

Mitigating Electrical Grid Congestion using Thermal Energy Storage for Thermal Demand Shifting in Buildings

*A Design-to-Operation Framework for Integrated Building Thermal Energy Storage
Systems*

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Focus and restrictions - This research paper explores a Thermal Energy Systems implementation framework. This general framework is substantiated with a case study, targeting sensible heat storage systems, with a specific focus on air-source heat pumps combined with stratified water tanks for cooling and heating.

Abstract - As global energy systems transition toward full electrification, peak demand congestion has emerged as a primary bottleneck for decarbonization. Thermal Energy Storage (TES) offers a critical solution for strategic peak shifting; however, the lack of a standardized design workflow often leads to inefficient sizing or failure to maintain operational stability. This thesis develops a multi-zone optimization model that integrates transient thermal load profiles and hydraulic stability requirements into a unified control framework. The model processes dynamic inputs, including real-time grid constraints and variable load demands, against user-defined performance preferences. By utilizing a multi-objective function, the model identifies optimal design solutions that prevent the common pitfall of oversized storage vessels while maintaining occupant thermal comfort boundaries.

The research quantifies a two-layer buffering effect. Firstly, structural thermal inertia acts as a passive buffer that dampens thermal demand peaks through the building's intrinsic heat capacity. Secondly, the active TES system integration acts as a predictive buffer: by utilizing real-time data to either pre-charge the building's structural mass or the active TES system, as defined in the control strategy, the system effectively shifts thermal demand temporally. This way the reliance on the physical thermal storage tank during peak periods is reduced.

The general framework is validated with a case study. Sensitivity analysis for the case study reveals a non-linear relationship between heating capacity and required storage volume, with a turning point at 95 kW; increasing heating capacity from 95 kW to 115 kW yields a 21.08% reduction in hot tank volume for fixed scheduling and 18.47% for dynamic Model Predictive Control (MPC) strategies. Furthermore, the analysis demonstrates that cold tank sizing is, at some point, constrained by hydraulic stability requirements, rather than thermal cooling demand. These findings provide a robust methodology for determining optimal storage capacities, ensuring grid-compliant delivery while strictly adhering to system performance constraints.

Key words - Thermal Energy Storage, Thermal Buffering, Sensible Heat Storage, Stratified Water Tank, Heat Pump, Control Strategy, Simulation, Load Shifting, Grid Congestion, TES Integration, Framework, Building Energy Modelling

Preface

This thesis was written as part of the MSc Building Technology program at the Faculty of Architecture and the Built Environment, Delft University of Technology. The research was conducted during an internship at the engineering consultancy firm ABT.

I would like to express my sincere gratitude to my academic supervisors for their invaluable guidance and for challenging me to expand the scope and quality of my work. Specifically, I am grateful to Willem van der Spoel for his profound insights into building physics; his methodical approach was instrumental in helping me simplify complex physical models and integrate them into my framework. I would also like to thank Azarakhsh Rafiee for her critical evaluations and the fresh perspectives she brought to my work throughout this process.

I also extend my thanks to Jeroen Verwer at ABT. His guidance regarding the integration of real-life mechanical systems was essential to the development of my case study. His expertise allowed me to bridge the gap between theoretical modelling and the practical constraints of operational building installations, providing me with a deeper understanding of how these systems perform in the built environment.



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Terminology

This section provides a list of the abbreviations and symbols used throughout this paper. To ensure clarity and technical precision, specific notations and units are defined below. Unless otherwise stated, these conventions remain consistent across this thesis paper.

Definitions

- **Thermal Energy Sources** Within the context of this study, thermal system and heat source refer broadly to the primary components providing thermal energy. These terms are used to represent any system supplying heating or cooling loads, regardless of the specific underlying technology.
- **Heat Transfer:** $\dot{Q}$ or $Q(t)$ (Heat Transfer Rate): Represents the rate of heat flow, measured in kilowatts (kW). In the context of this research, $Q(t)$ represents the thermal power demand or supply (kW) at each specific simulation time-step (t). This notation is used throughout to emphasize the time-dependent nature of the building and system loads.
- **Thermal Capacity Notation:** Areal Heat Capacity (C_{spec}): The effective thermal energy storage capacity per unit of surface area, expressed in $kJ/(m^2 \cdot K)$. This parameter quantifies the ability of building components to buffer thermal fluctuations and serves as a primary input for modelling passive thermal mass to optimize active storage volume.

Abbreviations

TES	– Thermal Energy Storage
HP	– Heat Pump
ASHP	– Air-Source Heat Pump
COP	– Coefficient of Performance (-)
PCM	– Phase Change Material
PV/T	– Photovoltaic/Thermal
SHS	– Sensible Heat Storage
LHS	– Latent Heat Storage
TCES	– Thermochemical Energy Storage
HVAC	– Heating, Ventilation, and Air Conditioning
AHU	– Air Handling Unit
VAV	– Variable Air Volume
FCU	– Fan Coil Unit
UFH	– Underfloor heating/cooling
SoC	– State of Charge
kVA	– kilovolt-ampere

1 Introduction

The energy transition in the built environment is increasingly hindered by grid congestion. At the same time, the sustainability focus is shifting from energy efficiency to material usage, due to its impact on CO₂ emissions. Regarding climate goals, the Paris Agreement states that emissions need to be reduced by 45% by 2030 and reach net zero by 2050 (United Nations, n.d.).

Transitioning to a net-zero world is one of the biggest challenges of the century. This requires a complete transformation of the energy system, especially the electricity sector. Replacing fossil-fuel-based electricity and heating with renewable energy introduces a fundamental challenge: renewable generation is variable, while electricity demand is not (IEA, 2022). Moreover, providing the built environment with enough electricity to power building installations like electric heat pumps requires more infrastructure than exists. Updating the existing infrastructure to handle the increased demand for electricity power costs hundreds of billions and involves prolonged lead times, insinuating the importance of other innovations that help alleviate the mismatch between supply and demand responsible for grid congestion (TNO, n.d.).

According to Tsekeris et al. (2024), harnessing demand response in electricity, is critical not only for reducing reliance on carbon-intensive peak generation but also for mitigating grid congestion. Demand response refers to the ability to temporarily lower or shift energy consumption to times when supply is more abundant. By reallocating rather than reducing end-use services, demand response maintains user comfort while improving overall system efficiency and resource utilization.

Demand response in buildings can be achieved through thermal buffering, which offers potential to spread energy generation over time, in some cases even enable seasonal storage, and reduce peak loads on the grid. By decoupling thermal demand from electrical supply, thermal energy storage enables buildings to operate within limited infrastructure capacities and maximize the self-consumption of volatile renewable energy. *“Thermal Buffering refers to the capacity of a material, structure, or environment to absorb, store, and slowly release heat energy, thereby moderating temperature fluctuations over time. This process is crucial for stabilizing internal temperatures and reducing peak energy demand in buildings”* (Thermal Buffering, 2025).

1.1 Problem Statement

Current literature demonstrates the technical potential of Thermal Energy Storage (TES), their application possibilities, thermodynamic capabilities, and their ability to shift grid demand load. However, the literature lacks in holistic design approaches as well as design implementation workflows from start to finish. Existing Building Energy Modelling (BEM) studies focus mainly on TES sizing in the design phase using deterministic, and sometimes static, assumptions. This approach overlooks the dynamic operational complexities required to manage supply-demand fluctuations in modern grids and operational schedules (De Wilde, 2014). Resulting TES systems are often sized and operated sub-optimally, limiting the true benefit of flexible and efficient operation. Moreover, literature has shown that most TES implementation approaches are very case-specific, lacking a more generalized workflow that is applicable to different buildings or building types.

