitates a rapid transport process and manageable pressure control [36] [32] [30]. As a result, the TCES component model simplifies fluid dynamics, assuming a uniform water vapor concentration and distribution throughout the reactor in this work. The accuracy of this model was ensured by comparing its simulation results with the numerical model on three crucial metrics: hydration power, thermochemical material (TCM) conversion status, and average TCM temperature. Moreover, the average power of the developed model is compared with the empirical formula by AJ de Jong, etc. [32]. Details of comparison results can be found in Appendix A.

Reaction Kinetic of TCM

The kinetic model employed to describe the energy conversion rate of de(hydration) reaction relies on three variables: TCM temperature, TCM conversion status, and vapor pressure. Equation 4.1 illustrates that this model can be parameterized by the temperature of the TCM (T), the conversion status of TCM (α), and water vapor partial pressure (P).

Given its high reaction enthalpy of 91.32 kJ/mol and system energy density of 0.96 GJ/m^3 in a closed system [37], Potassium Carbonate (K_2CO_3) is an ideal energy medium for TCES. Moreover, the discharge temperature range of K_2CO_3 is appropriate for fulfilling domestic heat demands in built environments (64 - 75 °C), and the temperature of the heat source for the evaporator is close to the ambient temperature (14 - 24 °C) as shown in Figure 4.4.

In this study, the hydration reaction parameters for K_2CO_3 were $K = 2.7 \times 10^{-9}$ [1/s], $E = -34828$ [J/mol], and $q = 0.7$, while the dehydration reaction parameters were $k = 225$ [1/s], $E = 43382$ [J/mol], and $q = 0.8$ (Equation 4.1). These values were obtained by calibrating experimental data from TGA measurements [39]. The equilibrium line of K2CO3 [40] is utilized as the equilibrium pressure formulation for all kinetic models (Equation 4.2).

$$\frac{d\alpha}{dt} = Ke^{\frac{-E}{RT}}(1-\alpha)^q(1-\frac{p_{eq}}{p}) \quad (4.1)$$

$$p_{eq} = 4.228 \times 10^{12} exp^{(\frac{-7337}{T})} \quad _R \quad (4.2)$$

Heat transfer of TCES reactor bed and heat exchanger

To account for the spatial temperature gradient in the TCES reactor bed, a two-dimensional discrete matrix has been incorporated into the TCES component model (see Figure 4.5). The heat capacitor and thermal conductance elements in the matrix are used to simulate heat accumulation and heat conduction inside the reactor bed.

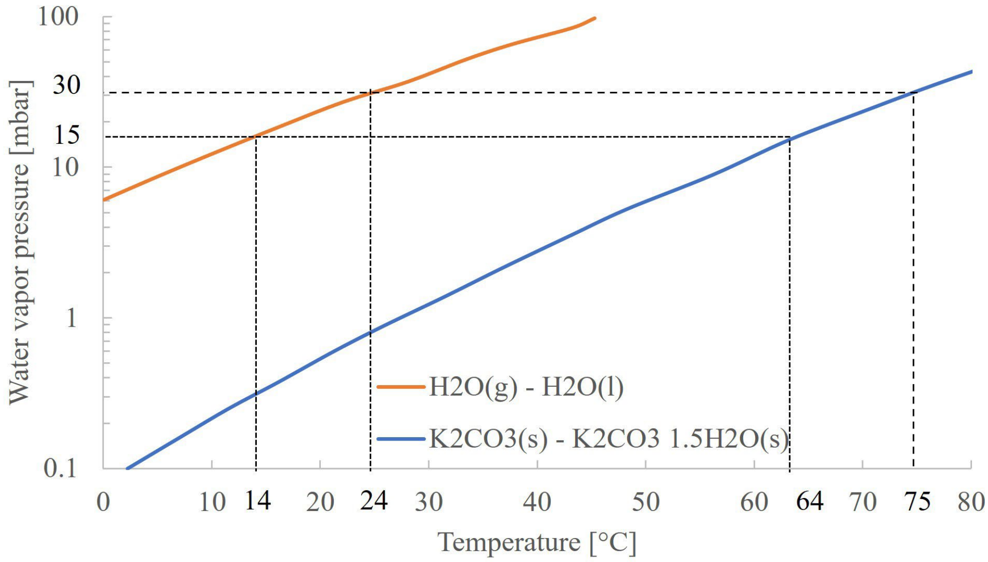

Figure 4.4: Phase diagram of K_2CO_3 is indicated by blue line [38]. Liquid – gas equilibrium of water is indicated by the orange line. A water vapor pressure of 15 mbar corresponds to a TCM equilibrium temperature of 64 °C, and at least 14 °C of heat source for the evaporator is required. To utilize high TCM temperatures up to 75 °C, the required evaporator pressure is 30 mbar, and the heat source for the evaporator at least to be 30 °C.

To present the entire TCM bulk inside the reactor bed, the TCM bulk is divided into (m x n) elements, where each element is represented as a heat capacitor with a designed mass in the unit of [J/K]. For thermal conduction, the thermal conductance of each element in the matrix is calculated by Equation 4.3, considering the TCM's thermal conductivity (λ_{TCM}), the contact area with other TCM elements nearby (A_{mn}), and the distance between TCM (L_{mn}) elements. The heat source in each discretized element can be calculated by the following equation 4.4.

$$G_{mn} = \lambda_{TCM} A_{mn} / L_{mn} \tag{4.3}$$

$$Q_{reaction,mn}[kW] = h_{reaction}[kJ/kg] \times m_{TCM,mn}[kg] \times \frac{d\alpha, mn}{dt}[1/s] \tag{4.4}$$

