Department of Mechanical and Aerospace Engineering

How Sizing of Thermal Energy Storage affects District Heating Networks and the Decarbonisation of Energy Demand substituting Peak Load with Base Load

Author: Stefan Mennel

Supervisor: Dr Paul G. Tuohy

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Signed: Stefan Mennel Date: Thursday, 25 August 2022

Abstract

In this dissertation, the challenge of how heating demand can be decarbonised is researched, focusing on district heating networks in particular. The aim of this concept design study is to substitute the energy demand met by peak load with the less carbon-intensive heat produced by base load systems. Thus, the fundamental research question is: **How can the integration of thermal energy storage contribute to the decarbonisation of district heating networks?** Two possible coping strategies – the peak shaving and the load shifting approach – are investigated and compared.

First, a sizing tool which helps to tailor the power ratio to meet a certain split of energy demand is introduced. Based on an energy balance model with fixed order control, the potential energy substitution for various capacities of the thermal energy storage is calculated. For an assumed energy split of 80% base load, 20% peak load, and for a moderate substitution below 5%, the proposed load shifting solution leads to a significantly smaller sized thermal energy storage compared to the peak shaving approach. This is assumed to originate from higher (dis)charging cycles during the spring and the autumn, when demand oscillates around the rated base load power and "valleys" help to cover subsequent "peaks".

In the second part of this dissertation, the economic analysis of a system combination relying on biomass to cover base load and natural gas for peak load is carried out. The price difference needed for substitution of 5% of the energy demand using a tank thermal energy storage is found to amount to EUR 0.07–0.10/kWh (i.e., natural gas surpassing biomass). The carbon reduction analysis shows that this substitution results in an amplification factor which expresses how much more carbon is saved compared to energy substituted (both measured in percentages as compared to the original system). The amplification factor depends on local standards and was found to be 2.2 for Switzerland and 3.3 for the UK.

Acknowledgements

This thesis is the result of my original research. However, it would not have been possible without external support and contributions which need to be addressed. I thank…

- … the **“Study Gang”** which openly welcomed and included me, the older stranger. You all offered moral support (and suffered with me): **Chris, Megan, Molly, Fraser, James, Luca, Leo, Andreas, and Yasser** – without you, the sky would be overcast every day. Thank you for letting me participate and share some sunrays!
- … **David Charles**, for once more offering access to a time series of measured heating demand. This piece of work would not be convincing without your support.
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Thomas Schluck, special thanks go to you! You did not only serve as a proof-reader, but more importantly, you offered moral support when the light at the end of the tunnel appeared to be the headlights of an approaching train. Your faith helped me to carry on, thank you.

There are two more persons who really made this piece happen:

Paul Tuohy advised, encouraged, and supported me passionately. Thank you dearly, Paul, for helping me stay on track! Your feedback and remarks stimulated my progress and motivated me to submit a piece that might serve as a stepping stone for future collaboration.

Finally, this year’s studies were only made possible by my partner’s support. She is clever as a crow, solid as a rock, hard-headed, but the best one I know. She was 1,000 km from where I was (but everywhere I went), and I love her deeply.[1]

Sonja, you are the love of my life, and I am thankful for every hour we spend together!

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[1] Reference to “And I love her” by Passenger (2017) who probably refers to “Hard Headed Women” by Cat Stevens (1970).

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Acronyms

By appearance	**Description**
DHN	District Heating Network
TES	Thermal Energy Storage
PCM	Phase Change Material (latent storage medium)
TTES	Tank Thermal Energy Storage
PTES	Pit Thermal Energy Storage
ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
BL	Base Load
PL	Peak Load
SoC	State of Charge

In alphabetical order	**Description**
ATES	Aquifer Thermal Energy Storage
BL	Base Load
BTES	Borehole Thermal Energy Storage
DHN	District Heating Network
PCM	Phase Change Material (latent storage medium)
PL	Peak Load
PTES	Pit Thermal Energy Storage
SoC	State of Charge
TES	Thermal Energy Storage
TTES	Tank Thermal Energy Storage

1.0 Introduction

> *"Scientists bring to our attention urgent but complex problems bearing on our very survival: a warming globe, threats to the Earth's ozone layer, deserts consuming agricultural land."*
> *Gro Harlem Brundtland (Oslo, 20 March 1987)*

More than 35 years ago, Brundtland addressed three urgent issues concerning "Our Common Future" [1], the second of which was amended by the Montreal protocol that same year [2, 3]. Concerning the last of these issues, July 2022 has been the driest month on record in southern England [4, 5] and "losses of 10–50% are expected for crops" [6], emphasising the pressure which has been applied to agricultural land. Global warming might be the foremost concern within the 21st century, and one possible contribution towards addressing this issue is investigated in this dissertation

1.1 Background

In Switzerland, 49% of consumed fossil energy carriers are used to heat buildings [7]. Recently, a study on the refurbishment of heating systems was carried out for the canton of Zurich [8]. The results were disillusioning: 94% of fossil-fuelled systems stayed fossil-fuelled, and only 20% of the customers examined alternative systems [9]. . One potential alternative in densely populated areas would involve connecting consumers to a district heating system, which exhibit a current market share of about 6% in Switzerland [10]. This could be fundamentally changed; a Swiss white paper covering district heating projected the potential market penetration of district heating systems to reach 38% by 2050 [11]. In 2014, a heat roadmap of Europe for the EU27 identified excess heat potential corresponding to 31% of total building heat demand [12]. In the UK, district heating systems cover only 2% of heat demand [13].

1.2 Challenge

It is an inconvenient truth that society faces the general challenge of decarbonisation – as has been reflected by the UN [14–16] and was recently discussed at COP26 [17]. Specifically concerning district heating systems, Hangartner and Hurni have revealed that the majority of consumers still rely on fossil-fuelled peak load coverage [18]. Ködel and Hangartner furthermore showed that many existing district heating systems are soon to be refurbished, and suitable strategies to decarbonise heating energy demand are needed [19]. This offers the opportunity to integrate thermal energy storage to serve as a substitute for fossil fuels.

1.3 Aims and Deliverables

This dissertation strives to present ways to decarbonise district heating networks by substituting carbon intensive peak load with more eco-friendly base load. The aim is to investigate how the sizing of thermal energy storage (TES) affects a district heating network (DHN). Consequently, it focuses on existing DHNs since there are more of them than new developments; additionally, they offer windows of opportunity, especially when they are refurbished or enlarged. The primary research questions are:

How can TES help decarbonise DHN? Which strategy promises a moderate size?

The hypothesis is that TES is integrated and used for either peak shaving or load shifting, and underlying: Which are strategies to reduce the carbonisation of DHNs? Implicitly, the following questions were also included as part of the research: Which of the two approaches is more promising? Most importantly: What are the implications for space needs; how economically feasible are the strategies; and how effective are they in terms of decarbonisation?

As deliverables, (i) a tool for sizing such systems is developed. This approach is based on hourly demand data, and corresponding duration curves are derived. The sizing of the system is a critical step in making use of economies of scale. The tool can help to determine which split of conversion technologies is most profitable for a project.

Additionally, (ii) the sizing of TES and its contribution towards substituting peak load with base load is researched. The two strategies are compared and contrasted. Their operating characteristics are explored to help determine which approach offers which opportunities or disadvantages.

Finally, (iii) an economic analysis of the chosen specific technology combination, using biomass and natural gas, is carried out. This ultimately showcases which TES size is feasible and how this might impact carbon emission reduction.

1.4 Approach

The starting point of this dissertation is a literature review, which serves as the basis for historical trends and the most recent developments, leading to a general understanding of the topic and the identification of sources to build upon (see Chapter 2.0). A detailed system definition reveals the need for simplifications to enable the modelling of the topic within the given timeframe (see Chapter 3.0). Next, the demand data (as hourly datasets) is scrutinised, and appropriate sizing, deduced by making use of a tool that is developed and may serve design engineers in future work, is performed (see Chapter 4.0). Based on a chosen split of power, the influence of implementing different sizes of TES is investigated (see Chapter 5.0). Finally, for one specific technology combination of biomass covering the bulk and natural gas peaks, an economic analysis, along with an analysis of the resulting car-bon reduction, is provided (see Chapters 6.0 and 7.0, respectively). To conclude, the results are discussed, and areas for future work are identified (see Chapter 8.0), before conclusions are ultimately drawn (see Chapter 9.0). For each individual step taken in this research and the goals to be achieved, see Figure 1.

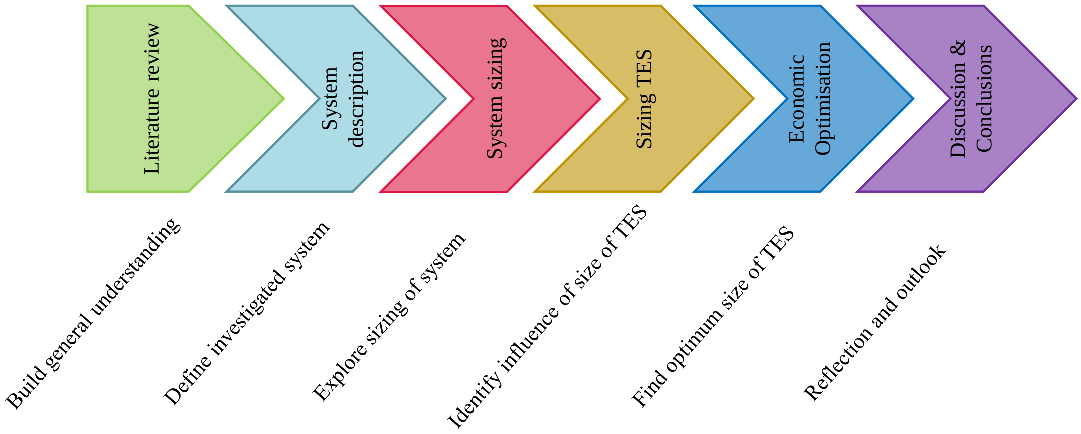

Figure 1: Methodological approach, with the steps in coloured boxes and the goals.

1.5 Scope

This dissertation is written from a Eurocentric – specifically Swiss – point of view.[2] It serves as a concept design study aiming to generate general insights for the integration of TES in DHNs for space heating and domestic hot water. Industrial heat or high-pressure steam are out of the scope of this study. TES run on water as a medium and the use of tank technology are the focal point; sector coupling is not considered. Mainly because of constraints in time, the system investigated in this dissertation was chosen to be as simple as possible, omitting influences such as thermal losses, stratification, and thermoclines due to limitations in the study's modelling capacities. The sizing of the system is exemplified using one year of measured data which has not been adjusted using methods such as heating degree days. The model-ling approach uses hourly timesteps to relate power and capacity (power input in kilowatt equals charging capacity of kilowatt-hours per hour). Instead of sizing TES according to a certain length of time (such as diurnal or seasonal), a parameter run is carried out, and capacities are derived instead of volumes. One system was specifically chosen and sized for further examination. Thus, conclusions are only applicable to that particular configuration. The economic analysis and the analysis of potential carbon reduction are based on documented assumptions. Most importantly, the cost curve used must be critically reflected upon by cost consultants, and calculations of economic viability should ultimately be based on a tender process.

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[2] Switzerland is the author's country of origin. In using a German version of MS Office, some peculiarities are caused by typographic constraints. In all graphs, the separator for 1,000 is the apostrophe instead of the comma.

2.0 Literature Review

Thermal energy storage (TES) can serve a system in a variety of functions. It can, for example, be used to control the shut-down of technologies when the burning chamber still contains fuel; this is a typical application for biomass boilers. Alternatively, they might help to bridge gaps in grid-based supply, a typical application for heat pumps. These applications have already been used in the last century. Furthermore, TES can decouple demand and supply such that supply does not have to follow demand at any particular point in time. This second aspect can help to shave peak demand and thus allow for smaller system sizes and greater flexibility in running the system. Shaving peak demand has thus gained consideration with new systems, such as solar energy harvesting and grid stabilisation attempts in the past decades.

This literature review strives to put TES and the available literature into context. After a short historical overview of solar energy (heavily relying on the decoupling of supply and demand), recent reviews and further reading are discussed. To conclude, TES and sector coupling are covered, and the available sources to build upon are named.

2.1 Solar Energy and TES

There has been an abundance of literature highlighting some aspects and the timely development of the state of the art. The fact that TES can be used to shift generation and consumption in time is especially beneficial for any system running on solar energy. In 1989, the first 100% solar-heated single-family house was built in Switzerland (700 m^2 living area heated by 113 m^3 TES) [20]. The project gained a lot of attention when on 31 January 1990 a press conference was held in the outside pool of 25 m^3 heated to 37°C with surplus energy harvested during summer 1989 [21]. In the following decade, solar energy and the role of TES were further researched (e.g., in Germany’s research and development programme “Solarthermie 2000”) [22]. Some of their presented figures can be found to date, in, for example, the IEA Task 45 final report covering viable seasonal storage systems [23].

2.2 Review Papers on TES

Whilst in this chapter, the most recent literature on TES is reviewed, the topic is not new and has been explored for decades [24]. There are several review papers in which the media favourable for storing thermal energy and which technologies for TES are commonly used now are described. The described media are characterised as thermal (sensible or latent, the latter often as phase change materials [PCMs]) or chemical. The described technologies encompass tank and pit TES (TTES and PTES, respectively) as large, partially buried structures. Aquifer and borehole TES (ATES and BTES, respectively) are other means and depend on local circumstances (ATES: whether there is a suitable, water bearing layer available underground, BTES: whether boreholes are possible due to underground circumstances). Concerning media used to store thermal energy and how they can be categorised, Sarbu and Sebarchievici provided an excellent review [25]. For PCM, Gracia and Cabeza showcased possible applications in buildings [26]. A more in-depth analysis, including properties of media, has recently been provided by Sood et al. [27].

A comprehensive work covering the aforementioned technologies to store heat, including an overview of realised projects and even touching on a few less common possibilities, was provided by Xu et al. [28]. This year, Cruickshank and Baldwin published a chapter about diurnal and seasonal storage, including a sub-section about modelling stratified TES [29]. A UK-based writer’s collective, Mahon et al. published a review on energy storage technologies for seasonal loops, involving a prediction of suitability for ATES, a description of a BTES configuration, an investigation of TTES and PTES behaviour over time (including thermal stratification), and an explanation of waste heat integration [30]. For further reading, a book about TES in German was published last year, describing the topic through 17 dedicated chapters [31].