Furthermore, while advanced control methods exists, there is lack of validated frameworks that directly integrate the complexities of Building Energy Models (BEM) models with dynamic system control strategies. In order to get more grip on the chosen TES system’s performance regarding its dual objective: maximal grid congestion relief and sustained thermal comfort, this thesis directly addresses the current gap in the literature by establishing and validating a complete simulation-to-control pipeline.

1.2 Objective and Research Questions

The aim of this research is to analyse to what extent thermal buffering can be an effective and sustainable solution to grid congestion. The design of a workflow for TES system integration into building design is central in this research. Furthermore, a simulation model with an optimization

framework explores optimal TES system sizing and control strategy of thermal buffers to guarantee maximum peak load shifting and ensuring sustained occupant thermal comfort.

Hence, the main research question: *How can a design-to-operation framework facilitate the co-optimization of Thermal Energy Storage (TES) capacity and control strategies to enhance load-shifting potential while guaranteeing occupant thermal comfort in buildings?*

Since this research paper aims to develop a TES integration and control framework, the main sub-question are formulated as:

1. How do specific building load curves and grid congestion windows dictate the selection of a suitable TES technology?
2. What are the primary infrastructure and system-level requirements for integrating TES into building climate systems to ensure alignment with both spatial constraints and dynamic operational performance?
3. How can coordinated control strategies integrate active TES and passive building thermal mass to minimize total storage volume while maximizing load-shifting performance and maintaining occupant thermal comfort?
4. How does the use of dynamic simulation modelling improve the reliability of load-shifting predictions compared to simplified static sizing methods?
5. To what extent does the application of the design-to-operation framework to a case study achieve the necessary peak-load shifting to meet local grid constraints?

1.3 Definition and Scope

The main research question of this paper focusses on a general TES implementation framework. The general framework will then be applied to a case study: The Broedplaats Performing Arts Center in Breda, the Netherlands. Even though the general framework does not prioritize a specific TES system, the second part of this research will focus in depth on the performance and integration of stratified water tanks combined with air-to-water heat pumps. TES systems combined with heat pumps represent one of the most relevant and widely applicable configurations for low-carbon thermal systems, and suitable for a broad variety of building typologies.

1.3.1 Boundary Conditions

General Framework

- The framework can be used as a basis for thermal buffering rather than a precise implementation manual for every TES system;
- The methodology focuses on energy aggregation & delivery and grid-load shifting, prioritizing global system performance over localized, high-resolution thermal delivery modelling;
- The framework is structured for system-level design rather than detailed equipment specification, identifying universal optimization drivers while allowing for project-specific constraints.

Case Study

- Short term sensible thermal energy storage;
- Solely focussing on space heating and cooling, not DHW (Domestic Hot Water);
- Generation system: air-source heat pump, calculated with theoretical COP performance within the python simulation model;
- PV integration is included in the simulation model;
- Focus on performance based on the extreme climate dataset for the Netherlands from the NEN 5060-B2 1%.

1.4 Relevance

Scientific Relevance

This thesis addresses the lack of general integration workflows for thermal energy storage systems in buildings by developing a design-to-operation framework that connects TES selection and sizing with advanced operational control. Additionally, dynamic simulation-based validation is part of this framework.

Literature states that TES integration is complex because neither storage technologies nor the processes they serve are "one-size-fits-all". Each application involves unique energy sources, sinks, and factors that are interdependent. To manage this complexity and ensure an optimal match, it is essential to characterize the specific requirements of the mechanisms and capabilities of TES systems independently before attempting to integrate them into a unified application (Gibb et al., 2018). Moreover, the lack of coordination between building design and the design of the energy storage results in systems that functioned as isolated "add-ons", sized merely to meet existing loads rather than being developed as integrated components of a holistic climate strategy (IEA, z.d.).

More reasons for underutilized TES applications are mentioned in the research paper of Ayalew en Andrzejczyk (2025), *Recent Advancements in Latent Thermal Energy Storage and Their Applications for HVAC Systems in Commercial and Residential Buildings in Europe—Analysis of Different EU Countries' Scenarios*, stating that fragmented (EU) building standards and insufficient training are among the barriers for TES adoption.

This study investigates how coordinated design and operational decisions can enable optimized charging and discharging strategies that minimize peak electrical demand while maintaining occupant thermal comfort under variable loads. The proposed approach advances the current state of knowledge by demonstrating how coordinated design and control decisions can enhance system-level performance and support grid-responsive building operation. In doing so, this research seeks to bridge the gap between the theoretical potential of thermal energy storage and its practical implementation in building energy systems.

Societal Relevance

The electrification of heating systems in buildings is expected to accelerate as a result of climate targets, increasing renewable electricity generation, and the gradual phase-out of fossil-fuel based heating technologies. Heat pumps represent a key solution in this transition due to their high efficiency and low CO₂ emissions compared to conventional heating systems. However, widespread adoption of electrically driven heat pumps may significantly increase peak electricity demand, thereby placing additional stress on local distribution grids and potentially increasing the use of carbon-intensive peak generation. In short, the transition to sustainable energy sources to mitigate fossil-fuel dependence introduces a critical counter-effect: the exacerbation of electrical grid congestion.

Thermal Energy Storage (TES) systems, such as stratified water tanks integrated with heat pumps, offer a low-cost and robust solution to reduce peak grid loads through load shifting and pre-charging strategies. These systems allow heat generation to be decoupled from building heat demand while maintaining occupant thermal comfort. Despite their technical maturity, TES systems are not yet systematically integrated into building design and operation. In practice, a general and transferable framework that guides the selection, sizing, and operation of TES systems is largely missing. Developing such an integration framework can support widespread and effective implementation of TES. This could ultimately contribute to grid stability, reduced operational costs, and a more resilient and sustainable energy system.

1.5 Approach and Methodology

The theory from the literature study serves as the basis for the development of the framework. This research provides two deliverables: a general framework that serves as a guide for the integration of TES systems in buildings. Secondly, an in-depth application of the framework is provided for a

sensible thermal energy system. The case study shows how the framework can be used as a solid basis and then be further developed for its specific application, exploring optimisation possibilities. Regarding TES integration, the case study will go into much more detail than the general framework and will therefore provide information that is not mentioned in the general framework. The reason is that the case study is context specific and the TES integration requires additional context related system design choices.