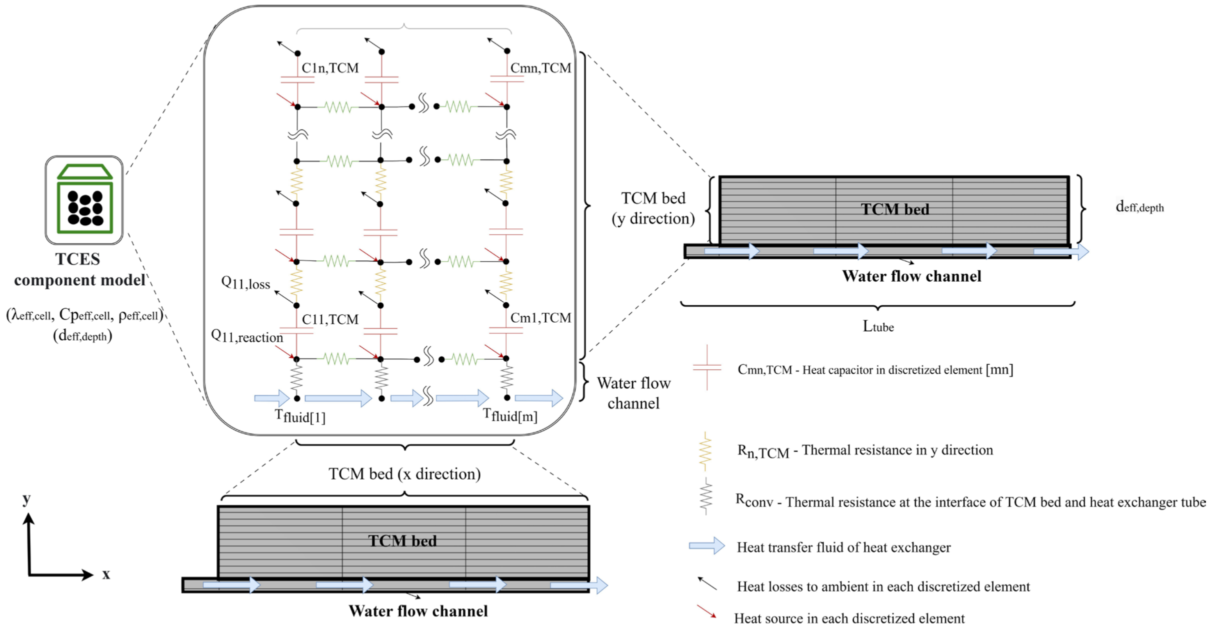

Figure 4.5: A matrix layout of a 2D discrete TCES component model with dimensions (m,n). It is a simplified version of a numerical model. The x-coordinate represents both the direction of the TCM bed length and the flow direction of heat transfer fluid in the heat exchanger, while the y-coordinate represents the depth of the TCM bed. The 2D matrix TCES (m,n) incorporates various heat transfer mechanisms within the TCM bed, such as reaction heat, thermal conduction between TCM, and convective heat transfer involving the heat exchanger and TCM bed.

4.2.2 Subsystem of TCES in 3rd DHs

the TCES subsystem comprises the TCES reactor, condenser/evaporator, vapor reservoirs, hot water storage (2nd), and the E-boiler, as depicted in Figure 4.6. The TCM is positioned within the TCES reactor. The evaporator connects to vapor reservoirs, utilizing heat from the hot water storage (2nd) for evaporation. Additionally, the E-boiler, situated close to the DHs supply line, elevates the flow temperature to the desired level. Further operational details during the charging and discharging phases of the TCES subsystem are elaborated below. Figure 4.6 (a) demonstrates the TCES subsystem's charging mode, where the DH supply line is utilized as a high-temperature heat source. To charge the TCES, the system draws the flow directly from the DH supply line and then returns it to the DH return line. However, when TCES operates at 12 mbar in charging mode, the TCES system's outflow temperature is still at a medium level, 61 °C (see Figure 4.4), which is still higher than the return flow temperature of 50 °C. Directly flowing back the TCES outflow and mixing with the DH return line will increase the DH return flow temperature, leading to low heat transfer efficiency with the primary network in the heat exchanger. Moreover, the temperature gap between the TCES outflow and the DH return line will result in redundant heat on the CHP, as heat from the CHP is not fully utilized. To tackle this issue, a two-step charging approach is used.

A small hot water storage unit, referred to as the ”hot water storage (2nd)”, is installed downstream of the TCES system and before the DH return line, functioning as a second step of charging that reserves the available heat before the TCES outflow returns to the DH return line. The stored heat in the hot water storage (2nd) can then be used later to meet peak load and provide the evaporator with the required evaporation heat during the discharging period. the TCES discharging process, illustrated in Figure 4.6 (b), utilizes the DH return flow to discharge the TCES system. The hot water storage (2nd) unit supports the TCES system during discharging mode, serving as the heat source for the evaporator heat and the heat to preheat part of the discharging flow.

During TCES discharging, the required heat for the evaporator is extracted from the hot water storage (2nd) unit with low-temperature heat ranging from 13 to 24 °C, depending on the evaporator pressure. The temperature level of the hot water storage (2nd) unit is monitored to ensure the required heat for the evaporator is reserved and prepared for the hydration reaction.

Additionally, to increase the utilization of heat in the hot water storage (2nd) unit, the hot water storage (2nd) unit can also contribute to peak load demand by preheating the discharge flow from the return line partly. By distributing part of the discharging flow to the hot water storage (2nd) unit, the energy stored in the hot water storage (2nd) unit can be better utilized, increasing the cycle frequency of the hot water storage (2nd) unit. Thus, a two-stream discharge approach is used. The discharging flow is split into two streams, with one flowing toward the hot water storage (2nd) unit and the rest toward the TCES reactor. Both streams will mix afterward and flow toward DH secondary supply line. However, it is observed that the mixed streams do not consistently reach the desired supply line temperature. This is primarily due to limitations in the TCES's ability to consistently generate the desired temperature level for the discharging flow, particularly toward the end of the TCES's discharging cycle. Similar temperature limitations are also observed in the stream flowing through the 2nd hot water storage. To ensure that the mixed flow consistently meets the required temperature criteria, an E-boiler is added to lift the temperature of the mixed flow to match the supply line temperature.

4.2.3 Control strategy for hot water storage and TCES

Coordinating hot water storage and TCES storage systems can be challenging due to their mismatch in response time and nominal power. To overcome this challenge, a strategy of charging and discharging for the dual storage system is developed. During the charging period, hot water storage should be given priority for charging, as it has a rapid response time and is suitable for abrupt changes in heat demand. TCES can be charged when there is surplus heat left from hot water storage charging, for example, when the water level in