2.3 TES and Sector Coupling

The coupling of sectors such as heating, cooling, electricity, and natural gas is a heavily researched field with regard to the decarbonisation of energy systems. In this field, energy storage – both thermal and electrical – can help to meet demand and stabilise grids challenged by the intermittent supply of new renewable energy sources such as photovoltaics and wind. For these, value and performance parameters were identified by Tuohy et al. [32]. Whilst “sector coupling” is quite common, this concept has also been called “smart energy systems” and has mainly been introduced by Danish authors [33, 34]. Lund even tried to showcase that this using approach would be cheaper than the electrification of the heating energy market [35]. This case study is based on Danish data, relying on a DHN market penetration of 55%, and might need critical assessment to be transferred to Switzerland (6%) or the UK (2%) [10, 13].

A very interesting approach to valorise TES is to couple it with heat pumps in an environment of time-of-use electricity prices [36]. This work has been further refined and developed into a modelling tool, PyLESA [37]. The combination of TES and time-of-use tariffs to make use of windows of opportunity (especially during peak wind times) is certainly an interesting field of re-search. Its applicability depends on local developments and how the electricity market continues to evolve. It is of higher probability that these scenarios may soon become reality in an environment such as the UK (or Scotland specifically), with very high intermittent energy supply, than it is to be in Switzerland, which relies on 60% hydropower and 29% nuclear power [38].

2.4 Sources to build upon

Within the framework of the EU Horizon 2020 initiative, Flexynets researched the fifth generation of DHNs [39].[3] All the same, the collection encompasses many helpful figures. In particular, the derived cost curves for TTES and PTES are very helpful for economic analysis. The authors elaborated on the importance of temperature differences across TES, cover the basics on heat losses, and provide information on piping cost as well as economic feasible distances for pipelines. In this dissertation, the influence of sizing TES is situated in a new context.

The decentralised placement of storage for residential buildings has recently been researched by Allison et al., who found that seasonal TES is unfeasible because of sizing issues [41]. Therefore, in this dissertation, the timeframe of coverage through TES is left as an open question and investigated in the form of the parameter runs provided. The TES is placed centrally in the heat station.

A general sizing recommendation has been published within the CIBSE framework [42]. This publication focusses on biomass boilers and provides rules of thumb in its fifth chapter on how to size buffer vessels. For a critical review, different sizes of TES are explored in this dissertation, aiming to answer the question of whether oversizing might be beneficial to the overall system’s efficiency and the resulting carbon reduction. This is done by choosing a specific system and performing an economic analysis.

In this limited literature research, one paper addressing “valleys” and “peaks” and how valleys could be used to charge a storage to be later released during peak times was found [43]. This is one of the pivotal ideas of this dissertation and is applied to TES.

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[3] People do not have an unambiguous understanding of this term, as discussed by Sulzer et al. [40].

3.0 System Description

This chapter covers the possibilities of how to set up a general model for any system within building technology. Subsequently, these parts are examined, a Sankey diagram and a simplified model are proposed, and the investigated configuration is described.

3.1 General Model

It has been shown that any system within building technology in its most basic form can be represented in accordance with the nomenclature of (i) source, (ii) conversion, (iii) storage (if applicable), (iv) distribution, and (v) consumption and room [44]. In accordance with this approach, the investigated DHN and its associated losses are represented in Figure 2. In this dissertation, the heat station, containing source, conversion, and storage is discussed in depth. However, distribution, consumption, and room will be excluded from further analysis. Each of the elements and the most important features are briefly described in the following chapters.

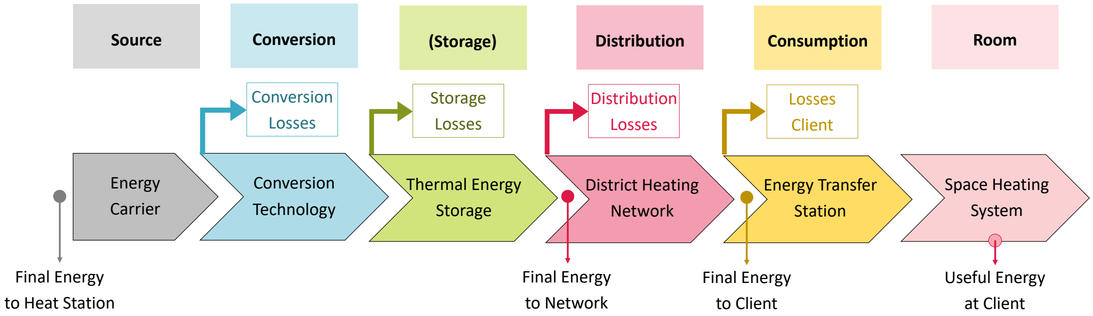

Figure 2: General description of the investigated system, including losses at various stages.

3.2 Source and Conversion

A limited number of primary energy carriers are available to serve as sources for heating. These sources could crudely be differentiated based on their conversion technology into carriers relying on combustion (such as natural gas, heating oil, or biomass) and carriers applying other methods (such as heat pumps or solar thermal collectors). Otherwise, they can be categorised based on the ways in which they are delivered into the grid (such as natural gas and electricity), delivered by road (such as through heating oil and biomass), or harnessed through ambient sources (such as solar radiation or ambient heat from air, water, ground). In this dissertation, the specific choice of sources is secondary and only important in terms of differences in energy prices and carbon emissions in Chapters 6.0 and 7.0.

Table 1: Selected sources, their conversion technology, and ways of delivery.

Sources (selection)	Grid-based	Delivered	Ambient
Combustion	Natural Gas	Heating Oil Biomass	
Other method	Electricity (Heat Pumps)		Solar radiation Air, water, ground

Of greater importance to the system description is the chosen approach of conversion technology. In particular, the strategy of how to cover peak demand is crucial. Smaller systems such as single-family houses or multi-family homes typically rely on one type of conversion technology. This is called a "monovalent" solution. Thus, this single component is sized to cover the peak demand and runs most of its operation time in part-load. The specific behaviour for part-load depends on the technology chosen and is illustrated in Figure 3 with demand on the y-axis decreasing, showcasing the system's ability to reach a certain turn-down ratio. Once a certain turn-down ratio is reached, the system needs to enter in a cycle with on-off behaviour. The turn-down ratio thus defines the minimal load coverable in a continuous operation mode. Turn-down ratios typically range from 1:2.5 (40% minimal load) to 1:3.5 (30% minimal load). Thus, monovalent systems experience high number of cycling hours.

Figure 3: Monovalent characteristics of heat supply including turn-down ratio.

In larger systems such as DHN, it is common to divide the coverage of power demand by using at least two different technologies. This is called a "bivalent" solution, in which several sub-categories can further be differentiated (bivalent-alternative, bivalent-partially parallel, or bivalent-parallel). In Figure 4, the bivalent-parallel behaviour is exemplified since it is the most general solution for bivalent approaches. This is mostly because of the resulting high number of operation hours for the system covering the base load (BL). In contrast, the back-up system covering peak load (PL) has a reduced runtime. This directly impacts the choice of applicable technologies.

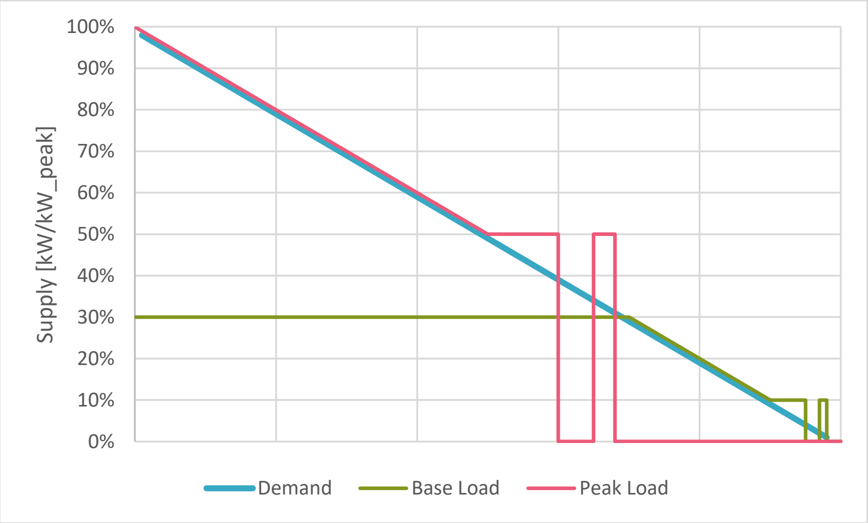

Figure 4: Bivalent characteristics of heat supply, including the system's turn-down ratios.

The choice of applied technologies is typically based on economic considerations. It has therefore become common to use technology options with high capital expenses (CAPEX) but low operating (fuel) expenses (OPEX) to cover BL. Widespread examples of BL coverage include combined heat and power schemes, heat pumps, or biomass boilers. The opposite is true in efforts to cover PL, where low CAPEX are typically favoured and high OPEX accepted. Typical examples for these technologies include boilers using fossil fuels (natural gas or heating oil) or electric resistance heating.

In this dissertation, the chosen system configuration is comprised of a bivalent-parallel system with one unit covering BL and another covering PL. This system configuration is the simplest system configuration. In more complex designs, BL and PL can be covered by more than one conversion unit. There are good reasons for this – especially for PL coverage – such as the security of the supply, more advantageous turn-down ratios, or redundancies to cover maintenance intervals. Implicitly, to act as sources for BL and PL, the energy carriers need to differ to allow an economic analysis and the accounting of carbon reduction (see Chapters 6.0 and 7.0).

3.3 Storage

If storage is included into the system, the literature review indicated several possible media and technologies. For this dissertation, water is used as a liquid medium rather than phase change materials (PCMs) because TES running with water has no delay regarding (dis)charging time. For PCMs, a certain maximum charging and discharging capacity applies. In contrast, stored hot water can be released in its entirety within one timestep, resulting in the development of a very simplistic model.

Tank and pit storage (TTES and PTES, respectively) are included in the technologies considered in this research. Unlike aquifer and borehole storage (ATES and BTES, respectively), TTES and PTES can be built independent of underground conditions and restrictions. Again, this is only applicable for the economic analysis and does not affect the study's general findings.

Heat losses are influenced by the following three factors: (i) external heat losses due to convection and conduction, (ii) thermoclines arising because of conduction over a longer timeframe, and (iii) losses because of sub-optimal stratification during (dis)charging. Here, it is worth inspecting the typical geometry of TTES. In essence, these are cylindrical structure works, the largest of which, when constructed as a free-standing steel construction, have been found containing 28, 000 m^3 (30 m diameter, 50 m height, 1.3 MWh capacity) [45]. For smaller storage units, a diameter to height ratio of 1:3 is more typical, and for both ratios, the surface area to volume ratio and the needed height are depicted in Figure 5.

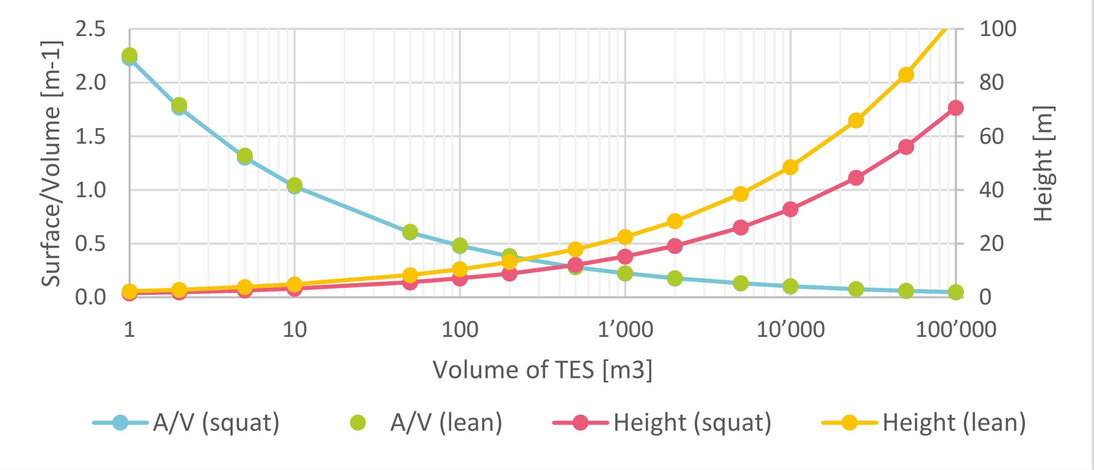

Figure 5: Surface area to volume ratio A/V and resulting height for volumes of TES.

It is noticeable that the surface area to volume ratio A/V for a squat (3:5 = 0.60) or a lean geometry (1:3 = 0.33) basically remains unchanged. It is also evident that this ratio declines rapidly for larger volumes (from close to 2.5 for 1 m^3 to less than 0.5 for 100 m^3). Thus, external heat losses rapidly loose importance for larger TES since the volume is less exposed to the outside. Therefore, external heat losses are excluded from this study. It is, furthermore, obvious that a leaner geometric design results in a greater height, which can be beneficial in reducing the influence of thermoclines (ii).

As is shown later, the needed volume exceeds 1,000 m^3. Therefore, thermoclines are also excluded. For further reading, the concept of a thermocline is described well by Goeke (page 50f [31]). Stratification (iii) is mostly influenced by (dis)charging velocities and the constructive solution (e.g., number of inlets, use of diffusors, and sizing pipes; cf. Goeke page 52ff). In this dissertation, stratification is deemed “perfect”, not causing losses. These assumptions lead to a simple model for energy balancing.

The capacity of any storage system follows the calorific laws described in Formulae 1a and 1b. When water is used as a medium, this can be simplified using a calorific heat capacity of 4.2 kJ/kgK. This is true at 85°C, whilst the often used 4.186 kJ/kgK applies at 65°C. Glück published the relevant tables and formulae in the 1980s [46]. The resulting deviation is less than 1% (0.33‰). Using a density of 1,000 kg/m^3 (at 4°C) results in a somewhat higher deviation of 2.0% (compared to 65°C).

$$C_{TES} = V \cdot \varrho \cdot c_{P_{water}} \cdot \Delta t \qquad \text{(Formula 1a)}$$

$$C_{TES\_simplified} = V \cdot 1000 \frac{kg}{m^3} \cdot 4.2 \frac{kJ}{kgK} \cdot \frac{1}{3600} \frac{h}{s} \cdot \left(t_{charge} - t_{return}\right) \qquad \text{(Formula 1b)}$$

where **C_{TES}** is the heat capacity stored within the TES (in kWh), **V** is the volume [m^3], **ρ** is the density (in kg/m^3), **c_{Pwater}** is the calorific heat capacity (in kJ/kgK), and **Δt** is the temperature difference between charging and return temperature (in K).