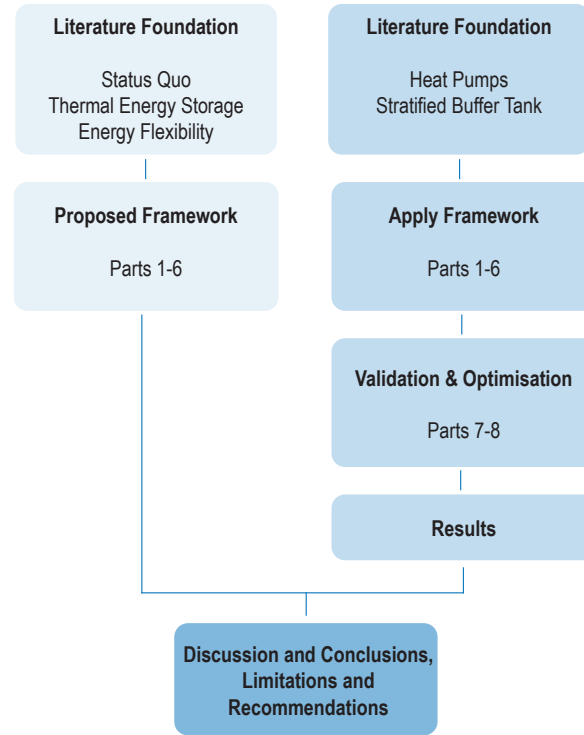


Figure 1: Methodical approach

The schematic in Figure 1 shows the methodical subdivision of the process. This line of approach is also reflected in the structure of this report. The general framework uses chapter 2 as a foundation, and further supports each part of the framework with additional literature within chapter 3. The final result of the general framework is a simulation model, programmed in python, that calculates the required minimal storage volume based on a selected control strategy.

2 Thermal Energy Storage

This chapter explores the the current landscape of TES adoption in buildings in the Netherlands. TES is becoming ever more important as we transition towards a gas-free built environment but have limited electricity grid capabilities. Furthermore, this chapter identifies key obstacles that prevent universal adoption ranging from technical gaps and policy barriers. Finally, this chapter provides a brief market analysis of TES technologies currently on the market or under development.

2.1 The Energy Transition

the Netherlands is currently undergoing a major shift in its energy strategy, aimed at completely phasing out natural gas by 2050. This transition, often referred to as being "gas-free" (*van het gas af*), is a central part of the the national plan to meet international climate goals. For decades, natural gas was the standard for heating Dutch homes and buildings, but this is now being replaced by more sustainable alternatives. The focus has shifted to all-electric solutions, such as heat pumps, and the expansion of district heating networks, using the geothermal heat, to reduce CO_2 emissions and end reliance on local gas extraction or import.

The Decline of Natural Gas

Data from TNO, *Netherlands Organisation for Applied Scientific Research*, regarding the Dutch services sector shows exactly how this transition is playing out in the real world. The graph in figure 2 highlights a steady drop in natural gas usage. By 2024, consumption fell to 92 PJ, a 4% decrease from the year before. On average, gas use in this sector has been dropping about 4% every year since 2014. This shows that the move away from traditional gas boilers is not just a plan, but a measurable reality.

The Rise of Electrification

At the same time, electricity use has risen to 130 PJ. While modern appliances are becoming more efficient, the total demand for electricity is still going up. TNO attributes this primarily to the growing number of heat pumps being installed. Because heat pumps use electricity to move heat from the air or ground into a building, they are the primary reason the "green line" for electricity is rising as the "pink line" for gas falls (Dashboard Klimaatbeleid - Gebouwde Omgeving, n.d.).

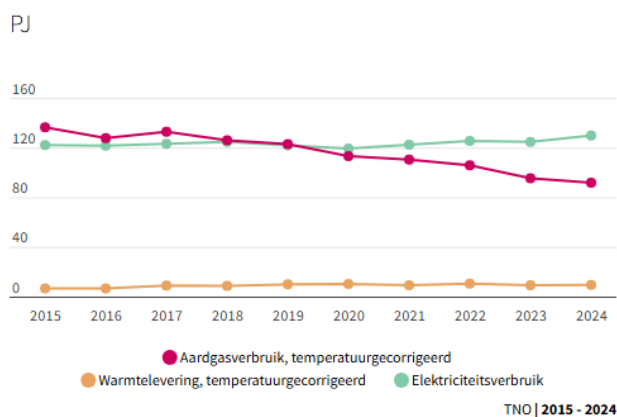


Figure 2: The final natural gas, electricity and heat consumption of the service sector in the Netherlands, normalized for degree days.

Adapted from TNO via Dashboard Klimaatbeleid - Gebouwde Omgeving (n.d.).

The Growing Need for Storage

As the Netherlands continues to swap gas for electricity and heat networks, the energy system faces a new challenge: balancing supply and demand. Unlike gas, which can be burned instantly whenever it is needed, a grid powered by electricity and renewables requires a way to "buffer" energy.

This is why Thermal Energy Storage is becoming increasingly important. It allows buildings to store heat when electricity is available during off-peak periods and use it when demand is highest (grid-congested periods). While modern TES storage can technically be connected to a gas boiler, it is rarely done for two main reasons:

- **Economics:** Gas prices are usually stable throughout the day. Unlike electricity, which has "cheap hours" when renewable production is high, there is no financial incentive to store gas-generated heat for later.
- **Efficiency:** Using gas to heat a storage medium, only to lose some of that heat through insulation over time, is less efficient than simply burning the gas at the exact moment it is needed.

Consequently, the push for TES is almost entirely driven by the electrical shift. As more buildings move to all-electric or hybrid setups, the storage ensures the transition remains affordable, stable, and capable of handling peaks loads with overloading the grid.

2.2 TES Adoption Barriers

As the Netherlands moves towards a carbon-neutral built environment, TES is emerging as a solution for grid stability and climate resilience. While the technology is reaching maturity, its standard application in large-scale building is currently in an upward trend. However, there remain several obstacles that need to be overcome in order for standard widespread adoption. While technical barriers regarding integration and digital control are being actively researched, policy and economic hurdles remain equally significant in standardizing the market and unlocking the full potential of large-scale thermal buffering.

2.2.1 Technical Barriers

Changing Thermal Demands

According to TNO (2025), climate change is fundamentally altering long-term energy requirements, with projections suggesting that cooling demand in the Netherlands will exceed heating demand by the latter half of the century. This shift necessitates a transition toward versatile energy infrastructure. Modern climate systems must be designed with flexibility to provide both heating and cooling interchangeably or simultaneously to meet evolving demand and ensure climate resilience.

Lack of Standardization

Moreover, TNO (2025) emphasizes that the current lack of a unified analytical framework across the Netherlands, stemming from different data sets usage and conflicting assumptions, obstructs a cohesive national heat transition. To facilitate transparency and cross-sector collaboration, it is essential to establish a standardized catalogue of that metrics and open-source dynamic calculation models that integrate technological, economic, and sustainability parameters in TES applications.

Smart Design and Control

The smart design and control of TES systems face significant complexities stemming from the vast technological diversity of storage mediums and their unique operational requirements. Key barriers include the optimal sizing and integration within existing infrastructure, where physical constraints must be balanced against fluctuating energy demands.

Furthermore, the dynamic nature of energy systems, driven by intermittent renewable sources and weather variability, requires control strategies capable of real-time adaptation. These systems must

also account for lifecycle management, specifically non-linear ageing and degradation effects caused by thermal cycling, to ensure long-term reliability and performance (IEA ES TCP, 2025).

2.2.2 Policy Barriers

Awareness and Financial Complexity

According to Directory (2025), a significant barrier to TES adoption is the limited understanding of the technology among stakeholders. This lack of familiarity often leads to hesitation, even when TES is a viable solution. This issue is intensified by the difficulty of performing accurate cost-benefit analyses, as decision makers struggle to account for volatile energy prices, carbon regulations, and available subsidies without accessible financial models.

Policy and Market Integration

A transition toward broader TES usage depends on a unified national energy strategy that sets clear goals and consistent guidelines. Such a strategy should focus on reducing regulatory barriers through the simplification of permits and the alignment of policy incentives. Furthermore, incorporating storage requirements into national building standards would create the necessary structural demand to move the technology into the mainstream (Directory, 2025).