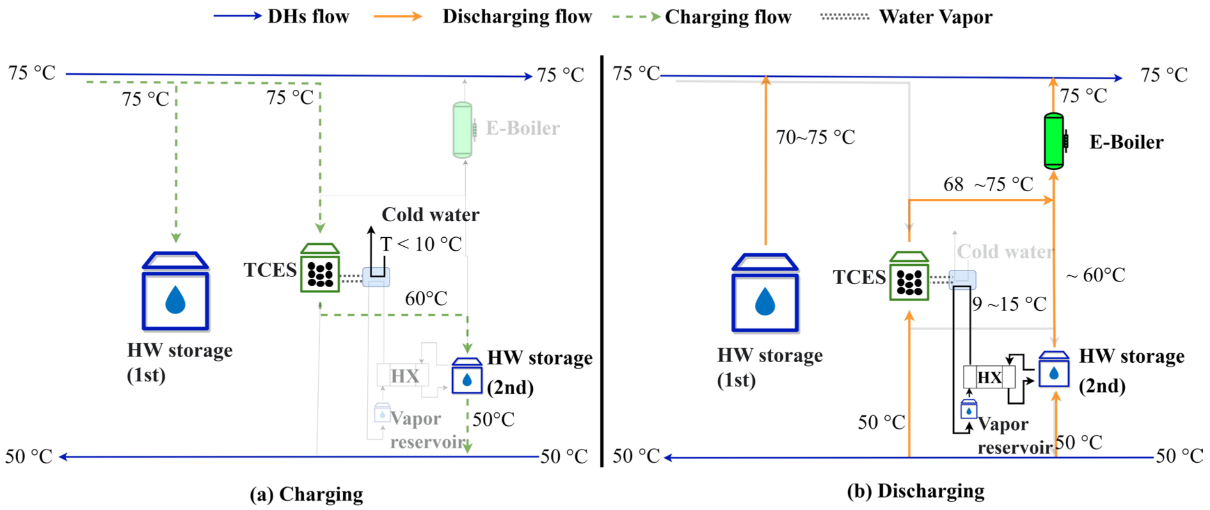

Figure 4.6: The charging mode (a) and discharging mode (b) of the dual storage system. The dual storage system gives priority to 1st hot water storage during charging mode. If 1st hot water storage is full, the remaining charging heat is used to charge TCES and 2nd hot water storage. During discharging mode, 1st hot water storage is given priority. TCES system starts the discharging process when 1st hot water storage is empty. The discharge stream is distributed to TCES and hot water storage (2nd). An E-boiler is installed upstream of TCES to maintain a 75 °C discharged flow.

storage is full. During peak demand, it is best to prioritize the use of hot water storage for discharge, with TCES acting as a backup. TCES should not be solely relied upon due to its slow ramp-up of discharging power, which could result in inadequate peak load shaving.

Optimizing the control strategy for the transition from hot water storage to TCES during peak load demand is crucial for effective peak load management in the system. One approach to achieve this is by distributing the discharging task between the two storage units. As previously mentioned, TCES functions as a backup for hot water storage, being triggered by specific conditions. To initiate the operation of TCES at the appropriate time, two types of checking signals have been tested to evaluate their performance in reducing peak load generation. The first signal is the absolute value control, where TCES is activated only when the state of charge (SOC) of the hot water storage (or water height level) drops below a certain predetermined value. This ensures that TCES is engaged when the hot water storage is nearing depletion.

The second type of signal, gradient control, focuses on the rate of change in water level. It checks the time gradient of the water level change and assesses if the current SOC of the hot water storage is capable of withstanding the anticipated peak demand for the upcoming hours. By considering the rate of change, the control system can better predict the storage capacity required for the expected peak load period.

When one of the control signals confirms that the energy level of the hot water storage is deemed safe, the hot water storage unit takes full responsibility for the discharging task. This ensures that the available energy in the hot water storage is utilized before relying on the TCES. In situations where the energy level of the hot water storage is insufficient to meet all the incoming peak load, the TCES is initiated and partially shares the peak load generation task. This allows the TCES to provide additional energy to supplement the hot water storage and meet the peak load demand. By introducing the TCES early and operating both storage units in parallel, sudden high power output requirements from the TCES can be avoided, resulting in a smoother and more stable operation.

In situations where the hot water storage is fully depleted and unable to contribute to the discharging task, the entire burden shifts to the TCES. In this scenario, the TCES becomes the sole provider of energy to meet the peak load demand, which is not the preferred situation for TCES. Nevertheless, this approach guarantees the continued effective operation of the system even when the hot water storage is completely exhausted. In the event of insufficient energy support from the TCES, a final backup heat source will be utilized to fulfill the remaining peak load requirement. Therefore, a control strategy for operating both hot water storage and TCES has been developed based on the operating priority and is presented in Figure 4.7.

4.2.4 Dual storage system with hot water storage and TCES system

To increase storage capacity without increasing water capacity volume and the consequent effect of heat losses, a TCES system is introduced to form a dual thermal storage system, wherein the first hot water storage capacity remains fixed at 200 m3 while the TCES system is added to expand the storage capacity. The study findings from the single storage scenario suggest that the primary storage is optimal for a water volume ranging from 200 m3 to 400 m3 (see Figure 4.2). Beyond this range, there is a decrease in the improvement in peak load reduction due to heat losses as previously discussed. Thus, a water capacity volume of 200 m3 is chosen for the first hot water storage.

A power profile of the peak gas boiler in dual thermal storage is presented in Figure 4.8. Comparing it with Figure 4.3 in which both cases share the same heat storage capacity, the dual storage case experiences less high power value of peak gas boiler generation than the single storage system. It is mainly due to the maintained TCES energy level. The peak value is only observed when the TCES capacity reaches its minimum as indicated (d) in Figure 4.8.

To determine the optimal combination of parameters for the TCES system, a thorough sensitivity analysis is conducted. the TCES system configuration is altered by two sets of parameters: the storage volume of the TCES subsystem for varying storage capacities, and the evaporator pressure of the TCES for varying discharging temperatures. As previously