Given a medium (water) and a used volume, the capacity of any TES is thus only tied to the temperature difference between charging and return temperature. It is notably not tied to the difference between the system’s supply and return temperature since the supply temperature could be less than the charging temperature when using a three-way valve (see Figure 6). Consequently, for a given medium and a given charging temperature (e.g., 90°C), the capacity per volume only depends on the return temperature of the system. This is later used to size the TES (see Chapter 5.0).

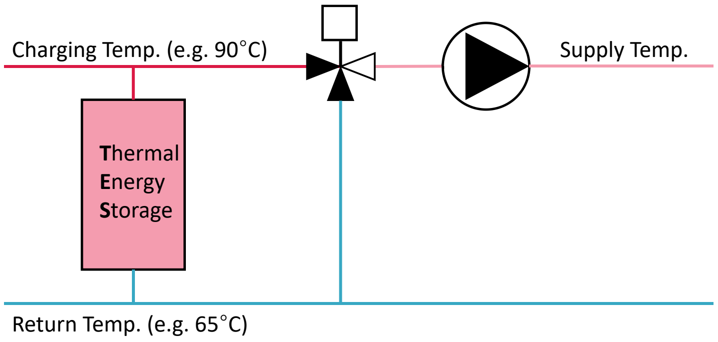

Figure 6: Capacity of TES as the difference between supply and return temperatures.

3.4 Distribution and Consumption

Once the heat has been generated in the heat station, it needs to be distributed to the consumers with demand. If a network covers a specific demand (heating or cooling), the technology applied was established in the 1880s, and additional reading has already been made available [47]. Recent years have seen a keen development of new features and detailed discussions of how to categorise district heating networks. The most cited concept was proposed by Lund et al. and differs four different generations depending on the supplied temperature (and subsequent requirements for piping) [48]. Most of the work presented since then has covered the topic of how to reach lower supply temperatures and thus minimise the thermal losses of the heating network.

These thermal losses follow the laws of thermodynamics and cannot be avoided. They depend on the distribution temperature, as well as the sizing of pipes and their respective level of insulation, ground temperature, and properties. An important factor in thermal losses is flow velocity, which is typically lower in the summer and thus leads to higher losses. Therefore, recent research has focused on decreasing supply temperature. In contrast, the capacity of any integrated TES depends on the return temperature since, for systems relying on combustion, the charging temperature can be assumed to be 90°C. These losses lead to a difference in the “final energy entering the heat station” and the “final energy delivered to the consumer”, some-times causing insecurities. A potential solution that also provides seasonal bench-marks for losses of DHN has been proposed [49]. Finally, the useful energy that reaches a room is very much dependent on the configuration within a consumers’ home and out of scope of this work.

3.5 Simplified Model and Sub-Categories

After introducing the general model in Chapter 3.1, the considerations of Chapters 3.2–3.4 in combination with the assumptions taken allow for a simplified approach. The model representing the system's properties is demonstrated below in Figure 7. The respective heat fluxes are reduced to the final energy input to the heat station and the heat delivered to the network. These simplifications allow the modelling of different scenarios using an energy balance approach.

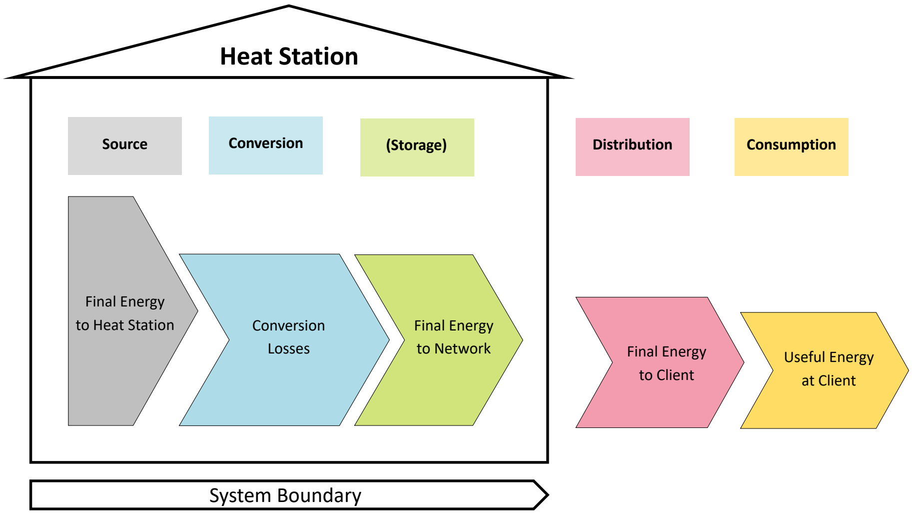

Figure 7: Heat fluxes of the simplified model and system boundary.

Hence, three possible scenarios can be investigated. First, a system without using TES.[4] Second, a system using TES to shave peaks and thus reduces the installed power. And third, a system that uses TES to shift loads. This is the prioritised subject of this research (details are provided later in Chapter 5.0). Table 2 summarises a qualitative comparison of the resulting capacities, goals, and expected loading cycles.

Table 2: Sub-systems, how capacity is tailored, the goals, and the expected loading cycles.

Sub-System	**Capacity**	**Goal**	**Loading cycles**
No TES	None	Low CAPEX	
Peak shaving	Tailored to cover peak	Reduce peak load	One cycle each of (dis)charging
Load shifting	Optimised for substitution	Substitute energy with BL coverage	Many (dis)charging cycles and hours

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[4] It is noteworthy that according to CIBSE this does not mean that no storage capacity is used as for biomass boilers, since at least a buffer vessel should be installed for security reasons, c.f. Chapter 5 and page 47 [42].

4.0 The Sizing of Systems

First, the demand profile and how it can be deduced are discussed. Then, the conversion of demand profiles into duration curves is described. This leads to a closer analysis of power versus energy demand and how power meets a certain fraction of energy demand. Subsequently, the sizing tool that provides answers to this question is introduced. The section concludes by stating the sizing chosen for the subsequent analysis.

4.1 Demand Profile

At the beginning of sizing a system, the demand profile should ideally be known. This dataset can be supported by measured data or derived from a dynamic simulation. If not, at least the peak demand should be known, calculated according to the national interpretation of European standards [50]. This may lead to less accurate results since only one point in time is used. Goeke and Popp exemplified how a linearised approach to generating an appropriate time series can be deduced based on peak demand. They account for heating demand in relation to outside temperature using statistical weather data and adding a fixed value for domestic hot water [51]. In contrast to such an approximation, this dissertation benefits from a measured demand profile of a university campus in Scotland. Half-hourly data of energy leaving the heat station was converted to an hourly dataset, thus resulting in a slightly less fluctuating profile. This profile was then scaled to 1,000 kW to allow for comparison with other demand profiles. Because of limitations in time, this comparison ultimately could not be carried out. In Figure 8 below, the power demand used (average hourly value per day) is shown.

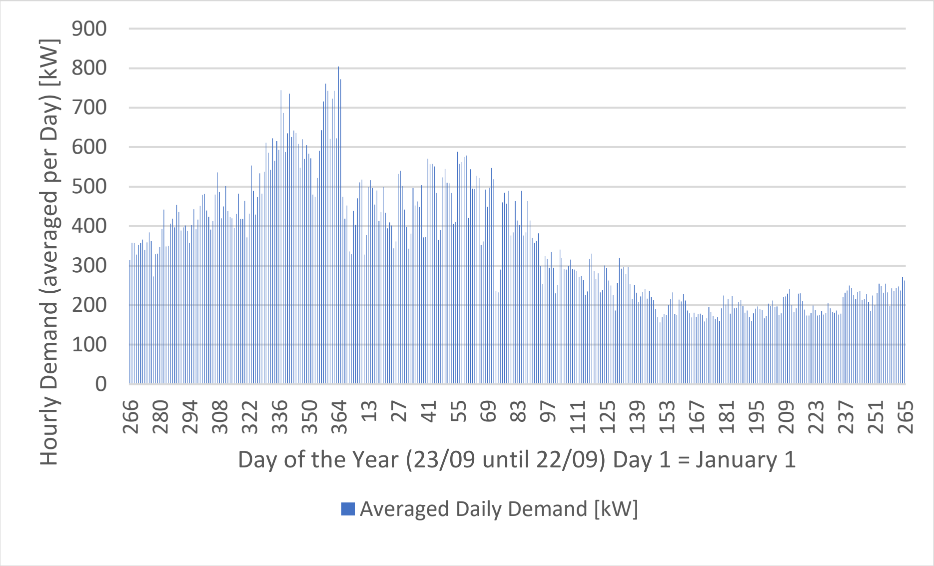

Figure 8: Yearly profile with average demand, starting at the autumn equinox.

4.2 Duration Curve

Once the demand profile is known, the corresponding duration curve, measured as the alignment of the demand according to size and independent of its time of occurrence, can be generated (see Figure 9). This curve makes it evident that a high level of demand is limited to very few hours in a year (e.g., demand exceeding 700 kW only exists during about 440 hours of the year). Furthermore, this dataset displays demand throughout the year (8,760 hours) whilst peak demand occurs only one hour of the year. Thus, the distribution of demand over time is not uniform. This is a general truth and leads to the question of how this distribution impacts the sizing of systems.

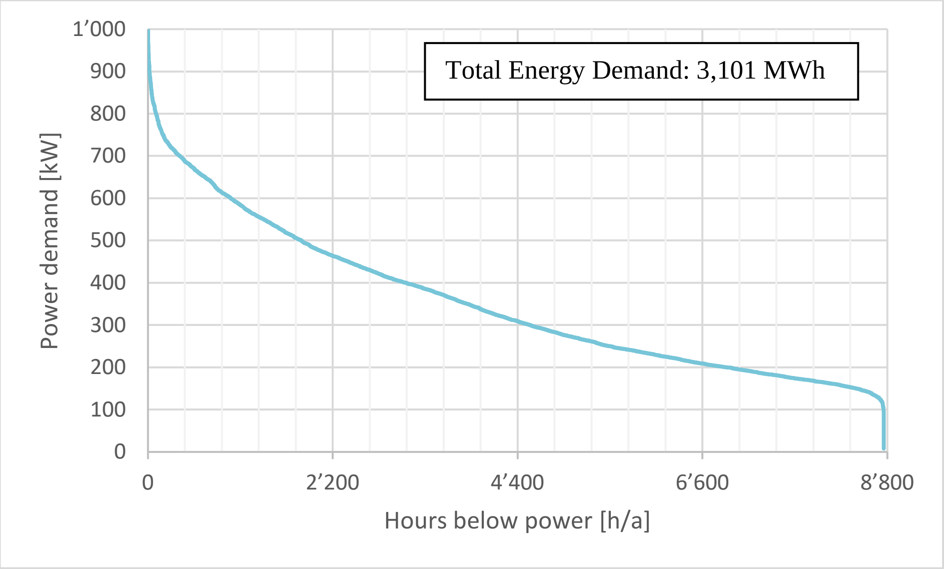

Figure 9: Duration curve as power demand, and hours below power needed.

4.3 Power vs. Energy

To account for sizing, demand profiles and the subsequent analysis of duration curves are very helpful. The area below a certain rated power represents the energy requirement met by a specific bin of power. For example, the demand hardly ever falls below 100 kW. Thus, the energy provided by the first 100 kW of any system is 876 MWh (8,760 h times 100 kW). A total demand of 3,101 MWh equals 28%. This exemplifies how low power demand dominates energy consumption.

Subsequently, to size a system, a desired fraction of energy demand met can be used. Typically, bivalent systems are tailored for 80% energy demand met by BL, leaving 20% for PL as suggested by Ködel and Hangartner [19].

In Figure 10, the power demand to meet a given fraction of energy demand is depicted. This suggests that to meet 60% of the energy demand, only a little more than 200 kW power are needed (represented by the green dot). For 80%, slightly more than 300 kW suffice (the orange dot), whilst close to 500 kW (red dot) are needed to meet 90% of the power demand. This illustrates the challenges in appropriately sizing heating systems since for the last 10% of energy, more than half of the PL power is needed.

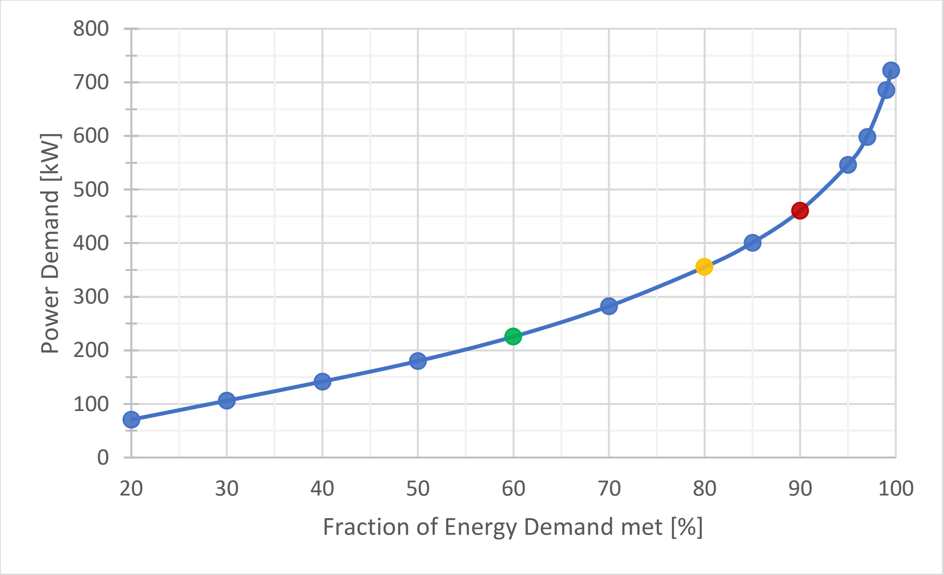

Figure 10: Power need to meet a given fraction of energy demand.