2.3 Energy Flexibility

Energy flexibility refers to the ability to manage a building's demand and generation according to local climate conditions, user needs, and grid restraints. It is the capacity to shift, shed, or modulate energy loads in time without significantly compromising the comfort of the occupants or productivity of the processes within.

2.3.1 Flexible Mechanisms

Demand Side Management (DSM) can be divided into two categories: energy efficiency (EE) and demand response (DR) (Palensky and Dietrich, 2011). Both methods can heavily influence the load profile of a building. International Energy Agency et al. (2019) describes different types of DSM techniques:

- **Peak clipping:** Focuses on reducing the load during periods of maximum demand. The primary goal is to lower the stress on the grid without necessarily moving that demand to another time, often resulting in a net decrease in total energy usage.
- **Valley filling:** Involves increasing the load during off-peak periods when the system is underutilized. This is common in scenarios where base-load power plants produce excess energy at night that needs to be consumed or stored.
- **Load growth:** Represents a general increase in energy demand across the entire profile. This often occurs due to increased electrification (e.g., more electric vehicles or heat pumps) or the expansion of a building's functional capacity.
- **Load conservation:** This is the opposite of load growth, representing a permanent reduction in energy demand across all hours. This is typically achieved through energy efficiency (EE).
- **Load shifting:** Moves the demand from peak periods to off-peak periods, unlike clipping. It is a cornerstone of thermal energy storage, where energy is stored during "valleys" to meet the demand of "peaks" later in the day. This study will primarily focus on load shifting, as it provides a strategic solution for grid congestion by moving peak demand into off-peak valleys without sacrificing total energy use. By leveraging thermal storage technologies, buildings can decouple their thermal needs from electrical consumption (hindered/reduced due to a congested grid), effectively "flattening" their load profiles.

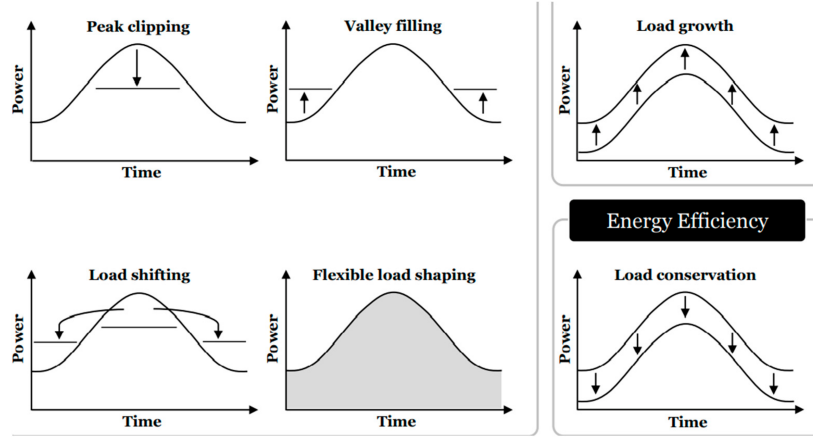


Figure 3: Different demand-side management (DSM) techniques.

Adapted from Lampropoulos (2014).

2.3.2 Building Energy Loads

Building energy loads can be classified into three categories based on the requirements and priorities regarding potential changing or shifting of loads:

- **Shiftable loads:** Represents flexible demands that can be rescheduled to align with favourable pricing periods, such as off-peak hours in real-time markets. By moving operation of appliances and electric vehicle chargers, peak demand can be mitigated without significant disruption to user comfort (Belhomme and Bouffard, 2009; Hong et al., 2015). *"Within this class, it is possible to distinguish between load, which can be shifted but the energy profile cannot be changed, and load where the total volume must be met over a set of time periods but the profile can change within limits"* (Ottesen and Tomasgard, 2015).
- **Non-shiftable loads:** These are rigid demands essential to immediate occupant needs, also known as a base-load. Such loads are often considered inflexible because their consumption patterns cannot be altered by price signals or system constraints without directly impacting the building's functionality (International Energy Agency et al., 2019).
- **Other controllable loads:** This category includes complex systems, such as HVAC units, that offer flexibility through active control strategies. Rather than simple time-shifting, these loads can be adjusted via thermostatic set-point modulation, fan speed, or dimming. This allows for the dynamic reduction of consumption during peak intervals to lower electricity use (International Energy Agency et al., 2019).

TES serves as a transformative mechanism that converts non-shiftable load into a shiftable load. While certain demand profiles are traditionally rigid due to immediate occupant needs or fixed operational schedules, TES decouples the timing of energy generation from its eventual use. By storing energy during periods of low demand or costs, the system allows a building's total energy volume to be met flexibly across a wider time frame.

2.4 Types of Thermal Energy Storage

Thermal energy storage systems can be divided into three main categories: sensible heat storage, latent heat storage, and thermochemical heat storage.

- **Sensible heat storage:** Sensible heat storage is the simplest form of thermal energy storage. It works by increasing or decreasing the temperature of a storage medium such as water, rock, concrete, or molten salts. The material stores energy as its temperature rises and releases that energy when it cools down, without undergoing any change in physical state.
- **Latent heat storage:** Latent heat storage stores thermal energy by using a material's phase change properties, such as melting or solidifying. During these phase transitions, the material absorbs or releases a significant amount of energy in the form of heat, at nearly constant temperature. Phase change materials, also known as PCMs, are commonly used in this type of storage. This method offers higher energy density than sensible heat storage, allowing large amounts of heat to be stored in relatively small volumes. PCM-enhanced installations are often more expensive than sensible TES but are a good alternative in cases with a lack of available space.
- **Thermochemical heat storage:** Thermochemical heat storage uses reversible chemical reactions to store and release energy. Heat input drives an endothermic reaction that separates a chemical compound into its components. In reverse, the components recombine in an exothermic process that releases the stored energy in the form of heat. This type of storage can achieve very high energy densities and allows for long-term storage with minimal losses, making it well suited for applications such as seasonal energy storage. (Thermal Energy Storage Market, 2025)

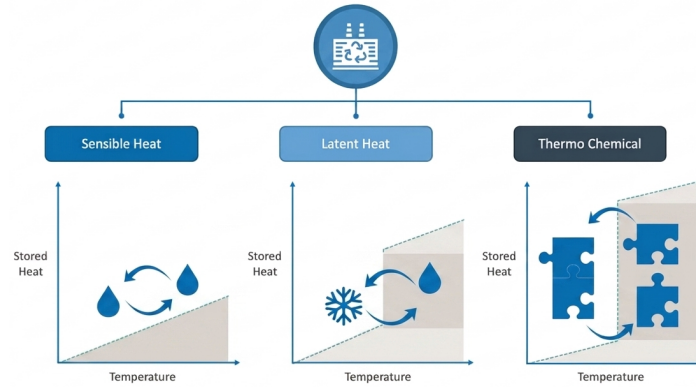


Figure 4: Classification of TES types and the heat stored with temperature variation.

Adapted from Beceiro & Saeterli (2024).

2.4.1 Overview of TES Technologies

The following overview is provided of thermal energy storage systems that are currently on the market and under development. Most sensible and latent TES is quite mature. Thermochemical TES on the other hand, is still being researched and is not yet available on the market for building applications. Table 5 is a summary of the literature review on thermal energy storage systems. It highlights the maturity of the systems, its operating temperatures, scale, and mentions key characteristics. A TES and BTES are not direct energy supply systems. The stored temperatures are often upgraded by other systems like a heat pump. The TES technologies inside the overview table are discussed more in-depth later in this chapter.