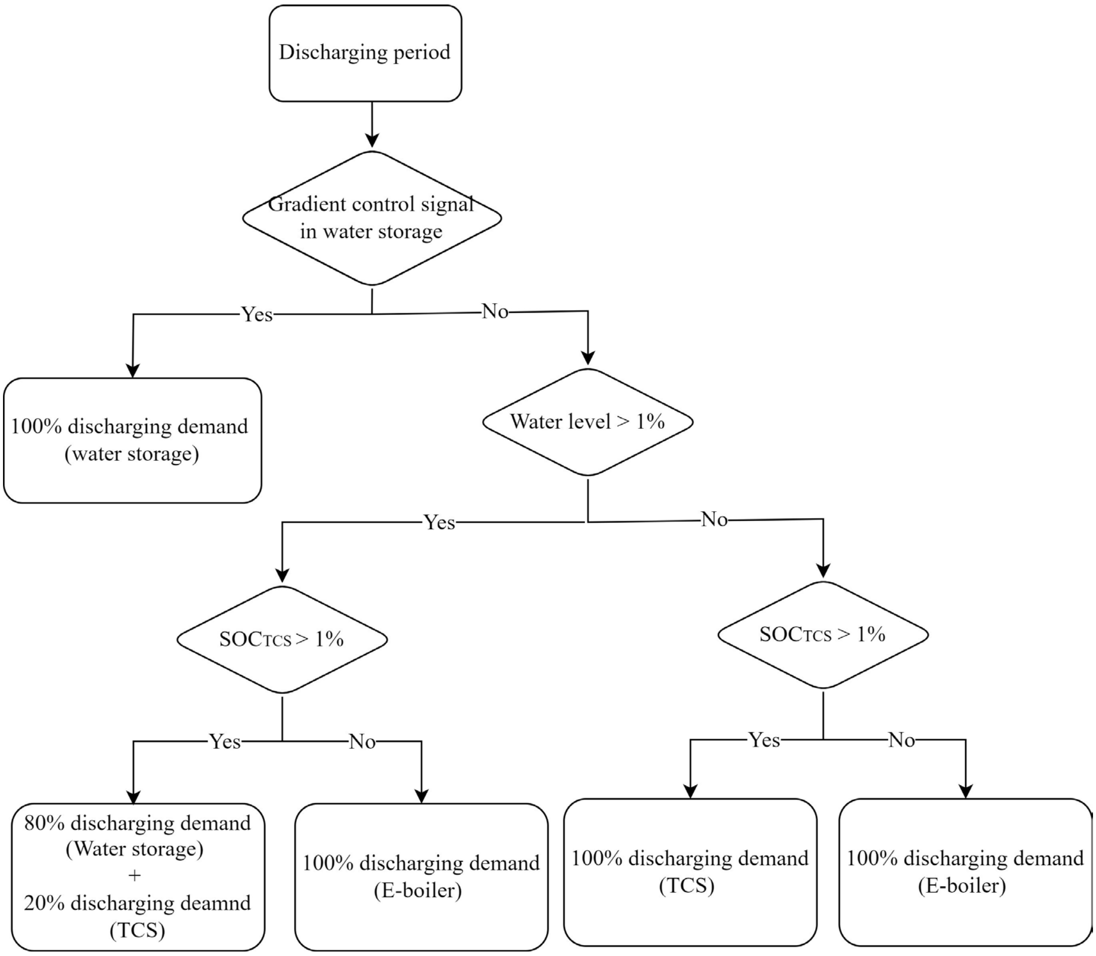

Figure 4.7: Decision tree for the control strategy of the dual storage system in the discharging period. Discharging priority is given to utilizing hot water storage, and TCES is used when the water level is in an emergent condition determined by the control signal. These critical values, such as the percentage of water level threshold and the ratio of power contribution from each storage, are obtained through optimization.

stated, the water volume at the 1st hot water storage is kept constant at 200 m^3 in the sensitivity analysis.

4.2.5 Sensibility analysis

Variable 1: Storage capacity of TCES system

The total storage capacity of the dual thermal storage system is determined by two storage units: a 1st hot water storage unit which is fixed at 200 m^3 in the sensitivity analysis, and a TCES unit with a variable storage capacity in the sensitivity analysis. The capacity of the TCES unit is determined by the volume of the TCM and the water volume in the hot water

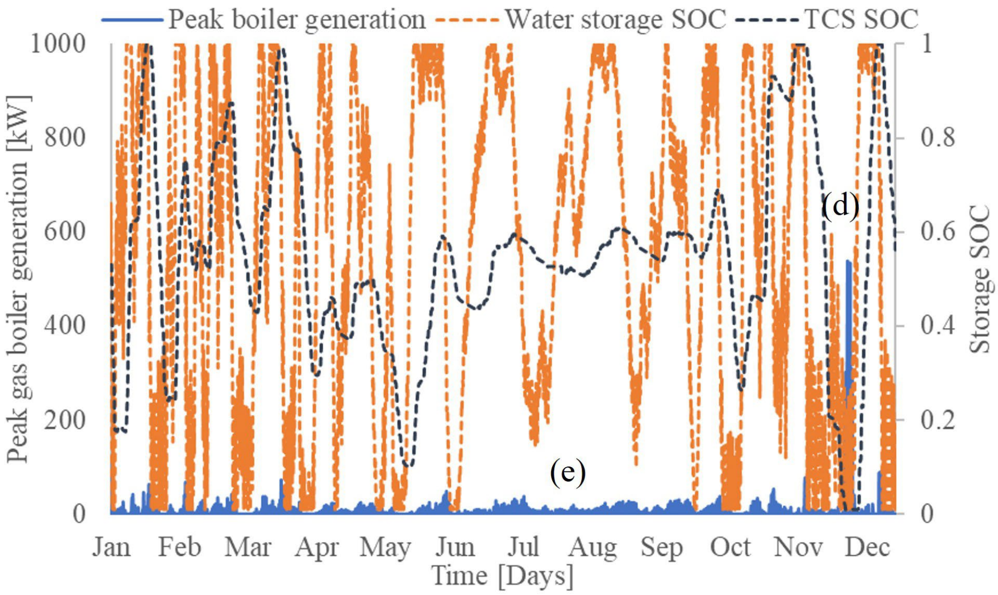

Figure 4.8: The power of the peak boiler generation profile, the profile of normalized water level profile, and TCES state of charge throughout a year in the case of dual thermal storage of 200 m^3 water volume (1st), TCM 50 m^3, and 100 m^3 water volume (2nd). The overall storage capacity is equivalent to 800 m^3 of water volume as same in Figure 4.3. As supported by TCES, the peak load only happens when both storage approaches their minimum capacity at the same time, for example, the period indicated as (d). Moreover, the low value, as indicated (e), is observed to be smaller than Figure 4.3.

storage (2nd) unit. In the sensitivity analysis, the TCM volume is considered a variable with four levels, ranging from 30 m^3 to 90 m^3 with increments of 20 m^3. Meanwhile, the volume of the hot water storage (2nd) is changed with TCM volume and determined based on the energy requirement for the TCES hydration reaction. In this study, the volume of the hot water storage (2nd) is varied from 75 m^3 to 150 m^3 in increments of 25 m^3. The decision to determine the volume of the hot water storage (2nd) is driven by the hot water storage capacity needed to supply sufficient energy for evaporation heat during the hydration reaction. The hot water storage (2nd) capacity is capable of supplying the amount of evaporation heat that is equivalent to 50 % of the TCM volume through a hydration reaction. As illustrated in Figure 4.6, a heat exchanger is connected to the hot water storage (2nd) unit to heat the flow from the vapor reservoir to the required temperature for evaporation, which provides energy to the evaporator loop. Therefore, the water volume in the hot water storage (2nd) unit must increase proportionally to the increase in TCM volume for sufficient evaporation heat.