The results for the demand profile used are presented in Table 3 below. To help engineers tailor their systems, the mechanism of accounting used is provided as an Excel tool and is further described in the following chapter.

Table 3: Energy fraction of total demand met by power needed for coverage.

Energy Fraction [%]	30	60	80	90	95	97	99	99.5
Power Needed [kW]	106	226	355	460	546	598	686	722

4.4 Sizing Tool

The sizing tool used in this dissertation makes use of Excel and is made available on request.[5] Its goal is to convert a time series of demand, providing a summary of properties pertaining to the profile to offer duration curves and to account for the power needed to meet certain fractions of energy demand. This tool has been designed to help engineers in the design process. The dataset to be scrutinised is copied to cell C:10 (marked yellow). Subsequently in a first table PL, minimal load, the number or hours with demand, total energy demand, and the scaling factor are shown (see Table 4).

Table 4: Summarisation of important properties of the dataset to be analysed.

Peak Load [kW]	12’450
Minimal Load [kW]	90
Hours with Demand [h]	8’760
Energy Demand [MWh]	38’613
Scaling Factor [-]	8%

The macro “Duration Curve” generates graphs for both the original dataset as well as a scaled dataset with a PL of 1,000 kW.[6] The motivation for using a standardised PL is to allow for the comparison of different networks and thus to benefit from lessons learnt. Here, the result for the original dataset is presented; however, the scaling of the y-axis is automated by Excel and might need adjustments (see Figure 11).

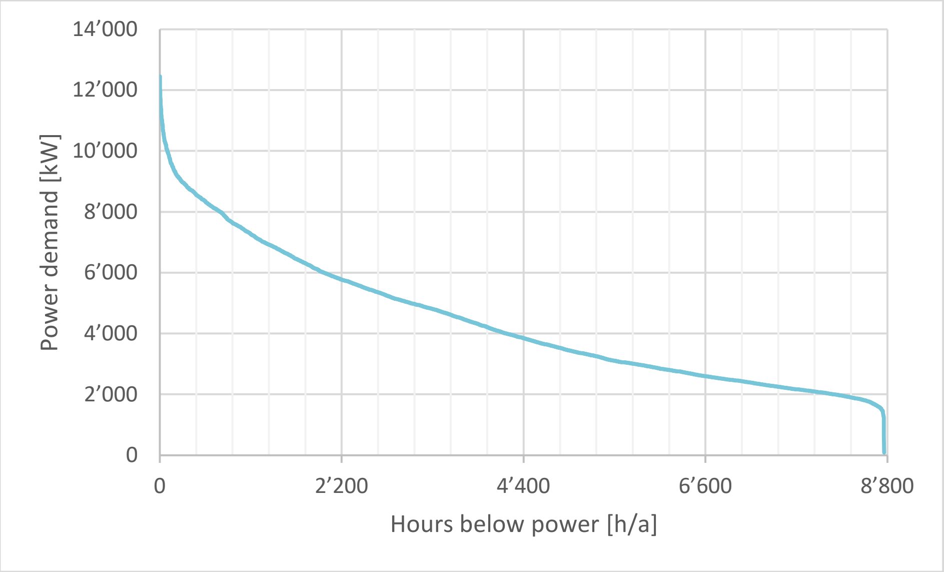

Figure 11: Generated duration curve for the raw dataset.

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[5] Since Github does not accept *.xlsm-files, please contact stefan.mennel@hslu.ch to get access.

[6] The mechanism for generating the duration curve involves the alignment of all hourly values starting with the highest (Z-A arrangement). The graphs referencing the aligned values have been prepared.

To answer the question of how much power is needed to cover a certain fraction of energy demand, the macro “DemandFraction_PowerNeed” was integrated.[7] The results are presented as a second table (see Table 5).

Table 5: Power need to meet a certain fraction of the energy demand (tabulated, excerpt).

Demand Fraction [%]	**10%**	**30%**	**50%**	**70%**	**80%**	**90%**	**95%**	**97.5%**	**99%**
Power Need (scaled) [kW]	35	106	180	283	356	460	546	614	682
Power Need (unscaled) [kW]	441	1’323	2’242	3’519	4’427	5’733	6’803	7’639	8’490

These results are graphically visualised in Figure 12. For higher fractions of energy demand, the spacing has been adapted. This was motivated by the sharply increased power demand to meet higher fractions. The results were also transferred to the duration curve for an exemplary 30% (e.g., combined heat and power), 80% (BL), and 95% (possible PL coverage by TES; see Figure 13).

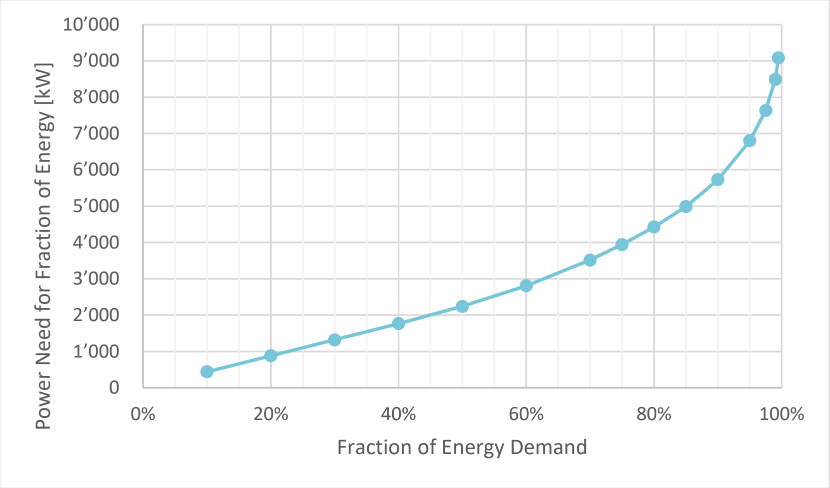

Figure 12: Power need to meet a certain fraction of energy demand (visualised).

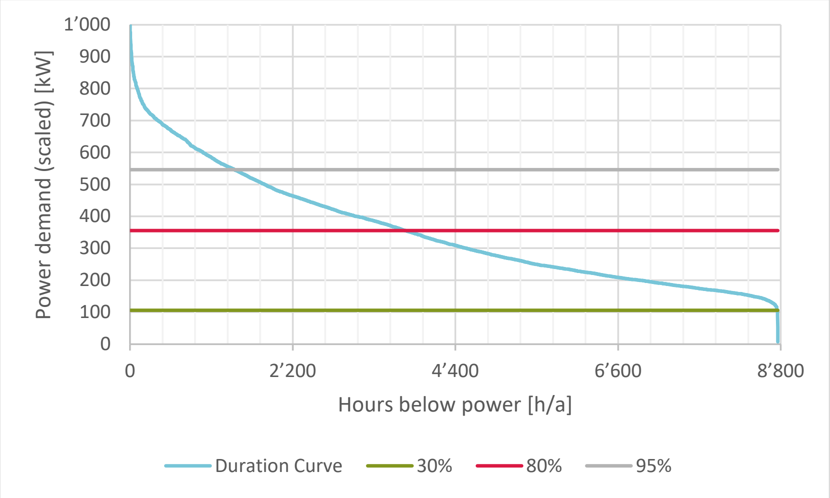

Figure 13: Duration curve (scaled) and power needed to cover fractions of energy demand.

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[7] The macro uses the “target-value” function. Excel basically iterates the power needed to meet a certain fraction of energy demand. BL is allowed to meet the need of the hour for this but not to exceed its own rated power.

4.5 Sizing chosen for subsequent Analysis

Additional analysis was carried out using one chosen sizing. BL is tailored to cover 80% of energy demand, leaving 20% to be covered by PL. This is a very common split and was proposed by Ködel and Hangartner for economic reasons [19]. In accordance with the aim of this dissertation – to substitute PL with BL – the threshold of 95% energy demand is added to serve as a reference point. This appertains to a 25% decrease of PL coverage (15% instead of 20%).

Some effects of this particular sizing can be exemplified by more closely examining representative weeks of the used demand profile. During cold winter days, the rated power of the BL hardly exceeds the demand. Thus, BL runs at fully rated power throughout this period. If 5% of energy demand is available as stored capacity, all peaks above the grey line can be covered by TES (see Figure 14).

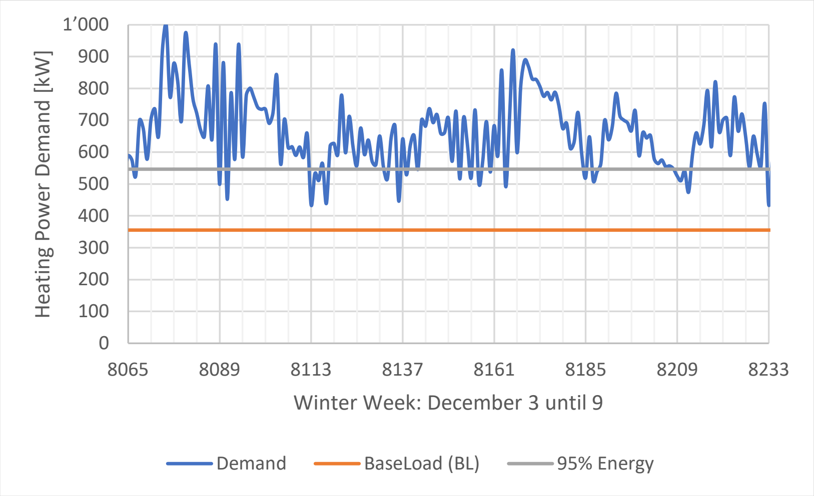

Figure 14: Representative week for winter (December 3–9).

The opposite is true for summer. Here, BL always exceeds demand (see Figure 15).

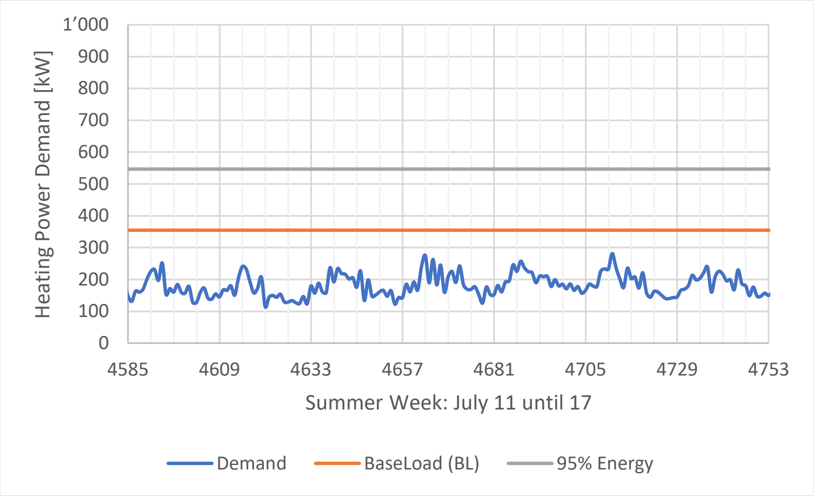

Figure 15: Representative week for summer (July 11–17).

Of particular interest are spring and autumn since they represent the bulk of the year. During this time, demand tends to circle around the rated power output of the BL. Times of demand undercutting BL power are henceforth called “valleys”, whilst periods when demand is exceeded are called “peaks” (see Figure 16). During this time, demand typically does not exceed the grey line, representing 95% of the energy fraction. Therefore, a readily available capacity to cover this demand is not necessary.

Much of the choice to investigate this topic was motivated by the opportunities presented by “valleys”, during which excess heat could be collected and then later released during “peaks”. The promising short duration of circles could lead to maximum utilisation of TES potential and possibly to smaller storage sizes. The potential for this is further investigated in the following section on the sizing of TES.

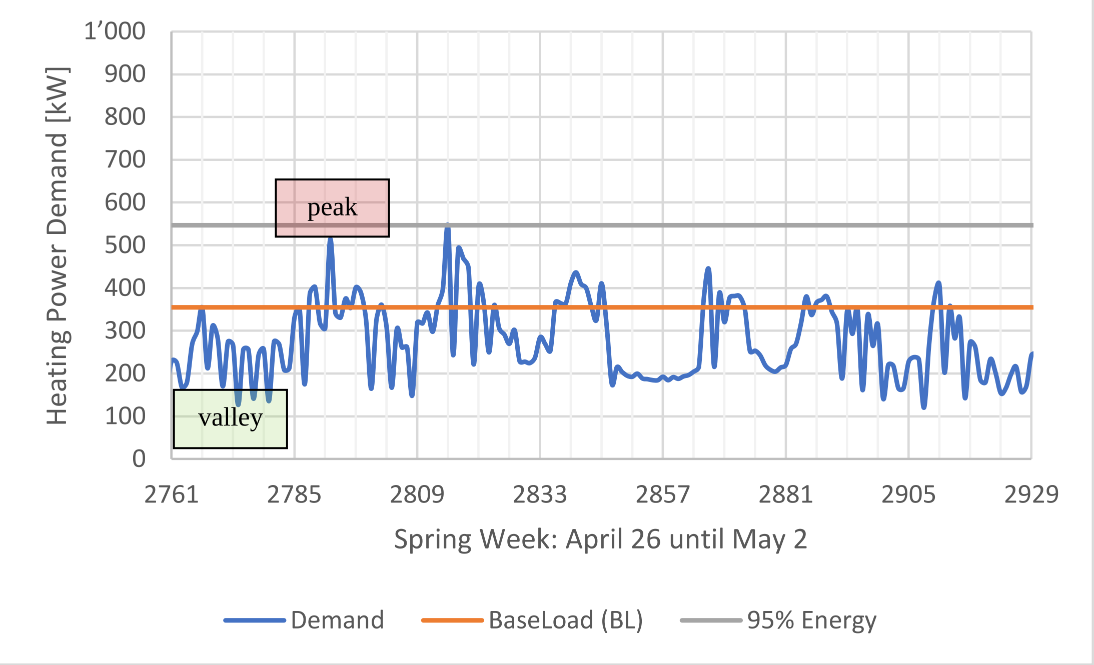

Figure 16: Representative week for spring (April 1–7).

5.0 Sizing of Thermal Energy Storage

In this section, different approaches to integrating TES are discussed. The model used is described, and the results are critically reflected upon. To conclude, the resulting size, which is dependent on capacity need and return temperature, is calculated.