Technology	Type	Status	Temp. Range	Key Characteristics / Scale
Buffer Tank	Sensible	Mature	4–95°C	Building scale; thermal stratification.
ATES (Aquifer)	Sensible	Mature	Low-grade	Seasonal groundwater storage; open-loop.
BTES (Borehole)	Sensible	Mature	Low-grade	Seasonal ground arrays; closed-loop.
Molten Salt	Sensible	Mature	290–565°C	Utility scale; primarily for CSP plants.
Concrete Core	Sensible	Mature/Dev.	30–70°C	Building scale; utilizes structural mass.
PCM / LHS	Latent	Dev.	Various	High energy density via phase change.
PCM Tank	Latent	Dev.	Stable	Maintains temperature during demand-response.
Ice Storage	Latent	Mature	0°C	Shifts cooling loads; high latent heat of water.
Zeolite	Thermochem.	Dev.	Variable	3–30x density of sensible storage.
Salt Hydrates	Thermochem.	Dev.	Variable	Seasonal storage via chemical bond dissociation.

Table 1: Overview of Thermal Energy Storage Systems.

TES system choices are often driven by multiple factors, dependencies, and limitations: required temperature levels, storage duration, available space and integration, economic and operational aspects, climate, and thermal demand characteristics (Tafere, 2026). In this study, the thermal demand profile (load curve) of a building will serve as a primary criterion for determining the appropriate TES system.

2.5 Sensible Heat Storage

Sensible heat storage systems are already quite mature in the literature, with many systems already being deployed in buildings and districts. Listed below is an overview of the most prominent systems on the market and under development.

2.5.1 Buffer Storage Tank with Thermal Stratification

Status: Mature - Scale: Building

A buffer storage tank is a tank filled with water at different temperature levels. Thermal stratification refers to the natural layering of water at different temperatures inside a thermal storage tank (hot on top, warm in the middle, cold at the bottom). "*Stratification allows different water temperature levels to be used directly for different purposes. The top zone of the tank is kept at the maximum temperature for instant domestic hot water production or to heating radiators, whilst at the same time the water at a lower temperature can be used for underfloor heating systems*" (Buffer Storage Tanks With Thermal Stratification, z.d.).

Depending on the heating and cooling demand of a building, the integration of buffer tank requires two tanks: A hot-water storage tank operating between 40-95 °C. Used to warm water during winter.

And a chilled-water storage tank operating between 4-12 °C. Used to cool water during summer.

2.5.2 Aquifer Thermal Energy Storage (ATES)

Status: Mature - Scale: Building & Campus

ATES is a seasonal thermal energy storage technology that stores heat or cold in natural underground aquifers. It is an extremely low open-loop energy system that just requires pumping of water. During winter, warm groundwater is extracted from one or more warm wells and passed through a heat exchanger where it transfers heat to a working fluid. A heat pump then raises the temperature of the fluid, which is circulated through the building to provide heating. The cooled working fluid returns to the heat exchanger for reheating by the groundwater, and the cooled groundwater is re-injected into the aquifer via cold wells.

In summer, the process is reversed. Cool groundwater is pumped from the cold wells and used to cool the working fluid through the heat exchanger, providing cooling to the building(s). This can be achieved without a heat pump in most systems (direct cooling). In some systems, however, a heat pump further reduces the working fluid's temperature. The warmed fluid is returned to the heat exchanger to be cooled by the groundwater, and the heated groundwater is re-injected into the aquifer via the warm wells for future use in winter (Jackson et al., 2024).

As mentioned, ATES does require temperature upgrading before using the hot or cold water. Therefore, ATES can not be used as a direct thermal buffer. This system does store energy, but not useful heat.

2.5.3 Borehole Thermal Energy Storage (BTES)

Status: Mature - Scale: Building & Campus

BTES is a type of seasonal thermal energy storage system that stores heat or cold in the ground using arrays of vertical boreholes. It is commonly used in district heating, large buildings, and renewable energy systems to balance mismatches between energy supply and demand over long periods (especially across seasons). This is a closed-loop system.

The system consists of boreholes, typically arranged in a grid, containing pipes that circulate a heat-transfer fluid. Warm fluid from sources such as solar collectors, industrial processes, or excess building heat is pumped into the boreholes, storing energy in the surrounding ground. When heat is needed, the cooler fluid absorbs energy from the ground and returns to the surface, where it can be used directly or via a heat pump for space heating or hot water. This approach enables efficient seasonal storage and use of thermal energy across different heat sources (Directory, 2025).

Similar to ATES, BTES does require temperature upgrading before using the hot or cold water. Therefore, BTES can not be used as a direct thermal buffer. This system does store energy, but not useful heat.

2.5.4 Molten Salt Tanks

Status: Mature - Scale: Utility

"The energy storage in molten salt tanks is a sensible thermal energy storage system. It is a mature technology that has been widely used in concentrating solar power (CSP) plants, for which it is essential. This technology gives the CSP plants the ability to store the energy of solar radiation from the hours of sunshine and convert it into electricity when required, adapting the energy source to the electricity demand of the grid" (Prieto et al., 2024).

Needless to say, the scale of this TES (utility-scale system) is much bigger than building-scale. Molten tanks are not applicable to building design, since the temperatures in molten salt tanks can range from 290 - 565 °C (Torres-Madroñero et al., 2025). A heat pump in buildings for example operates at much

lower temperatures: space heating: 30-55 °C and DHW: 55-70 °C, these temperatures are far below the freezing point of molten salt.

2.5.5 Activated Concrete Core

Status: Mature & Under development - Scale: Building

The research of Barbhuiya et al. (2023) explores the potential of, an already well-known thermal energy storage material: concrete. This paper: Thermal energy storage in concrete: A comprehensive review on fundamentals, technology and sustainability, besides covering basic characteristics of concrete, also dives deeper into optimizing/intensifying thermal energy storage in concrete.

Concrete's extensive usage in construction has sparked interest in its potential as a TES medium. It boasts advantages, including availability and cost-effectiveness, making large-scale implementation viable.

“Thermal energy storage (TES) in concrete can be achieved through various methods. One common approach is sensible heat storage, where the excess thermal energy is stored by raising the temperature of the concrete itself. This can be done by circulating heated fluids through embedded pipes or by direct contact with a heat source. Another method is latent heat storage, which involves incorporating phase change materials (PCMs) into the concrete. These PCMs absorb and release thermal energy during the phase transition, effectively storing and releasing heat. Thermochemical heat storage is another technique, where chemical reactions within the concrete absorb or release heat energy for storage and retrieval. These different methods offer flexibility in designing concrete-based TES systems to meet specific energy storage requirements” (Barbhuiya et al., 2023).

2.6 Latent Heat Storage

PCMs have the ability to absorb and release large amounts of heat as the materials changes state from solid to liquid (melting) or from liquid to solid (freezing) at a nearly constant temperature. PCMs in building elements are very energy dense, boosting thermal mass without adding relatively much weight.

2.6.1 Phase Change Materials

Status: Under development - Scale: Building

“On the basis of their chemical composition, PCMs are mainly classified as organic, inorganic and eutectic materials. Each category has a range of working temperatures and thermo-physical properties; thus, they are more suitable for specific application than others” (Al-Yasiri & Szabó, 2020). Paraffins and salt-hydrates are most relevant for thermal comfort applications in building design, since the temperatures (melting) of these PCMs are within a relevant range.