Variable 2: Evaporator pressure of TCES

The evaporator pressure of TCES strongly affects the hydration temperature of TCM and, consequently the maximum TCES discharging temperature. Higher evaporator pressure enables higher TCES discharging temperature, reducing reliance on the downstream E-boiler (see Figure 4.6) for achieving the desired supply line temperature. In the sensitivity analysis, the evaporator pressure of TCES is varied from 15 mbar to 30 mbar in 5 mbar increments. The corresponding hydration temperatures range from 64 °C to 75 °C (see Figure 4.4). Additionally, temperature control is implemented on the heat exchanger connected to the 2nd storage unit to ensure that the hydration reaction occurs under the desired conditions.

4.2.6 Results and Discussion

Annual peak gas boiler generation

Figure 4.9 illustrates simulation outcomes for annual peak boiler generation in single and dual storage setups. The dual storage configuration exhibits lower peak energy demands compared to the single storage design. This decrease is attributed to TCES preserving energy levels in storage, reducing reliance on the peak gas boiler due to maintained energy levels. Within the dual storage approach, TCES's remaining capacity allows continuous discharge, enabling the downstream E-boiler to maintain required flow temperatures. Additionally, dual thermal storage's advantage in peak reduction comes from even load distribution across two units. Regulating discharge flow between these units prevents storage depletion, ensuring continuous discharge. Moreover, the figure reveals that larger TCM volumes correspond to reduced annual peak generation at constant evaporator pressure. Larger storage capacity increases stored energy, bolstering energy supply security. However, for the same storage capacity, higher evaporator pressure yields the highest annual peak boiler generation. More energy extraction from TCES storage under elevated evaporator pressures is offset by simultaneous energy depletion, heightening storage's low energy level risk.

Power profile of peak gas boiler and its nominal power

Figure 4.10 illustrates storage capacity's influence on nominal peak generation power over operation in dual thermal storage at two evaporator pressures. Each case's maximum peak power is numbered in the same figure. Results reveal that a peak power value lower than 766 kW (single storage's 800 m^3 water peak power demand) is achieved only when TCM volume surpasses 70 m^3 at both 15 mbar and 25 mbar. High peak power emerges when storage energy

depletes (second peak generation condition). To mitigate peak values, sufficient energy during the high discharge-demand period is crucial, and it can be achieved by equipping with a large TCM volume for storage capacity. Furthermore, comparing TCM 30 m^3 at 15 mbar and 25 mbar, larger TCM volumes and lower pressure yield fewer high values in the peak power profile. For instance, at 15 mbar, peak power over 400 kW persists for
2.6 hours, while at 25 mbar, it's 3.25 hours. Longer high-power operation occurs at 25 mbar. Similar trends emerge for peak power over 100 kW: 7.25 hours at 15 mbar and 11.75 hours at 25 mbar. Lower evaporator pressure retains more energy, reducing peak load generation from the gas boiler, especially for the first peak generation condition. Additionally, dual thermal storage cases have smaller second-condition peak power, attributed to the E-boiler elevating TCES discharge temperature to the supply line level, reducing peak gas boiler flow compensation needs.

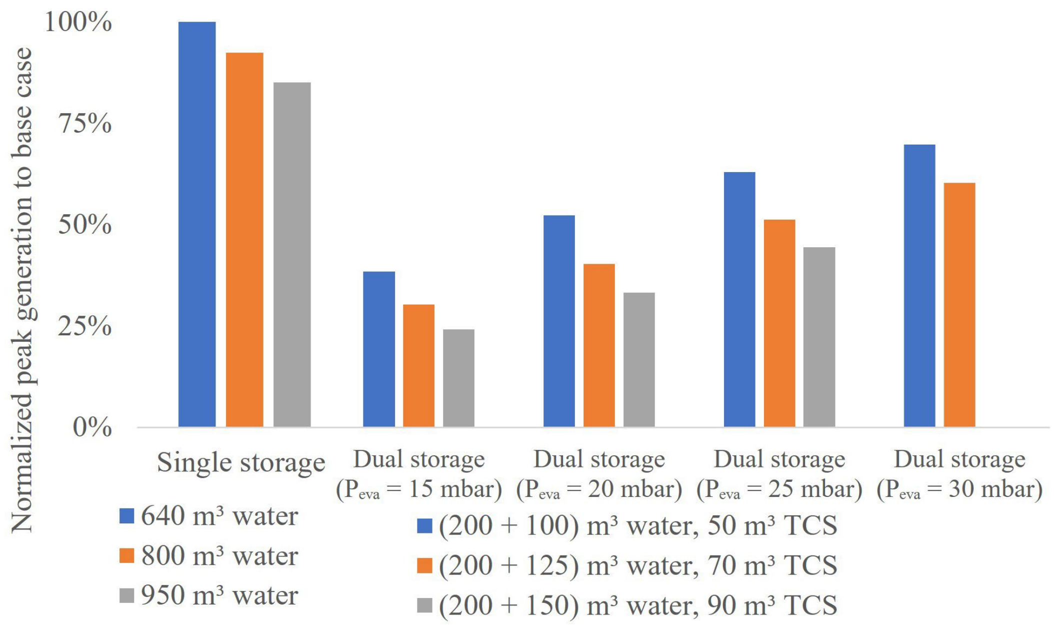

Figure 4.9: The annual peak generation of a peak gas boiler with the overall storage capacity of single and dual storage systems. Results showed that, in the dual storage system, the annual peak generation was lower than that of the single storage system, particularly at large TCM volumes and low evaporator pressures.