5.1 Approaches for Integration of TES

On the upside, integration of TES allows for shifting of demand in time. Of course, another approach is to abstain from the integration of TES, thereby requiring the heat station to cover the demand as precisely as possible at any given time to avoid temperature fluctuations. The advantages of abstaining from the integration of TES are that it would neither demand space nor require additional investment for TES.

Another approach is to shave the peaks of the demand. As has been shown, high peaks are very limited in occurrence (see Figure 13 on page 19) and constrained to the winter months (see winter week, Figure 14 on page 20). Thus, using TES to cover energy demand can reduce the power need of the PL system. The priority in this approach is to first meet the demand by BL and then PL up to its maximum capacity, followed by TES, guaranteeing that demand requirements are met using pre-stored capacity. An example of the demand as met by these three technologies is represented in Figure 17. Power and capacity demand (as dyed area) are provided alongside energy fractions met in ascending order, according to the sizing tool.

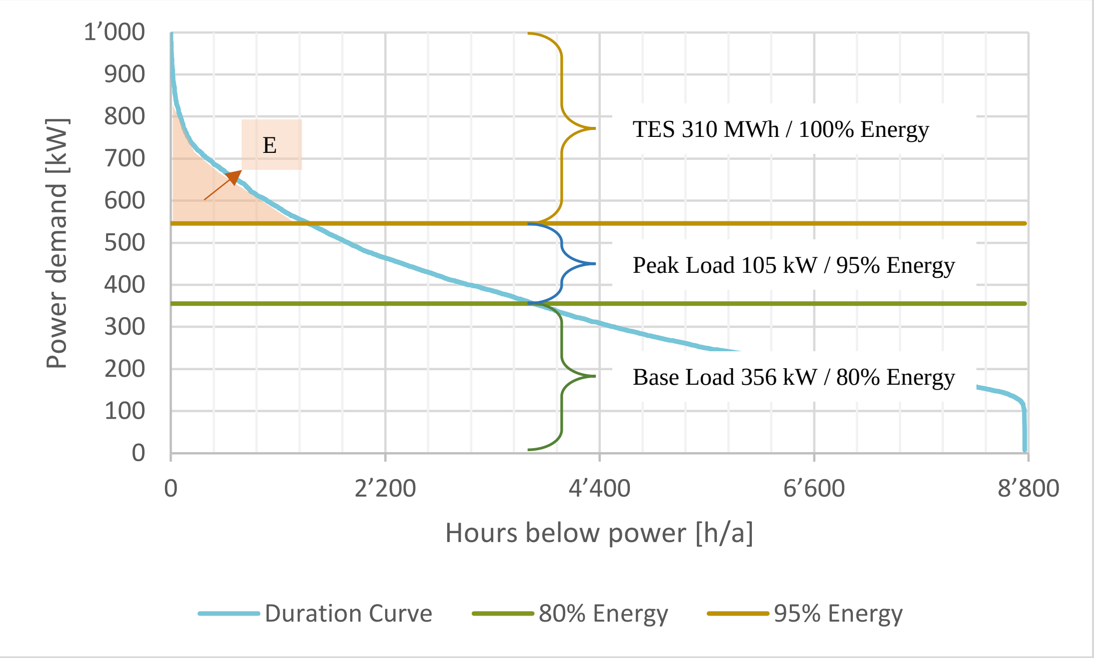

Figure 17: Peak shaving with energy demand met by BL (80%), PL (15%), and TES (5%).

This is exemplified in Table 6, where power needs for BL and PL and the resulting capacities for TES integration are provided (0% TES means no integration). Note that the TES used must not be considered a conversion technology but rather a coping mechanism to reduce power need. Power demand is reduced by a factor of more than three in this example, which compares no TES with a moderate 5% TES integration (155 MWh). The TES still needs to be charged to be able to release its capacity later to substitute PL power demand. Additional details are provided in Chapter 5.2.

Table 6: Percentage of energy coverage by BL and PL with the rest met by TES.

	10% TES	5% TES	0% TES
TES [MWh]	310	155	-
Peak Load [kW]	105	191	644
Base Load [kW]	356	356	356

A third approach to integrating TES is to make use of the periods where demand oscillates around rated BL power. This is a load shifting approach which the limited literature review has not discussed yet. The priorities for meeting demand are shifted here. First, BL covers demand, followed by TES (if capacity allows). Once the capacity of TES is exhausted, PL covers the demand, resulting in PL needing to be sized to meet the full peaks since TES could be exhausted at the times at which peaks occur.

The demand covered by TES for both cases is represented as a brownish area and is equal to 5% of the total energy demand. This exemplifies the potential of using duration curves in which distribution over time is included. Optically, it is deceiving to judge the equivalence of areas. Thus, the power of the sizing tool is illustrated.

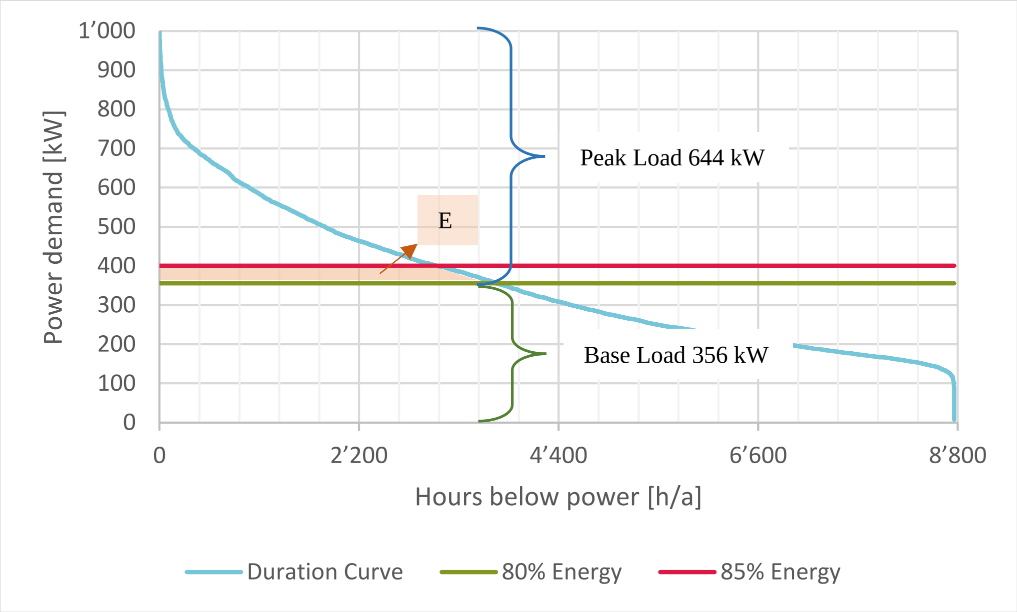

Figure 18: Load shifting with energy demand met by BL, TES, and PL.

5.2 Peak Shaving Approach

For the peak shaving approach, energy needs to be stored before it can be released to later substitute PL. The aim of this dissertation is to substitute PL with the energy provided by BL. Thus, this energy needs to be stored during the summer before demand exceeds the BL power. This need is more obvious when the average hourly demand per day is depicted over a year, starting from the autumn equinox (September 23). In Figure 19, the blue bars represent the average hourly demand per day, the green curve represents a polynomial approximation, and BL is represented as a horizontal orange line. The highest peaks appear between the 330th day of the year (the end of November) and last until the beginning of the new year, whilst the lowest demand can be found around the 200th day (the end of July). This is very typical for European profiles, which are dominated by space heating and domestic hot water demand.

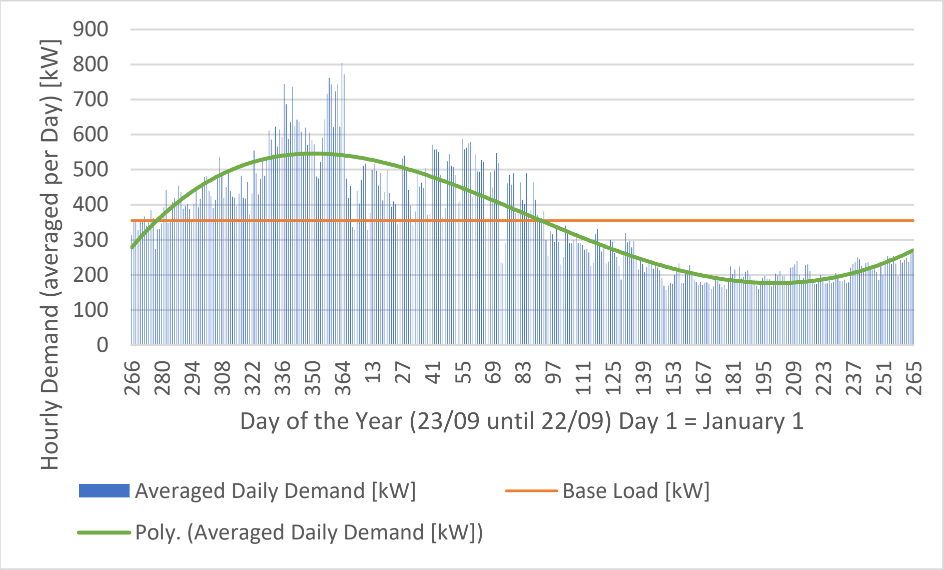

Figure 19: Average hourly demand per day for a year starting at the autumn equinox.

The need to have the capacity charged before the heating season results in long storage intervals and few (dis)charging cycles. Consequently, it is expected that the TES is subject to thermal losses. A modelling approach not taking thermal losses, stratification, and thermocline into account is bound to be biased. Nevertheless, these opportunities are worth mentioning. The approach's clear advantages include allowing for the sizing of smaller systems (for new systems) and further expanding systems (for existing systems). Additionally, even a biased capacity (underestimated and therefore too small) can serve to contrast the two approaches, peak shaving and load shifting.

5.3 Load Shifting Approach

In this work, the peak shaving approach is contrasted to a load shifting solution which is deemed promising. The load shifting approach strives to use the periods when demand oscillates around the BL power rating (cf. Figure 16 on page 21). Thus, it makes use of "valleys" in demand to charge the TES and releases this energy shortly after, when demand "peaks" and surpasses the ability of the BL system to meet it. This is illustrated in Figure 20, where a 36-hour period is represented. Demand is shown as light green line; the load for BL is depicted as blue bars (note: it is always full load). Charging is a power flow leaving the DHN (into the TES) whilst discharging covers the demand and is represented as a stacked bar atop BL. Once the capacity of the TES is exhausted, PL covers the rest and tops up as stacked bar (in grey) to meet demand. This simplified example starts with an empty TES.

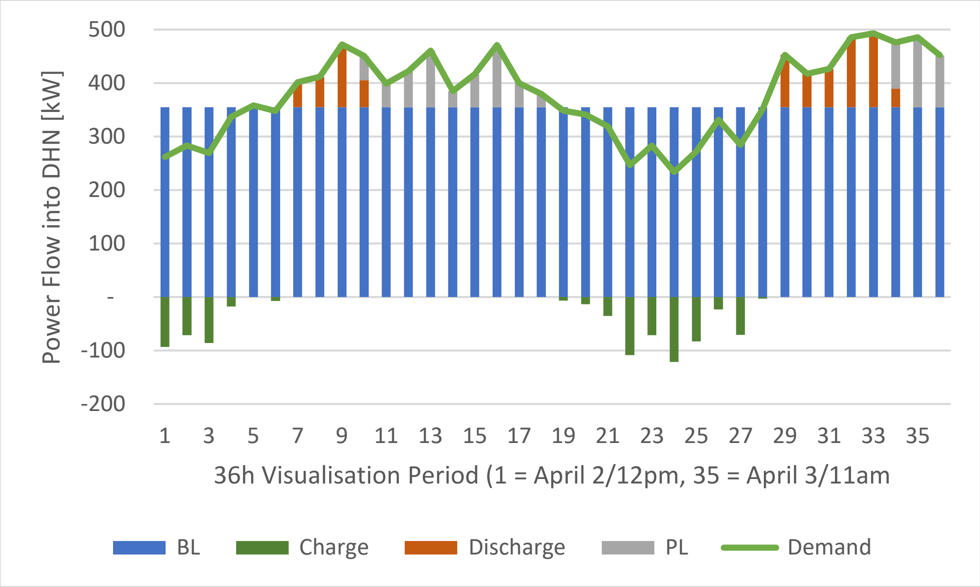

Figure 20: Simplified example showing (dis)charging during "peaks" and "valleys".

Up to this point, all considerations have been based on duration curves and energy fractions. This new load shifting approach, however, calls for additional examination: **What is the state of charge (SoC) of the associated TES?** The SoC expresses the level to which the TES is charged. It is thus the ratio of the capacity of the TES at the timestep compared to the maximum capacity. Once the SoC reaches 100%, no further charging is possible, and discharge is also no longer possible once SoC has dropped to 0%. This happens in hours 10 and 34 when TES capacity is depleted, and PL is needed to cover the remaining demand. Furthermore, between hours 18 and 26, a total of 536 kWh is stored, implying that the size of the TES used is of appropriate volume. This is further explored in the next chapter.

5.4 Model Description

The model is a simplified energy balancing model that makes use of Excel. The leading parameter is the demand, which always needs to be met.[8] The model uses fixed order control and has no foresight abilities (see Figure 21 and description below). To gain insights, the TES is not sized by the model but in a parameter run.

In a first sequence during low demand, the model seeks to maximise BL to its rated power of 356 kW. This is possible if the surplus can be used to increase the SoC (Prio 1b). Overfilling is prevented, and the BL is reduced for a SoC of 100%. (Prio 1a)

In a second sequence during high demand, the BL no longer suffices to meet demand. Thus, the model seeks to maximise the discharge of TES until its SoC falls to zero (Prio 2). If residual demand is left, this is covered by PL (Prio 3). In each timestep, the capacity can be fully used for both discharging and charging.