“Encapsulation is a suitable method to avoid the leakage issues of PCM and to enhance its compatibility with the building structure. Encapsulation is performed by covering the PCM by a shell for protection from the outside environment as well as for leakage prevention. This method is also essential to increase the heat transfer area and, hence, the thermal conductivity of PCM to ensure effective utilization of its storage capacity. The PCM can be macro-encapsulated using shells, tubes, channels and thin plates or micro-encapsulate when the micro-sized PCM is covered by unique polymeric material” (Al-Yasiri & Szabó, 2020).

2.6.2 PCM-enhanced Buffer Storage Tank

Status: Under development - Scale: Large building/high load profile

The research paper of Sun et al. (2025) explores the integration of PCM-materials to enhance water tanks. The paper highlights findings that conventional heat pump water heater (HPWH) loses control of its target water temperature 65% of the time during demand-response events (periods when the

heat pump is intentionally turned down or shut off to reduce grid load).

A PCM-enhanced thermal storage tank (PCM-TES) paired with an HPWH only loses control of its target temperature 11.6% of the time under the same conditions. With PCM storage, hot water temperature inside the tanks stays stable almost all the time, even when the heat pump is not running. This is because PCM stores large amounts of energy at nearly constant temperature. It releases heat slowly and steadily, keeping water temperature within the control range.

2.6.3 Ice Thermal Storage

Status: Mature - Scale: Building

Ice thermal storage (ITS) is defined as a system that utilizes the latent heat of water to achieve high densities of cooling energy (freezing and melting of ice), allowing for the shifting of cooling loads to off-peak periods to reduce cost.

ITS systems use the latent heat from phase transitions of water to obtain high densities of cooling energy. Water is chosen as the cold storage media because of its high latent heat fusion (334 kJ/kg). Moreover, it is low cost, environmentally-friendly, and non-toxic. ITS is used to shift high-peak demands to off-peak periods to reduce cost and minimize grid demand (Zhang et al., 2022). During night-time, ice is either formed around coils: ice-on-coil method, formed in a tank: Ice Harvester, or formed in plastic balls: Encapsulated ice storage. During day-time, the ice is used for cooling.

2.7 Thermochemical Energy Storage

Thermochemical energy storage systems constitute a less mature but highly promising alternative to sensible heat storage. These systems store energy through reversible chemical reactions, enabling higher energy storage densities and minimal storage losses over time. While their theoretical potential is well established in the literature, thermochemical storage technologies are largely still under development, with only limited demonstration at building scale. An overview of the most relevant thermochemical energy storage concepts under research and development is provided below.

2.7.1 Zeolite Sorption Modules

Status: Under development - Scale: Building

Thermal energy storage (TES) is an effective and economical way to balance building energy supply and demand. While sensible heat storage (SHS) and latent heat storage (LHS) systems are well-established and commercially available, thermochemical energy storage (TCES) materials offer significantly higher energy densities, approximately 3–30 times that of SHS and 2–20 times that of LHS, depending on the material. TCES also exhibits lower heat losses, supports long-term seasonal storage, and can operate at lower charging temperatures, making it particularly suitable for storing solar energy for building applications (Kant & Pitchumani, 2022).

According to Y. N. Zhang et al. (2018), this system is suitable to supply space heating and hot water for buildings by storing solar energy or other low-grade heat. The working cycle of this system is divided into two modes, which are listed as follows.

During the charging process, the input heat is stored in the form of chemical potential by breaking the binders between the sorbate and the sorbent. Then, the sorbate and the sorbent are kept separated during the sorption period. The discharging process is motivated by the connection between the sorbent and the sorbate, which release sorption heat for heating supply when needed. Generally, the sorption materials are composed of solid adsorbent, liquid absorbent, chemical reactor, and composite sorbents. This TES system is classified as closed system and open system according to its configuration. Besides, it can also be divided into long-term storage system and short-term storage system based on the designed storage time span.

2.7.2 Salt Hydrate Thermochemical Storage

Status: Under development - Scale: Building

“In the charging (dehydration) step, thermal energy is used to dissociate the chemical bonds between molecules through an endothermic reaction. The dissociated materials are then kept separately (storage step). The stored thermal energy can be delivered in the form of heat, whenever required, through an exothermic reaction between the two dissociated compounds (discharging, hydration step). In this step, chemical bonds form, resulting in heat generation. After discharging, the storage material is regenerated and reused for the next cycle” (Clark et al., 2019).

A heat pump charges this TES system during off-peak periods. The salt-Hydrate thermochemical storage reactor contains salt granules (fixed or encapsulated). There is also a water vapour channel and heat exchanger for charging and discharging. In turn, a regular building heat distribution system is connected. The TES has a heat exchanger transferring heat to the building water loop. The heat losses in this system are very minimal. Heat can be stored in the chemical bonds from days to months. This is an option for seasonal storage (Balasubramanian et al., 2010).

2.8 Energy Density of TES Systems

Assessing energy density of TES mediums is important for determining space requirements and integration potential, while analysing investment ensures the economic feasibility of the system. In the real-world applications, these metrics heavily influence the selection of TES systems. In order to get a better understanding of the energy storage potential in the individual TES systems and their associated costs, the International Energy Agency organization provides an estimation regarding technical and economic specifications, see *Appendix A* for this overview.

Volumetric Thermal Energy Storage Capacity of Thermal Storage Materials

The research of Lizana et al. (2017) “Advances in thermal energy storage materials and their applications towards zero energy buildings: A critical review” compares the volumetric storage capacity of thermal storage materials reviewed in their work.

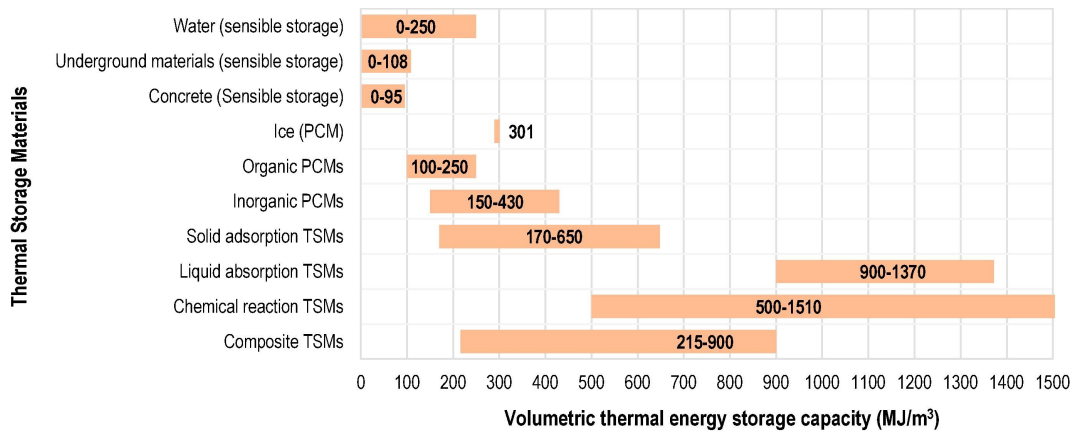


Figure 5: The overview above illustrates the ranges of volumetric TES capacity of technically developed and commercially available material groups (1 kWh = 3.6 MJ).

Adapted from Lizana et al. (2017).