Heat losses composition

The finding of peak generation discussed in the previous section indicates that the selection of low evaporator pressure in TCES and large TCM volume is optimal for reducing annual energy and the nominal power of peak generation. However, this desired condition creates a conflict situation due to heat loss control. A larger hot water storage (2nd) unit is required along with a large TCM volume since the hot water storage (2nd) unit is crucial for energy preparation during TCES discharging (heat source for evaporator). The detailed analysis of heat losses as demonstrated in Figure 4.11 reveals that heat losses from the hot water storage (2nd) unit are the bottleneck of storage efficiency. In the dual storage system, the

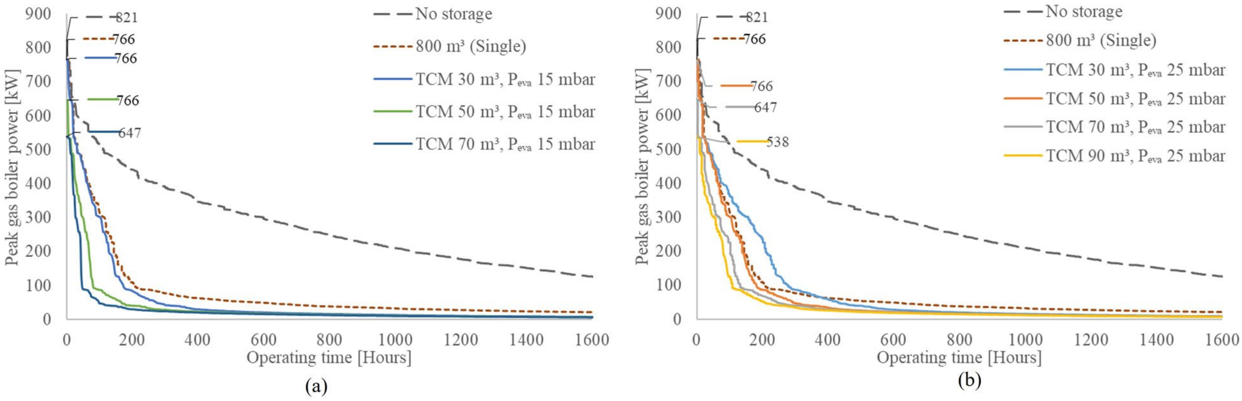

Figure 4.10: The peak generation power and its operating hours in a dual thermal storage system at evaporator pressure 15 mbar (a) and 25 mbar (b). The TCM volume varies between 30 m^3 to 90 m^3. The nominal peak generation power of the year is depicted in the figure, with a higher value indicating a need for a larger- sized of gas boiler.

overall heat losses across all storage units are comparable to those observed in the single storage system. For the situation with a TCM volume of 70m^3, the overall heat loss is 1.64 $\%$, which is comparable to that of the single storage system (1.77 $\%$). The heat loss from hot water storage (2nd) is 0.51 $\%$, accounting for one-third of overall heat losses. The amount of TCES storage capacity constitutes 63$\%$ of all storage capacity in the scenarios with TCM volumes of 70 m^3. However, contrary to expectations, increasing the portion of TCES capacity did not result in a reduction of heat losses. These findings suggest that increasing the TCES capacity beyond a particular threshold does not significantly reduce the overall heat losses, as the heat losses from the hot water storage (2nd) unit become notable.

Why TCES is not technically feasible in 3rd generation DHs

Although optimal combinations of large TCES storage capacity and low evaporator pressure for the reduction of peak generation are found from the sensitivity analysis, increasing the TCES capacity results in higher heat losses due to the extra hot water storage (2nd hot water storage) added to the TCES system. This extra hot water storage is necessary since it prepares the energy required for the evaporator heat during the hydration reaction, thus creating a conflict situation of causing more heat losses when having more TCES contribution to DHs. This conflict over having extra hot water storage has identified the TCES system's performance bottleneck concerning the evaporation heat source. This finding offers valuable insights for designing TCES systems in the 3rd generation of DHs and underscores the importance of considering the energy required for evaporation when simulating TCES systems.

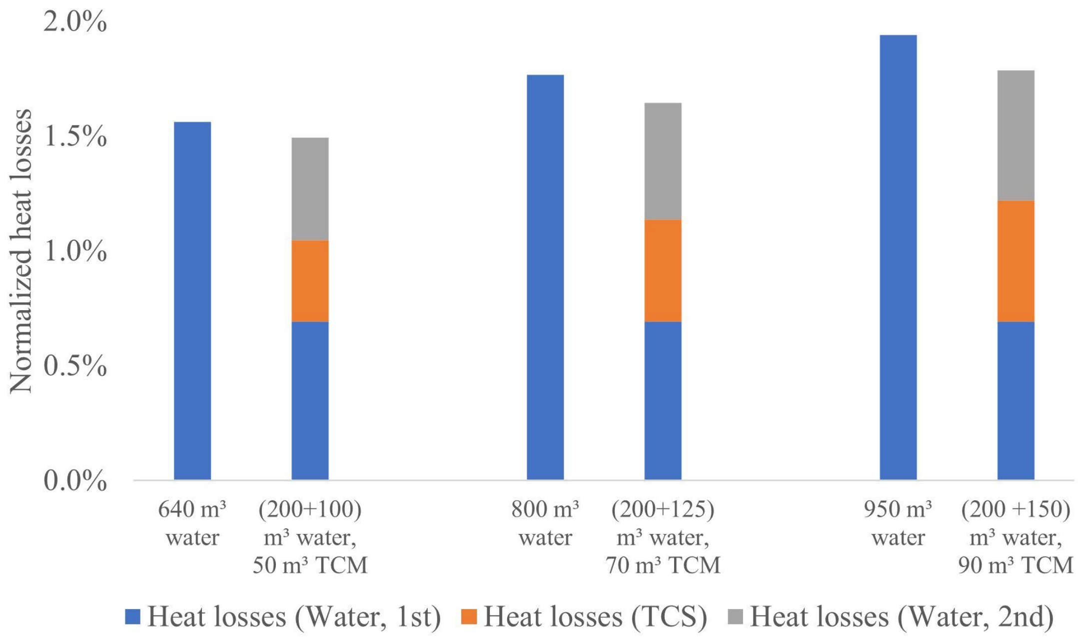

Figure 4.11: Comparison of heat loss composition between a single storage system with 800 m^3 of hot water storage and a dual storage system consisting of 200 m^3 of the 1st hot water storage, 70 m^3 of TCM, and 125 m^3 of the hot water storage (2nd) in three different evaporator pressure. These four scenarios have the same overall storage capacity and in 3rd DHs

In future scenarios for the 4th generation of DHs with lower supply line temperatures, TCES can play a more significant role since the evaporator pressure is lower and the energy for evaporation can be obtained directly from the environment. Additionally, this approach could eliminate the need for an E-boiler if the discharging temperature can meet the supply line temperature directly. Under such circumstances, the conflict between TCES capacity and heat loss control can be better managed, which is the focus of the next chapter.