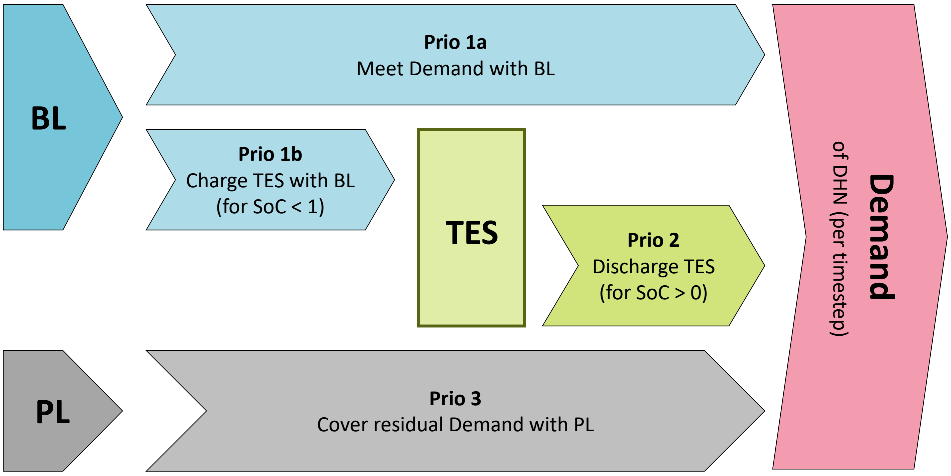

Figure 21: Modelled fixed order control to meet demand.

To illustrate the behaviour during low demand, the consequences are visualised for an exemplified capacity of 3,000 kWh, corresponding to 1‰ of total energy demand. **The first sequence** described pertains to an increasing SoC and how BL needs to be reduced once the SoC reaches 100%. In Figure 22, the BL system is run at full power (green bar), and the surplus is used to charge the TES (orange bar). This energy is then released with a time shift and therefore is not stacked. Charging can be used until the SoC reaches 100% (brown line, right y-axis). Next, the output of the BL system is reduced to exactly meet the demand (blue line), and the SoC remains constant (no thermal losses).

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[8] Please refer to the flow-chart provided in the appendix for more details.

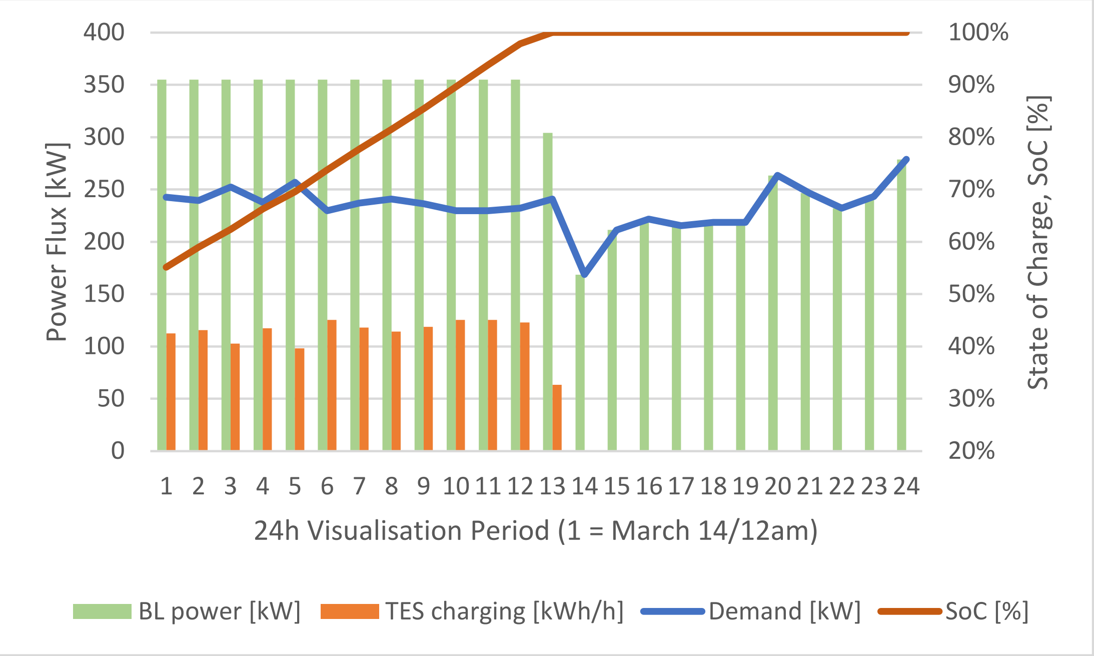

Figure 22: Sequence showing how increasing SoC leads to capped BL power output.

The second sequence described a decreasing SoC. Here, BL runs at full power (green bar) and the TES is discharged (orange bar), topping up power to meet demand (blue line). With TES discharged, the SoC is reduced (see Figure 23). Once the TES is fully depleted, the PL system covers residual demand. Note that in hours 12 and 15, as well as 23 and onwards, the demand is below full BL power. Consequently, the SoC slightly rises (charging indicated as black line), and in the following hours, the TES is discharged again.

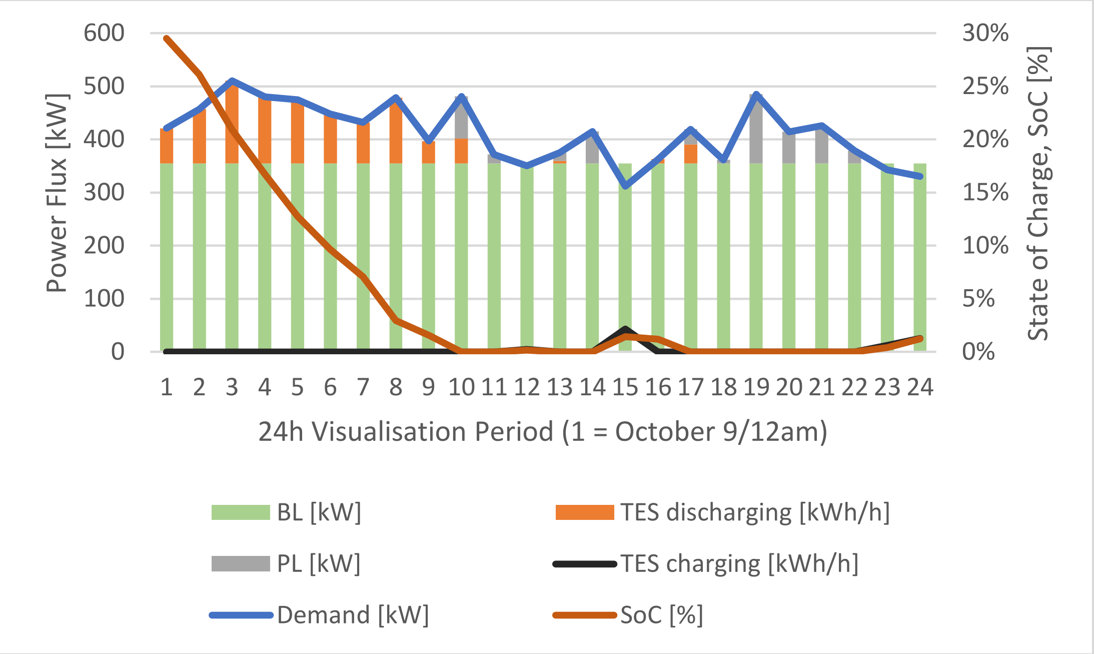

Figure 23: Sequence showing how decreasing SoC leads to depletion and coverage by PL.

5.5 Modelling Results

The leading key performance indicator to be determined is the additional energy demand substituted by BL. The energy substituted as a percentage of total demand experiences a steep increase for small capacities and is subsequently linear (see Figure 24). The aim of substituting 5% of PL with BL can be met by a capacity of 75,000 kWh.

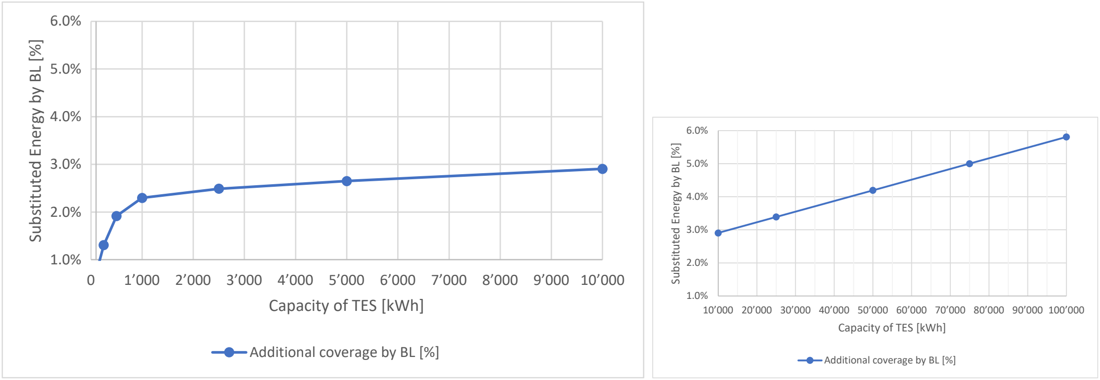

Figure 24: Substituted energy demand by BL for small (left) and large (right) capacities.

The steep incline for small capacities of TES is easily explainable. Their maximum charging rate per timestep (i.e., how much power flows into the TES compared to its full capacity) is extremely high, as represented by the orange line below in Figure 25. Thus, many (dis)charging cycles can be reached. Every “valley” is essentially a charging, and every “peak” is a discharging cycle. Therefore, a TES unit that is sized small compared to the energy demand reaches a high increase in the substitution rate.

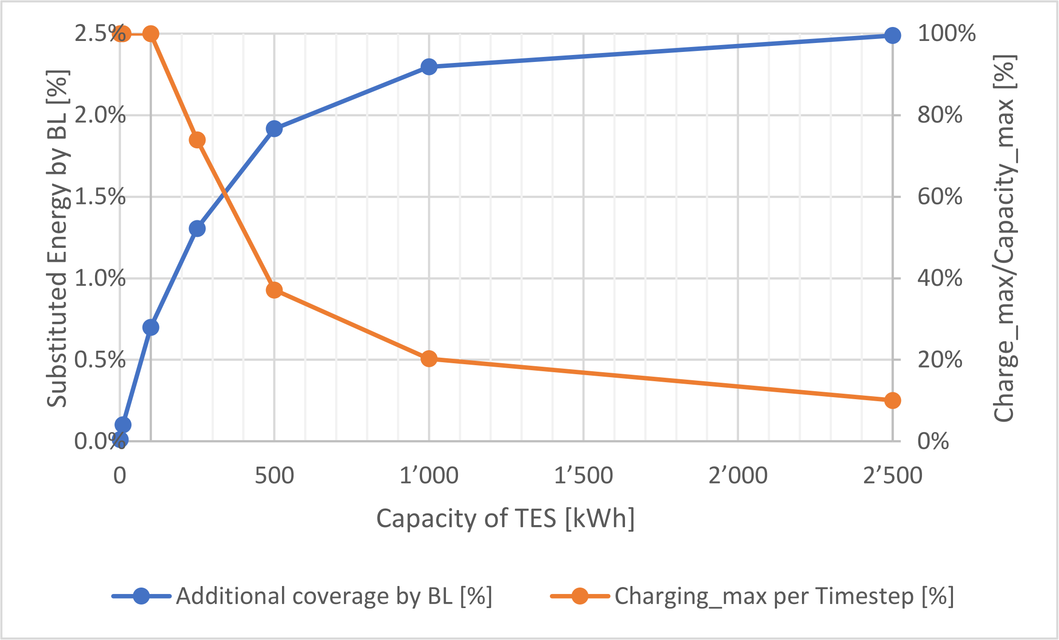

Figure 25: Substituted energy (left) and change of capacity per timestep (right).

Upon closer inspection, it becomes obvious that the ensuing full load hours for the BL follow a very similar pattern (see Figure 26). This insight impacts systems which depend on a high number of full load hours (such as combined heat and power schemes).

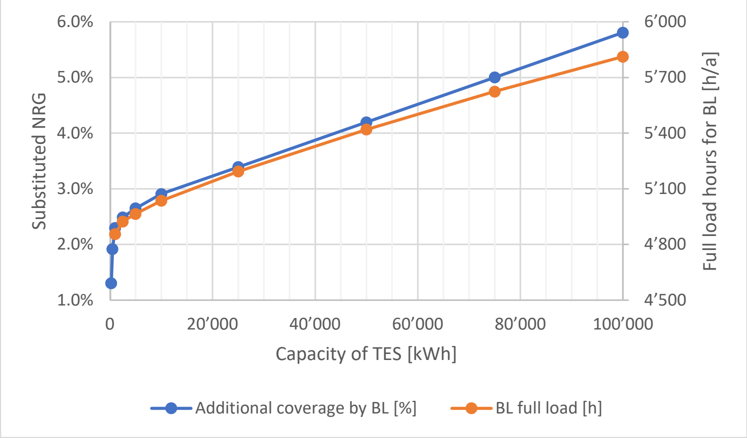

Figure 26: Substituted energy (left) and full load hours for BL (right).

This linear behaviour from about 5,000 kWh onward seems peculiar and requires further explanation. The expectation would instead be that larger TES could store more energy during "valleys" and keep it longer to be released when "peaks" occur. This applies, for example, during the spring when a warm spell is followed by cold weather.

Upon closer inspection, this characteristic is explicable and thus visualised in Figure 27 using generic demand over one year.[9] After winter, the TES is depleted (SoC = 0), and the first valley and peak pattern starts in the spring. Thus, an ideal size for TES which only stores a full amount of energy during valleys can be found. The same is true after the summer for the period in which the next valley and peak pattern occurs.

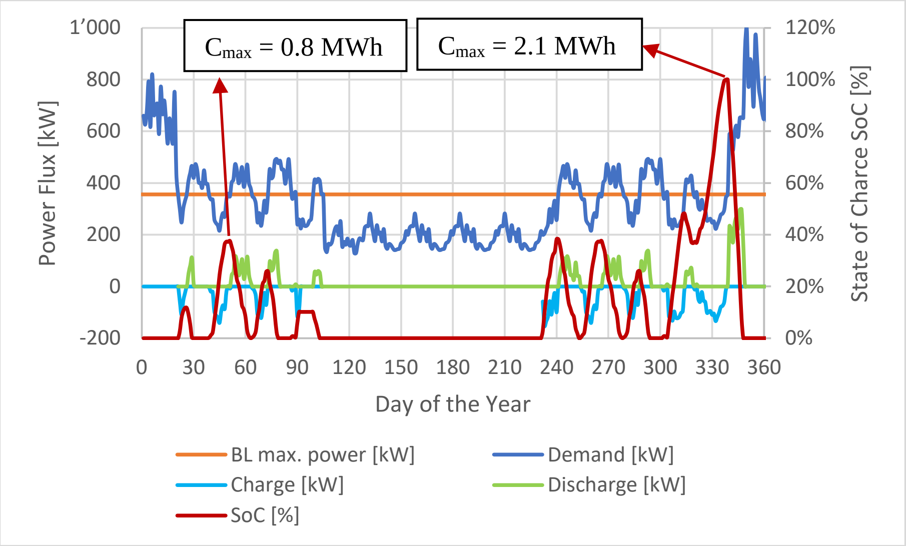

Figure 27: Generic year and power flux during winter/spring/summer/autumn incl. SoC.