3 Methods: Proposed Framework

The proposed framework establishes a structured, eight-part methodology for the implementation of thermal energy storage (TES) systems in buildings, of which the last two parts are case specific and therefore only present in the case study section of this thesis. Nonetheless, the methods used in the last two parts inform readers of potential validation and optimisation methods.

Rather than a prescriptive guideline, this framework provides a systematic approach for navigating the integration process. The execution of each stage is intended to be adaptable, though subject to project-specific variables such as building typology, selected technology, and budgetary constraints. Chapter 4 applies this framework to a case study involving air-source heat pumps and stratified water tanks, detailing the transition from system selection to tank sizing under a defined control strategy. This application serves to validate the framework and demonstrates possible methods for optimizing the simulation model.

Framework Elements:

1. **Thermal Demand Data:** Defining thermal demand data and identifying the specific data resolution required for the building's thermal demand. High-resolution load profiles are necessary to ensure accuracy in sizing and overall system reliability. A transient multi-zone first-order lumped capacitance model is designed and used.
2. **TES System per Load Curve Archetype:** Match common thermal profiles of buildings with the most compatible TES systems. Using established load curve archetypes allows for the selection of systems best suitable for specific demand signatures.
3. **Integration into Building Design:** Incorporate the selected TES system into the building's general climate design. This stage ensures the storage infrastructure is compatible with both new and/or pre-existing HVAC installations.
4. **Control Strategy:** Formulate the operational logic governing charging and discharging cycles. This strategy dictates the system's final required capacity by balancing occupant comfort thresholds with operational flexibility.
5. **TES Capacity:** Determine the required storage volume and thermal capacity based on the established control Strategy to ensure peak demand is met without comfort violations.
6. **Simulation Model:** Capture the all preceding steps into a Python-based simulation model.
7. **Validation - Case Study:** Verify the reliability of the integrated TES system, and customize the simulation model based on the case study.
8. **Optimisation - Case Study:** Optimise the variables inside the simulation model to minimize TES required capacity and maximize efficiency.

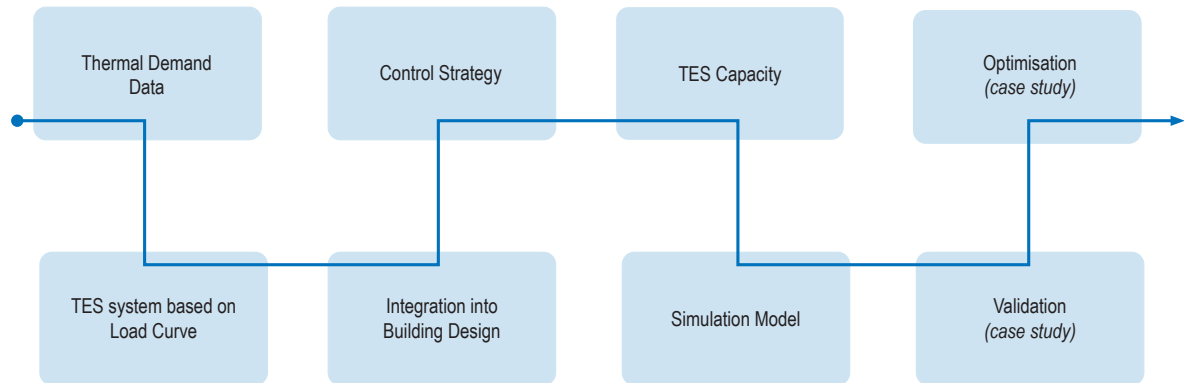


Figure 6: Design of the Framework

3.1 Part 1: Thermal Demand

The thermal demand of a building (often referred to as heating or cooling demand) represents the total amount of heat energy that must be added to or removed from a space to maintain a specific indoor temperature over a given period. This part of the framework will elaborate on how the thermal demand of a building is calculated and the thermal demand dataset format required for this research.

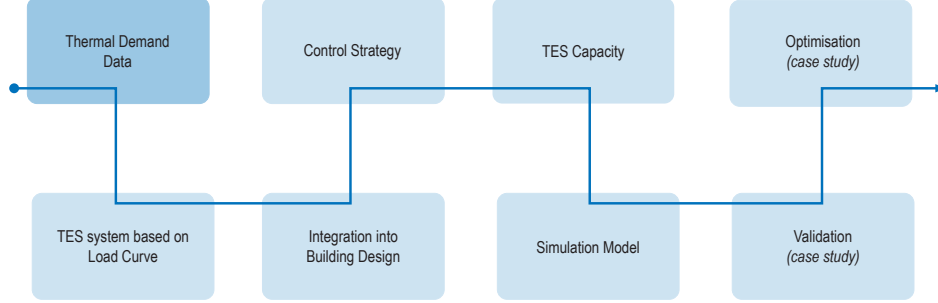


Figure 7: Part 1 of the framework

3.1.1 Thermal Demand Calculation

The thermal demand of a building is typically calculated through a dynamic energy balance. A robust energy balance framework is provided by the NEN-EN-ISO 52016-1. This approach calculates the energy required to maintain a stable indoor temperature by balancing the heat losses against the internal and external heat gains for every hour of the year. Performing this balancing calculation for 8760 hours provides a comprehensive profile of a building's annual thermal demand. The following equation illustrates the most simple version of this energy balance:

$$Q(t) = Q_{loss}(t) - Q_{gain}(t) \quad (1)$$

To better understand the key drivers of the building's thermal demand, we can break the energy balance down into its primary components. This equation accounts for the building's physical properties, environmental factors, and the buffering effect of its thermal mass:

$$Q(t) = [H \cdot (\theta_{int} - \theta_{ext}(t))] - [Q_{int}(t) + Q_{sol}(t)] - Q_{stor}(t) \quad (2)$$

Where:

- $Q(t)$ is the thermal demand at time-step (e.g., hour) t [kWh].
- H is the total heat loss coefficient [kW/K].
- θ_{int} is the internal set-point temperature [$^{\circ}\text{C}$].
- $\theta_{ext}(t)$ is the ambient outdoor temperature at hour t [$^{\circ}\text{C}$].
- $Q_{int}(t)$ represents internal heat gains [kWh].
- $Q_{sol}(t)$ represents solar heat gains [kWh].
- $Q_{stor}(t)$ is the thermal energy stored or released by the building's thermal mass [kWh].

The rest of this thesis will refer to the thermal demand per climatization zone per time-step as $Q_{zone}(t)$.

3.1.2 Identifying Climatization Zones

A climatization zone is defined as a specific space or grouping of thermal spaces within a building that share uniform heating, cooling, and ventilation requirements. These areas are grouped based on shared temperature set-points, emitter system, occupancy patterns, internal heat gains, and external environmental exposures, such as solar orientation and wind. Strategic zoning allows for the rationalization of varying thermal demands (Q_{zone}) across a building's footprint (Thermal Zones in Building Design, n.d.).

For the purposes of this study, references to thermal demand per zone (Q_{zone}) specifically refer to the aggregate demand of a defined climatization zone. The group of thermal zones within a specific climatization zone will be governed by the same control strategy, discussed in part 4 of the general framework.