Chapter 5

Conclusions and recommendations

TCES in 3rd generation DHs

While the study underscores the feasibility of TCES as a long-term thermal storage option for DHs, its application within 3rd generation DHs presents specific technical challenges. The proposed dual storage system exhibits promising reductions in peak gas boiler usage. Despite the sensitivity analysis indicating optimal configurations involving large TCES storage capacities and low evaporator pressures, the introduction of additional hot water storage (2nd hot water storage) leads to heightened heat losses with increased TCES capacity. These findings suggest that increasing the TCES capacity beyond a particular threshold does not significantly reduce the overall heat losses, as the 2nd hot water storage unit remains a performance bottleneck. Consequently, this study highlights the TCES system's limitations in the context of 3rd generation DHs, especially in managing the balance between TCES capacity and heat loss control. The findings provide valuable insights into the design considerations of TCES systems for the upcoming 4th generation DHs, wherein lower supply line temperatures could potentially mitigate these challenges.

Bibliography

[1] R. T. 1.0, “https://energiestrategietwente.nl/res-twente-1-0-strategische-koers,” Accessed 23-09-2022.

[2] I. Giebels, I. Minnes, T. Brandenburg, and T. Engels, “Transition vision heat enschede colophon.”

[3] J. Huang, J. Fan, S. Furbo, D. Chen, Y. Dai, and W. Kong, “Economic analysis and op- timization of combined solar district heating technologies and systems,” *Energy*, 2019.

[4] H. ur Rehman, J. Hirvonen, and K. Sirén, “A long-term performance analysis of three different configurations for community-sized solar heating systems in high latitudes,” *Renewable Energy*, vol. 113, pp. 479–493, 2017.

[5] ——, “Influence of technical failures on the performance of an optimized community-size solar heating system in nordic conditions,” *Journal of Cleaner Production*, vol. 175, pp. 624–640, 2018.

[6] R. Renaldi and D. Friedrich, “Techno-economic analysis of a solar district heating system with seasonal thermal storage in the uk,” *Applied Energy*, 2019.

[7] P. Dodds, I. Staffell, A. Hawkes, F. Li, P. Grünewald, W. McDowall, and P. Ekins, “Hydro- gen and fuel cell technologies for heating: A review,” *International Journal of Hydrogen Energy*, vol. 40, pp. 2065–2083, 2015.

[8] J. Li, J. Lin, Y. Song, X. Xing, and C. Fu, “Operation optimization of power to hydrogen and heat (p2hh) in adn coordinated with the district heating network,” *IEEE Transactions on Sustainable Energy*, vol. 10, pp. 1672–1683, 2019.

[9] H. Böhm, S. Moser, S. Puschnigg, and A. Zauner, “Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials,” *International journal of hydrogen energy*, vol. 46, no. 63, pp. 31 938–31 951, 2021.

[10] S. H. Yousefi, R. Groenenberg, J. Koornneef, J. Juez-Larré, and M. Shahi, “Techno-economic analysis of developing an underground hydrogen storage facility in depleted gas field: A dutch case study,” *International Journal of Hydrogen Energy*, 2023.

[11] A. Buttler and H. Spliethoff, "Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2440–2454, 2018.

[12] G. Airò Farulla, M. Cellura, F. Guarino, and M. Ferraro, "A review of thermochemical energy storage systems for power grid support," *Applied Sciences*, vol. 10, no. 9, p. 3142, 2020.

[13] F. Levihn, "Chp and heat pumps to balance renewable power production: Lessons from the district heating network in stockholm," *Energy*, vol. 137, pp. 670–678, 2017.

[14] K. Lepiksaar, V. Mašatin, E. Latõšov, A. Siirde, and A. Volkova, "Improving chp flexibility by integrating thermal energy storage and power-to-heat technologies into the energy system," *Smart Energy*, vol. 2, p. 100022, 2021.

[15] D. Patteeuw, G. P. Henze, and L. Helsen, "Comparison of load shifting incentives for low-energy buildings with heat pumps to attain grid flexibility benefits," *Applied energy*, vol. 167, pp. 80–92, 2016.

[16] C. Finck, R. Li, and W. Zeiler, "Operation of heat pumps for smart grid integrated buildings with thermal energy storage," in *12th International Energy Agency Heat Pump Conference*, 2017, pp. 2–8.

[17] P. Manz, K. Kermeli, U. Persson, M. Neuwirth, T. Fleiter, and W. Crijns-Graus, "Decarbonizing district heating in eu-27 + uk: How much excess heat is available from industrial sites?" *Sustainability*, 2021.

[18] G. P. Hammond and J. Norman, "Heat recovery opportunities in uk industry," *Applied Energy*, vol. 116, pp. 387–397, 2014.

[19] J. Pelda, F. Stelter, and S. Holler, "Potential of integrating industrial waste heat and solar thermal energy into district heating networks in germany," *Energy*, vol. 203, p. 117812, 2020.

[20] THALES, "Thales deploys an energy usage and efficiency plan," https://www.thalesgroup.com/en, Nov. 2022.

[21] Akzonobel, "Recycling and reusing process water in akzonobel," https://www.akzonobel.com/en, 2023.

[22] RVO, https://www.warmteatlas.nl/, Nov. 2023.

[23] B. Sibbitt, D. McClenahan, R. Djebbar, J. Thornton, B. Wong, J. Carriere, and J. Kokko, "The performance of a high solar fraction seasonal storage district heating system–five years of operation," *Energy Procedia*, vol. 30, pp. 856–865, 2012.

[24] A. Rosato, A. Ciervo, F. Guarino, G. Ciampi, M. Scorpio, and S. Sibilio, "Dynamic sim- ulation of a solar heating and cooling system including a seasonal storage serving a small italian residential district," *Thermal Science*, vol. 24, no. 6 Part A, pp. 3555–3568, 2020.

[25] R. Renaldi and D. Friedrich, "Techno-economic analysis of a solar district heating system with seasonal thermal storage in the uk," *Applied Energy*, vol. 236, pp. 388–400, 2019.

[26] C.-Y. Yeh, K. Boonk, G. Sadeghi, M. Mehrali, M. Shahi, G. Brem, and A. Mahmoudi, "Experimental and numerical analysis of thermal performance of shape stabilized pcm in a solar thermal collector," *Case Studies in Thermal Engineering*, vol. 30, p. 101706, 2022.

[27] D. N. Nkwetta and F. Haghighat, "Thermal energy storage with phase change material—a state-of-the art review," *Sustainable Cities and Society*, vol. 10, pp. 87–100, 2014.

[28] S. Pintaldi, C. Perfumo, S. Sethuvenkatraman, S. White, and G. Rosengarten, "A review of thermal energy storage technologies and control approaches for solar cooling," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 975–995, 2015.