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[9] For reasons of showcasing, perfect foresight has been used here (unlike in the model).

Unlike the example presented above, the model does not use perfect foresight and thus cannot optimise the needed capacity to meet the maximal requirements of demand for the spring and autumn valley and peak periods. Instead, capacity is fixed in a parameter run, and the model allows for full loading in the summer (until SoC = 1). Thus, larger TES can result in a larger substitution of PL with BL since their larger capacity serves as seasonal storage (remember that thermal losses are outside the scope of this thesis). Although this is again a biased result compared to expected real-life behaviour, the parameter run revealed the general patterns for the integration of TES. One remaining question is how large these capacities be-come when transferred to structure works.

5.6 Structure Size of TES

As introduced in the system description of storage systems (see Chapter 3.3 on page 10), the relationship between capacity, volume, and temperature difference can be described using the presented Formulae 1a and 1b. These can be converted to the volume, as expressed by the capacity and temperature difference. Using 90 °C as the charging temperature (any kind of combustion), the volume is only dependent on capacity and return temperature, as expressed in Formula 1c.

$$V = \frac{C_{TES}}{\Delta t} \div \left(\varrho \cdot c_{P_{water}}\right) \qquad \text{(Formula 1c)}$$

The resulting volumes for small and large capacities are provided in Figure 28 and Figure 29. Sizes can be derived from capacity and return temperature (and need to be scaled back to the full demand). How the sizing result performs both economically and in terms of carbon reduction is evaluated in the next chapters.

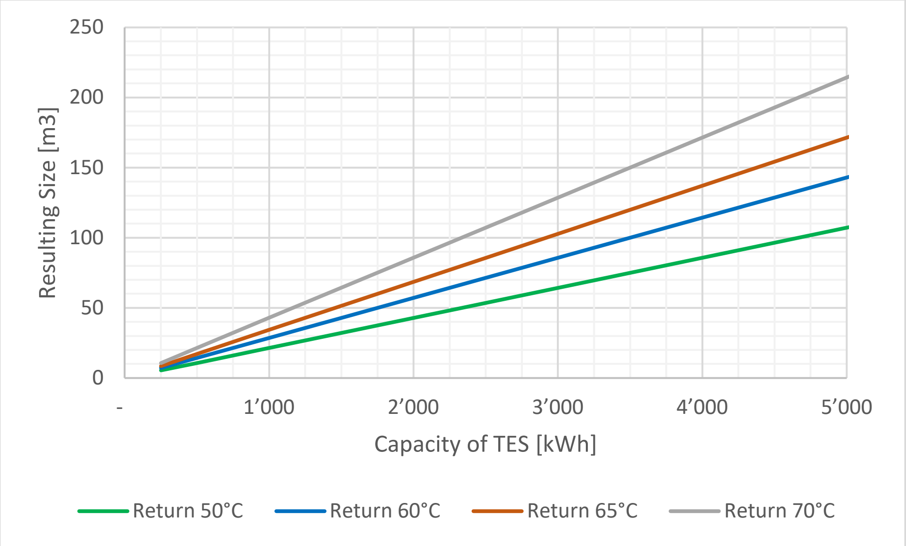

Figure 28: Resulting size of small TES depending on capacity and the return temperature.

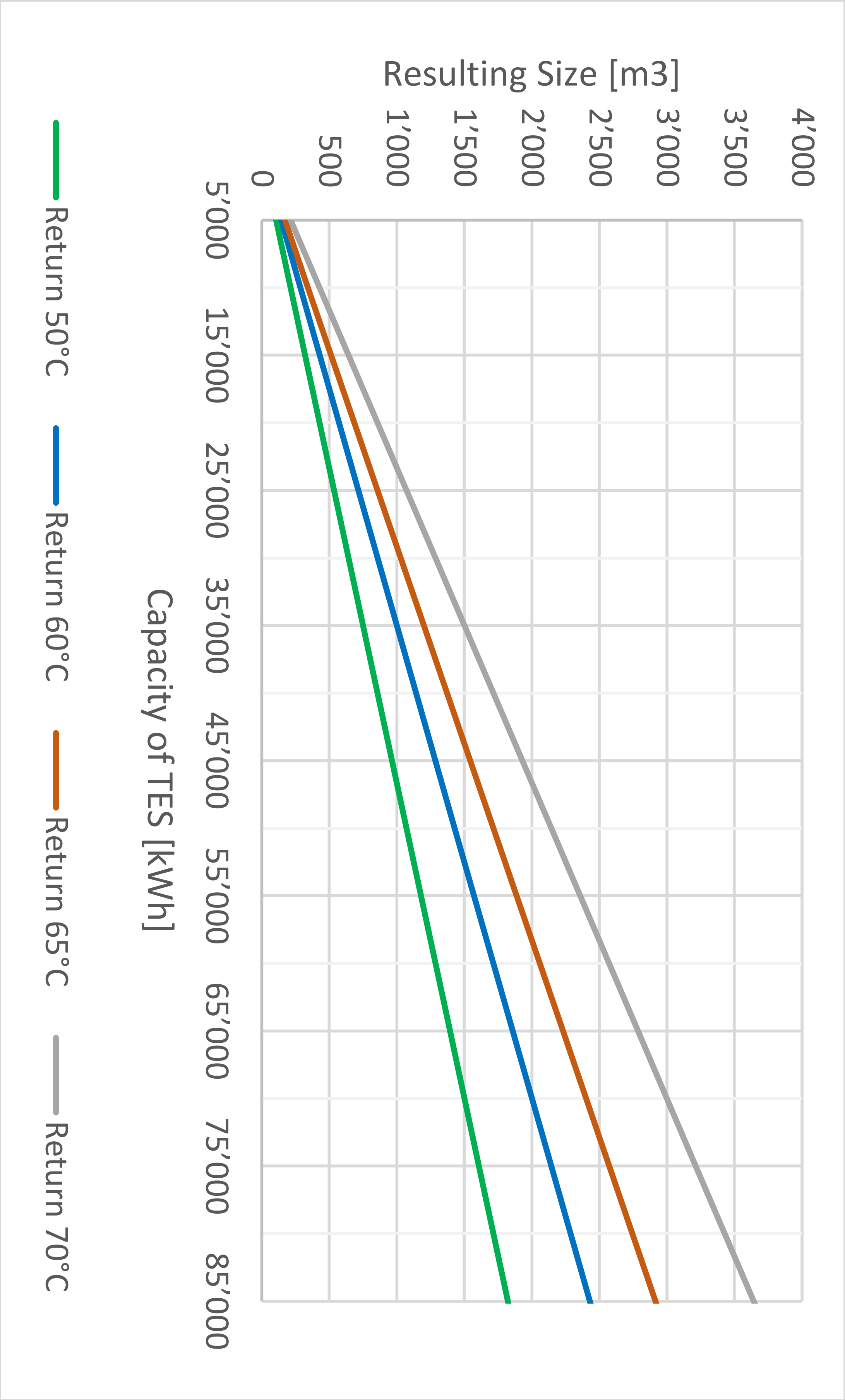

Figure 29: Resulting size of large TES depending on capacity and the return temperature.

6.0 Economic Analysis

In times marked by a new war in Europe and daily news about an imminent energy crisis coupled with rising energy prices, economic predictions for a lifetime of TES seem futile. Here, the mechanisms for optimising an existing system (80% biomass, 20% gas, no OPEX and only CAPEX) are explored. Thus, it is an analysis of a possible upgrade of an established DHN by integrating TES rather than an optimisation. The indicator used is the price difference between the delivered natural gas and biomass.

6.1 Assumptions for Economic Analysis

The following assumptions concerning conversion factors for gas and biomass boilers have been made (see Table 7). The resulting higher price for biomass compared to gas is a result of the difference in conversion factors. The system needed to be scaled up by a factor of 10 to fit the extent of the validity of the cost curve used for the TTES published by Flexynets within EU Horizon 2020 [39]. The payback period has been chosen to fit one lifecycle of boilers and is thus much shorter than the expected lifetime. This is intended to compensate for the cost of TES integration.

Table 7: Assumptions for economic analysis, scaled energy demand, and payback period.

Conversion Factor Gas	0.95	[-]
Conversion Factor Biomass	0.75	[-]
Higher Price (Conversion)	127%	[-]
Energy Overall for 10MW	31’010	[MWh]
Payback period (short)	15	[a]

The substitution of natural gas with biomass (BL instead of PL) has been taken from the model, and the resulting sizes of TTES have been calculated as a parameter run for various temperature differences. Prices have been validated using additional information published by Sveinbjörnsson et al. [39]. It is worth noting that in Table 8, dark grey, middle grey, and light grey results indicate that the cost curve for that area is based on only two data points. This should be critically reflected upon. Thus, the presented results should be taken with a grain of salt.

Table 8: Substituted energy by BL and resulting sizes for TES per temperature difference.

10MW: Capacity of TES [MWh]	**2.5**	**5.0**	**10**	**25**	**50**	**750**
Substitution [%]	1.3%	1.9%	2.3%	2.5%	2.6%	5.0%
Substitution [kWh]	40’474	59’453	71’227	77’162	82’161	155’108
For Dt 40K [m3]	54	107	214	536	1’071	16’071
For Dt 30K [m3]	71	143	286	714	1’429	21’429
For Dt 25K [m3]	86	171	343	857	1’714	25’714
For Dt 20K [m3]	107	214	429	1’071	2’143	32’143
€/MWh [Validation, Fig. 24]			16’253			
€/m3 [Validation 2, Table 3.4]			418			

6.2 Results of Economic Analysis

The results of the economic optimisation are indicated as the needed price difference for the delivered energy carriers – natural gas and biomass – to allow TTES integration. For small capacities, these price differences are small (see Figure 30).

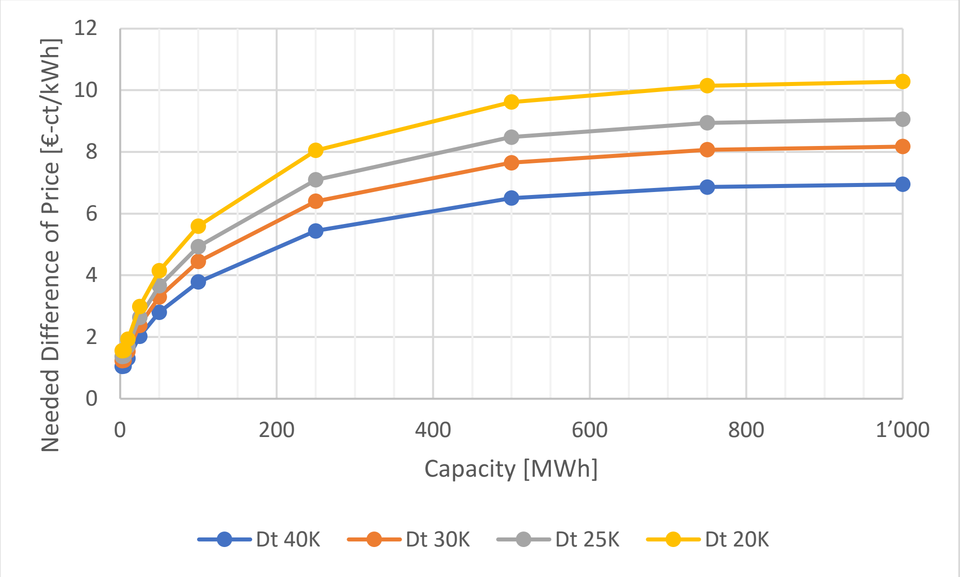

Figure 30: Needed price difference between natural gas and biomass for TTES integration.

Accounting for the cost curve and critically reflecting on the reliability of the data, an adjusted graph is presented below in relation to substituted PL (see Figure 31). For TTES substituting less than 3%, prices seem promising whilst the once targeted substitution of 5% appears costly. For a maximum of EUR 0.06/kWh, not more than 3%–4% can be substituted (depending on temperature difference). The impact of TTES integration on carbon emission reduction is explored in the next chapter.

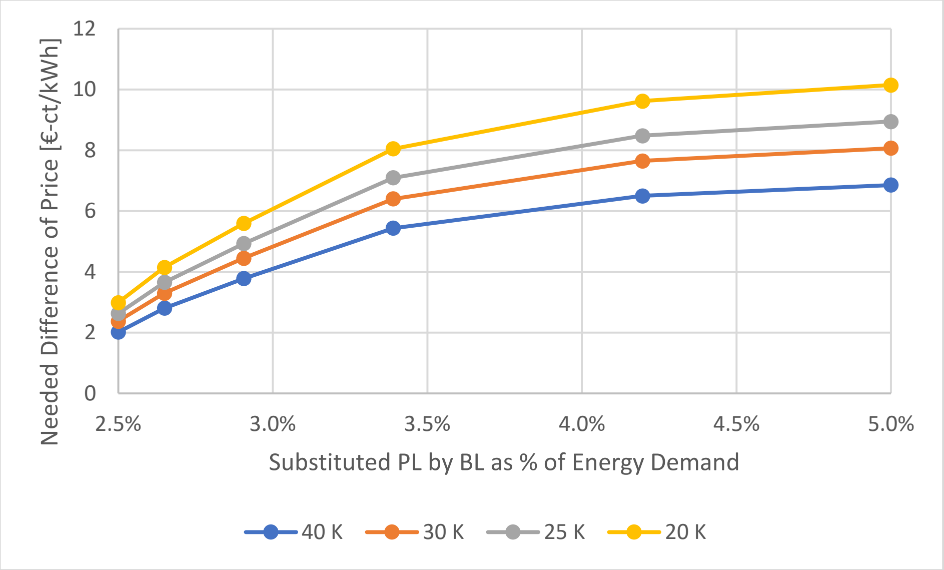

Figure 31: Needed difference of price in relation to substitution potential of TTES.