[29] K. E. N'Tsoukpoe and F. Kuznik, "A reality check on long-term thermochemical heat storage for household applications," *Renewable and Sustainable Energy Reviews*, vol. 139, p. 110683, 2021.

[30] K. Kant and R. Pitchumani, "Advances and opportunities in thermochemical heat storage systems for buildings applications," *Applied Energy*, vol. 321, p. 119299, 2022.

[31] G. Krese, V. Butala, U. Stritih *et al.*, "Thermochemical seasonal solar energy storage for heating and cooling of buildings," *Energy and Buildings*, vol. 164, pp. 239–253, 2018.

[32] A.-J. de Jong, F. Trausel, C. Finck, L. Van Vliet, and R. Cuypers, "Thermochemical heat storage–system design issues," *Energy procedia*, vol. 48, pp. 309–319, 2014.

[33] K. Kant, A. Shukla, D. M. Smeulders, and C. C. Rindt, "Performance analysis of a k2co3-based thermochemical energy storage system using a honeycomb structured heat exchanger," *Journal of Energy Storage*, vol. 38, p. 102563, 2021.

[34] R.-J. Clark, A. Mehrabadi, and M. Farid, "State of the art on salt hydrate thermochemical energy storage systems for use in building applications," *Journal of Energy Storage*, vol. 27, p. 101145, 2020.

[35] J. Lin, Q. Zhao, H. Huang, H. Mao, Y. Liu, and Y. Xiao, "Applications of low-temperature thermochemical energy storage systems for salt hydrates based on material classifica- tion: A review," *Solar Energy*, vol. 214, pp. 149–178, 2021.

[36] K. E. N'Tsoukpoe, G. Restuccia, T. Schmidt, and X. Py, "The size of sorbents in low pressure sorption or thermochemical energy storage processes," *Energy*, vol. 77, pp. 983–998, 2014.

[37] P. Donkers, L. Sö gü toglu, H. Huinink, H. Fischer, and O. Adan, "A review of salt hydrates for seasonal heat storage in domestic applications," *Applied energy*, vol. 199, pp. 45– 68, 2017.

[38] E. Washburn, "International critical tables of numerical data, physics, chemistry and technology," 2003, retrieved on April 23, 2023. [Online]. Available: http: //app.knovel.com/hotlink/toc/id:kpICTNDPC4/international-critical/international-critical

[39] A. Mahmoudi, P. A. Donkers, K. Walayat, B. Peters, and M. Shahi, "A thorough investigation of thermochemical heat storage system from particle to bed scale," *Chemical engineering science*, vol. 246, p. 116877, 2021.

[40] M. Gaeini, S. Shaik, and C. Rindt, "Characterization of potassium carbonate salt hydrate for thermochemical energy storage in buildings," *Energy and Buildings*, vol. 196, pp. 178–193, 2019.

[41] J. Wu, N. Li, and Z. Wu, "Experimental investigation of latent energy storage systems with the tree-pin-shaped fin," *Applied Thermal Engineering*, vol. 227, p. 120370, 2023.

[42] Y. Huang and X. Liu, "Charging and discharging enhancement of a vertical latent heat storage unit by fractal tree-shaped fins," *Renewable Energy*, vol. 174, pp. 199–217, 2021.

[43] M. Sheikholeslami, S. Lohrasbi, and D. D. Ganji, "Numerical analysis of discharging process acceleration in lhtess by immersing innovative fin configuration using finite el- ement method," *Applied Thermal Engineering*, vol. 107, pp. 154–166, 2016.

[44] M. M. Almutairi, M. Osman, and I. Tlili, "Thermal behavior of auxetic honeycomb structure: an experimental and modeling investigation," *Journal of Energy Resources Tech- nology*, vol. 140, no. 12, p. 122904, 2018.

[45] W. Wang, X. Yang, B. Han, Q. Zhang, X. Wang, and T. Lu, "Analytical design of effective thermal conductivity for fluid-saturated prismatic cellular metal honeycombs," *Theoreti- cal and Applied Mechanics Letters*, vol. 6, no. 2, pp. 69–75, 2016.

[46] M. Abuş ka, S. Ş evik, and A. Kayapunar, “A comparative investigation of the effect of honeycomb core on the latent heat storage with pcm in solar air heater,” *Applied Thermal Engineering*, vol. 148, pp. 684–693, 2019.

[47] J. Fatemi and M. Lemmen, “Effective thermal/mechanical properties of honeycomb core panels for hot structure applications,” *Journal of Spacecraft and Rockets*, vol. 46, no. 3,
pp. 514–525, 2009.

[48] A. Solé , C. Barreneche, I. Martorell, and L. F. Cabeza, “Corrosion evaluation and prevention of reactor materials to contain thermochemical material for thermal energy stor- age,” *Applied Thermal Engineering*, vol. 94, pp. 355–363, 2016.

[49] K. Walayat, J. Duesmann, T. Derks, A. Houshang Mahmoudi, R. Cuypers, and M. Shahi, “Experimental and numerical investigations for effective thermal conductivity in packed beds of thermochemical energy storage materials,” *Applied thermal engineering*, vol. 193, p. 117006, 2021.

[50] A. C. Caputo, P. M. Pelagagge, and P. Salini, “Manufacturing cost model for heat ex- changers optimization,” *Applied Thermal Engineering*, vol. 94, pp. 513–533, 2016.

[51] S. Westerop, “Peak shaving district heating system for daily and seasonal demand techno-economical assessment,” *Internship report*, 2023.

[52] T. Brown, *Engineering economics and economic design for process engineers*. CRC press, 2016.

[53] H. Silla, *Chemical process engineering: design and economics*. CRC Press, 2003.

[54] J. Houben, L. Sö gü toglu, P. Donkers, H. Huinink, and O. Adan, “K2co3 in closed heat storage systems,” *Renewable Energy*, vol. 166, pp. 35–44, 2020.

[55] Alibaba, “Aluminium honeycomb,” https://www.alibaba.com/trade/search?fsb= y&IndexArea=product en&CatId=&tab=all&SearchText=aluminium+honeycomb& selectedTab=product en, 2023.

[56] A. Carro, R. Chacartegui, C. Tejada, G. Gravanis, M. Eusha, V. Spyridon, P. Simira, and C. Ortiz, “Fmea and risks assessment for thermochemical energy storage systems based on carbonates,” *Energies*, vol. 14, no. 19, p. 6013, 2021.