7.0 Carbon Reduction

The goal of TES integration leading to PL substitution is the reduction of carbon emissions. Thus, this is the first step towards decarbonising the heating system. The same system examined in economic analysis is used to calculate the carbon abatement cost.

7.1 Assumptions concerning Carbon

For carbon emissions, the conversion factors remain, and carbon emission factors have been chosen according to the Swiss recommendation on LCA data for buildings [52]. In Table 9, the assumptions are presented, and the total carbon emissions before TES integration are calculated to be 3.7 $\mathrm{Mt_{CO2e}}$/a.

Table 9: Assumptions to calculate carbon emissions.

	Energy		Carbon			**Old System**		
Conversion Factor **Gas**	0.95	[-]	0.314	kgCO2/kWh		20%	2’050	tCO2e
Conversion Factor **Biomass**	0.75	[-]	0.050	kgCO2/kWh		80%	1’654	tCO2e
						Total	3’704	tCO2e

Carbon emission factors are issued for each country and can be compared between Switzerland (CH) [52] and the United Kingdom (UK) where corresponding values are published [53] (see Table 10). The carbon emission factors, the mean carbon emission factor of the old system, and the carbon savings per kWh gas substituted are presented. This leads to an amplification factor, which expresses how much more carbon is saved compared to energy substituted.

Table 10: Comparison of carbon emission factors for Switzerland and the UK.

	Carbon CH	**Carbon UK**	
Natural Gas	0.31	0.20	[kgCO2e/kWh]
Wood Chips	0.05	0.02	[kgCO2e/kWh]
Old System 80/20	0.12	0.06	[kgCO2e/kWh]
Gas substituted	0.26	0.19	[kgCO2e/kWh]
Amplification	**2.21**	**3.27**	**[substituted]**

With this amplification factor, for example, a substitution of 2.5% of PL by BL leads to 5.5% of decarbonisation in Switzerland and 8.2% in the UK. In other words, the impact in the UK is about 1.5 times greater than in Switzerland (the results using the Swiss factors are later presented). This underscores that even small changes of the system by TES integration leads to decarbonisation.

7.2 Results of Carbon Reduction

As before, the cost data of Flexynets is used to account for costs associated with TES integration. The resulting carbon reduction is expressed as (linearised) yearly investment per tonne of carbon saved – the so-called abatement cost. Figure 32 indicates that an abatement cost below EUR 100/t_{CO2e} is only feasible for small capacities (where the cost curve might be biased). Current abatement costs are CHF 120/t_{CO2e} (about EUR 120/t_{CO2e}) in Switzerland [54] and much lower in the UK [55].

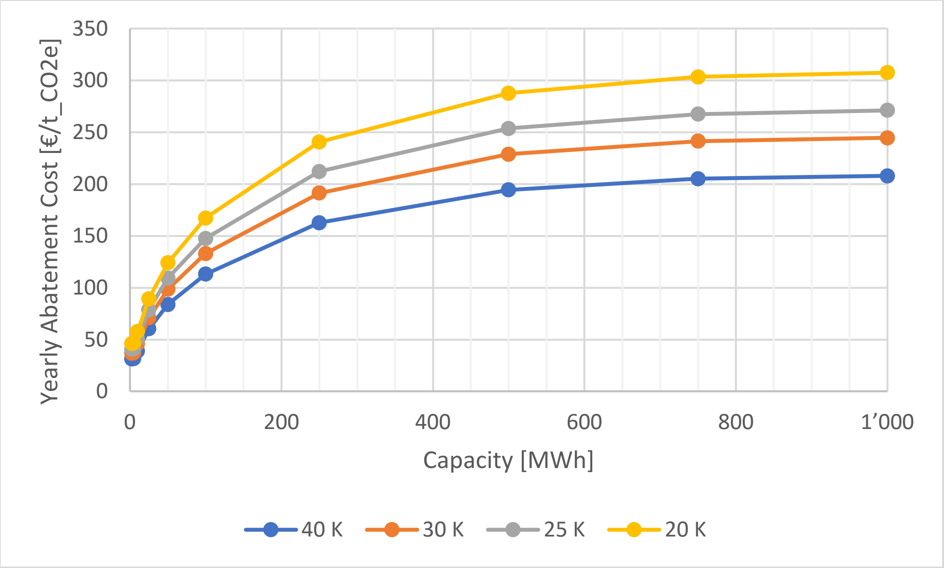

Figure 32: Carbon abatement cost and installed capacity of TTES.

In Figure 33 below, the results are again restricted to plausible data in relation to substituted energy demand. Here, it is obvious that the targeted 5% substitution result in abatement costs of EUR 200–300, which are unlikely to be met soon.

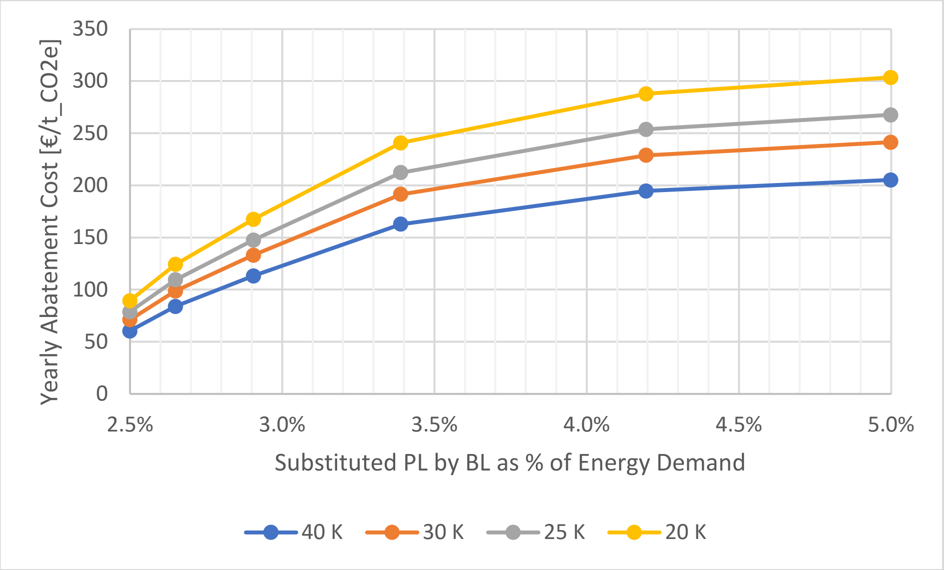

Figure 33: Carbon abatement cost and substituted energy demand by TTES.

8.0 Discussion

This chapter reflects achievements, explores limitations, and recommends future work.

8.1 Achievements

This dissertation aimed to provide a design concept study. In a first step, the sizing of systems has been critically reflected and an appropriate sizing tool provided. The tool can be used in the design process to decide how power demand is met and which part of the energy demand can be covered by the according conversion unit. The corresponding duration curves are provided, and the necessary statistical analysis is integrated such that decisions can be based on a solid basis. Put in a wider context, this is no novelty. All the same, the examples serve to highlight the superiority of using hourly demand data instead of following the traditional approach to account for peak load demand only.

In a second step and focussed on existing district heating networks, the question of how thermal energy storage may serve to substitute peak load with base load energy has been investigated. For a bivalent system and a certain power split, two different strategies have been researched. Making use of an energy balance model accounting for state of charge and following a fixed order control, the effect of different sizes could be defined. The comparison between the chosen peak shaving and load shifting is provided below in Table 11.

Table 11: Comparison of needed size to substitute energy: shaving & shifting approaches.

Substituted Energy Demand	**2.5%**	**2.6%**	**2.9%**	**3.4%**	**4.2%**	**5.0%**
Substituted Carbon (CH/UK)	5.5% / 8.2%	5.9% / 8.7%	6.4% / 10%	7.5% / 11%	9.3% / 14%	11% / 16%
Shaving Capacity [MWh]	772	822	901	1’051	1’301	1’551
Shifting Capacity [MWh]	25	50	100	250	500	750
Sizing: Shaving to Shifting [-]	**31**	**16**	**9.0**	**4.2**	**2.6**	**2.1**

Thus, the question of which strategy promises moderate size can be answered. A shifting approach designed to use demand oscillating around base load rated power at times when “peaks” follow immediately upon “valleys” is promising. This is especially true for “small” substituting values and becomes less apparent the bigger the substituted energy demand. Therefore, the described and potentially novel approach to focus on spring and autumn rather than seasonal storage seems promising. In a wider context, this is a field opened beyond the discussion about seasonal storage. It is apparent that there are limits and it is unclear if the shifting approach can be optimised since the study is using one specific case.

In a last step, the economic performance of the integration of tank thermal energy storage (TTES) and its contribution to carbon reduction has been analysed. For the combination of very low carbon emitting biomass as base load and rather carbon intensive natural gas peak load coverage, appropriate characteristics have been calculated. In short, the economic analysis shows that for a price difference of EUR 0.06/kWh a maximum substitution of 3%–4% seems feasible. Concerning carbon reduction, with abatement cost of EUR 100/t_{CO2e}, less than 3% are achievable using the Swiss carbon intensity factors. If the factors published in the UK were to be used, the carbon savings would be higher but without short-term traded carbon values cannot be incentivised.

Both results confirm that the integration of rather small thermal energy storage could be of interest and thus, a load shifting approach could be promising. Set in a wider context, it becomes understandable why large structure works to serve as thermal energy storage have up till now not found wide application. They are too expensive, energy prices (so far) have been too low, and levies on carbon are still unpopular.

8.2 Limitations

There is a large number of limitations to this examination. Many served to be able to work with a simple energy balance model. These are omitted losses, idealised (dis-) charging properties for thermal energy storage (TES), the system boundary set such that the distribution network is scoped out, and the fact that the measured dataset is deemed to be a “true” and perfect representation of the demand profile. Above, some of the expected impacts on biasing the results has already been commented on and are mostly concerning losses of TTES during long time periods (shaving strategy as seasonal, shifting as accumulating during summer to be released later).

There are some limitations which potentially impact the conclusions more. First, the power split (80%/20%) has been fixed and not been varied. All results on the performance of TES integration are thus bound to this choice. Second, the used fixed order control is probably quite close to real-life behaviour but could be advanced to model or data predictive control mechanisms. In particular, the starting point to charge TES for a shaving approach or the end of keeping the TES charged with the shifting approach could be further researched. Considering that losses are scoped out and conversion units run perfectly in part-load, this is probably not impacting results too much. Third, for the economic analysis and the carbon reduction the chosen system (biomass/gas) is probably the combination where TES exhibit their largest potential. The used cost curve is based on one source only and should be critically acclaimed especially for the rather "small" TES capacities reviewed. Prices are not analysed in detail and only proposed as a fixed difference between the energy carriers, a sensitivity analysis of projected prices or variable time of use tariffs may lead to differing results. Furthermore, the concept study has been based on "an existing district heating network" in general and does not incorporate the exact temperatures used. It sizes TES according to the proposed temperature difference of "charging" (at 90°C using a conversion relying on combustion) and return temperature. Whilst appropriate diagrams are presented, a more specific examination could be beneficial. These points lead to the recommendation on how to proceed in this field.

8.3 Future Work

For future work, a selection of enhancements is suggested and shortly described from a personal point of view. There is of course more to do!

- Improvement of the algorithm to analyse the "oscillating" period. When does it start, when does it end? Appropriately size TES to spring and autumn and define the period. Especially: How can the rated base load power be varied? What are the occurring effects? **Hypothesis**: There is a more favourable power split than 80%/20% for TES integration with a load shifting approach.
- Application in detailed research of a case study: How do longer series of measured data reflect on demand profiles? How can uncertainties be derived and ameliorated; how much back-up power should be considered? Does the integration of TES help the system to reach more robustness, does it offer opportunities to expand an existing system following a load shifting approach? Which strategies can be pursued to maximise TES capacity and minimise size? How simple is TTES integration and what are the conditions (space, time) to do so? **Hypothesis**: The confrontation with a real-world problem will take the concept study to the next level and will help to incorporate the most important boundary conditions whilst reasonable simplifications can be identified.
- The technological concept of a peak shaving approach should be applied to a variety of technology options. Which ones are suitable, and how would variable tariffs help/hinder TES integration? **Hypothesis**: The analysis of more technology options and its application to varying price schemes (potentially as sensitivity of future price development) will reveal opportunities for DHN.

9.0 Conclusions

This dissertation presented an analysis on how thermal energy storage integration were beneficial for district heating systems. A sizing tool to tailor installed power to meet a certain fraction of energy demand was introduced which simultaneously generates duration curves. Two differing approaches for thermal energy storage integration were examined aiming to substitute peak load energy with base load coverage. Those are, (i) the peak shaving approach reducing peak load power requirements and (ii) the load shifting approach allowing to use “valleys” to cover consecutive “peak” demand. Of these, the load shifting approach was found to be more beneficial in terms of moderate size of thermal energy storage, mostly because more (dis-)charging cycles were reached. Economic analysis provided insights into suitable price differences to substitute natural gas with biomass. For carbon emissions, it was found that the reducing effect is amplified compared to energy substitution by a factor of 2.2 (Switzerland) to 3.3 (UK). Thus, substituting 3.0% energy demand leads to a 6.6–9.9% of carbon emission reduction if applied to the researched configuration.

In terms of limitations, the specific system analysed based on 80% of energy demand met by biomass base load coverage and 20% by natural gas provided insights but needed critical reflection. The applied simplified energy balance model used fixed order control and disregarded losses. All insights were based on a one year measured demand profile without further examination of impact by differing demand.

It is suggested that future work encompass (i) improvements in the algorithm used to analyse “valley” and “peak” behaviour, hypothesising that there is a more beneficial split than the 80%/20% investigated in this dissertation; (ii) application of the proposed load shifting approach to a case study, expecting that the confrontation with real-world problems might further advance this concept study; and (iii) application to a wider range of technology options and tariff schemes, hypothesising that this may reveal opportunities in which TES integration affects DHNs, leading to carbon reduction.

On a personal note: This piece of work proved to be a hard nut to crack, facing my own characteristic traits. My motivation was based on the belief that **we are able to make a difference**. This, again, is more eloquently phrased by Gro Harlem Brundtland reflecting a common future:

> *“In the final analysis, I decided to accept the challenge.*
> *The challenge of facing the future, and of safeguarding the interests of coming generations.”*

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11.0 Appendix