Identifying climatization zones begins by verifying which areas are part of the building's overall thermal zones. According to the *ISSO*, the Dutch Knowledge Centre for the building and building services sector, climatization zones are determined as functional subdivisions of these thermal spaces. Following the guidelines in *ISSO 75.1, "Gebouwbegrenzing en indeling"*, spaces are categorized into specific climatization zones by applying the following stepwise decision schematics:

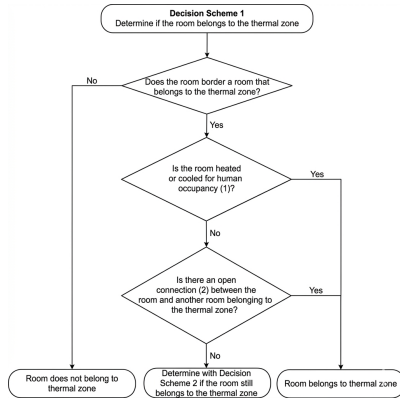


Figure 8: Decision scheme part 1 - Identifying thermal zone.

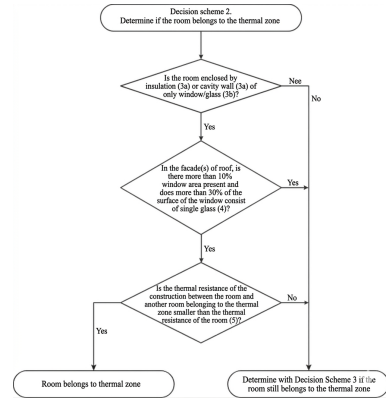


Figure 9: Decision scheme part 2 - Identifying thermal zone.

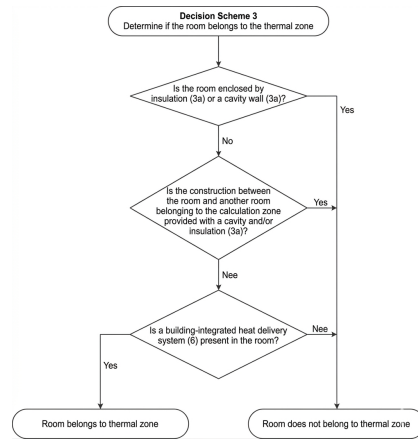


Figure 10: Decision scheme part 3 - Identifying thermal zone.

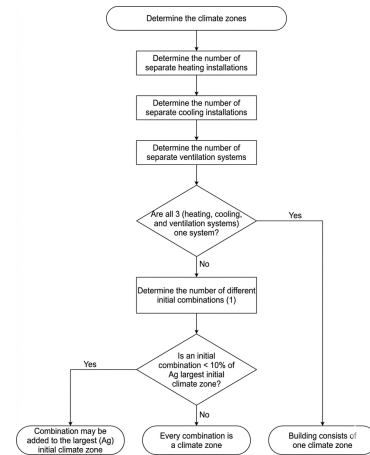


Figure 11: Decision scheme part 4 - Identifying climatization zone.

3.1.3 Obtaining Thermal Demand Dataset

To maintain a generalized framework, this study offers two distinct pathways for acquiring thermal demand profiles. The first treats the demand as given input data, utilizing thermal datasets exported from external third-party software. The second provides an integrated modelling option:

1. **External simulation software:** External building performance simulation (BPS) software, such as Vabi Elements which is an industry standard in the Dutch construction and engineering industry, can provide high-fidelity thermal demand datasets. This software, along with other BPS software provides a specialized environment for calculating hourly thermal loads, energy labels, and indoor climate performance.
2. **Simplified energy balance model:** Since external simulation software is not always available as an option to generate thermal demand datasets from buildings and to maintain an applicable general framework, this thesis provides an alternative route by modelling a multi-zone, first-order lumped capacitance model based on the hourly energy balance method of the ISO 13790 / NEN-EN-ISO 52016-1. Unlike the fixed external datasets, this internal model allows for the direct manipulation of parameters to influence the resulting thermal data, serving as a flexible, thermal demand dataset calculator within this study. This model can be found in the *Appendix D*.

3.1.4 Zonal Thermal Load

This research looks at the thermal demand of each climatization zone of a building. As mentioned earlier, the thermal demand per zone, $Q_{zone,i}$, is defined as the required energy in kilowatt (kW) per time-step (e.g. hour). Since each zone is different in geometry, orientation, construction, emitter system, occupancy, and temperature set-points, the thermal demand per zone will vary. The following schematic overview illustrates this zonal approach:

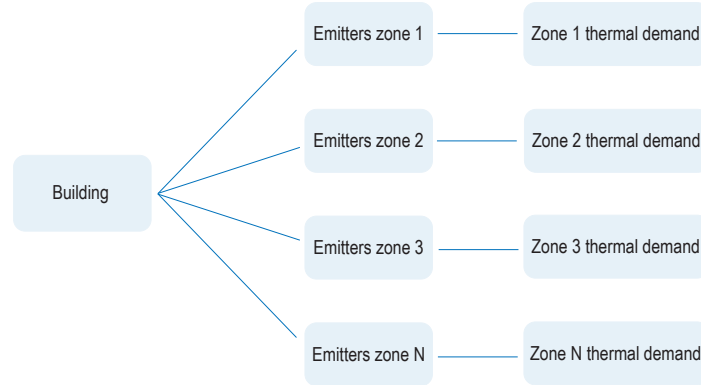


Figure 12: Schematic overview of thermal dataset required per zone.

Separate Heating and Cooling Aggregation

Once the thermal demand is calculated for each zone per time-step, you can determine the peak power requirements for the TES system. By summing the heating demands across all zones at each time-step, the maximum aggregate value over the year identifies the peak heating power requirement. For cooling, the same logic applies, where the most negative value of $Q_{total}(t)$ represents the peak cooling load.

$$Q_{total}(t) = \sum_{i=1}^n Q_{zone,i}(t) \quad (3)$$

Data format

The required thermal demand dataset is structured as a DataFrame (*see table 2*), indexing the zone's thermal demand at discrete intervals (time-steps). A high-fidelity demand profile is foundational to the framework, as the precision of the input data directly dictates the accuracy of the resulting TES dimensions. This means that the more accurate the demand per zone can be calculated (as close to reality as possible), the more efficiently the thermal system including buffer can be sized.

While an annual dataset captures seasonal fluctuations in thermal loads, the length of each time-step is just as important (high-time resolution). The smaller the time-step, the more effectively the model captures peak demand spikes and operational behaviours, without these fluctuations being masked by a big time-step.

Time-step	Zone 1	Zone 2	Zone 3	Zone N
Time-step 1	+/- .. kW	+/- .. kW	+/- .. kW	+/- .. kW
Time-step 2	+/- .. kW	+/- .. kW	+/- .. kW	+/- .. kW
Time-step 3	+/- .. kW	+/- .. kW	+/- .. kW	+/- .. kW
Time-step 4	+/- .. kW	+/- .. kW	+/- .. kW	+/- .. kW
Time-step 5	+/- .. kW	+/- .. kW	+/- .. kW	+/- .. kW

Table 2: Example of a multi-zone thermal demand dataset structured as a DataFrame, where '+' suggests a heating demand and '-' suggests a cooling demand.

3.2 Part 2: TES System per Load Curve Archetype

This section establishes the building load profile as the primary diagnostic tool for TES system selection. By analysing a building's thermal demand per time-step, this framework categorizes load profiles (which are heavily influenced by building usage patterns) into Load Curve Archetypes. This classification serves two purposes: first, it identifies potential grid congestion risks based on the timing of peak demand. Second, it maps these archetypes directly to suitable storage technologies. This methodology allows the framework to move beyond generic recommendations and instead provide a targeted selection of TES solutions based on a building's specific, expected load pattern.

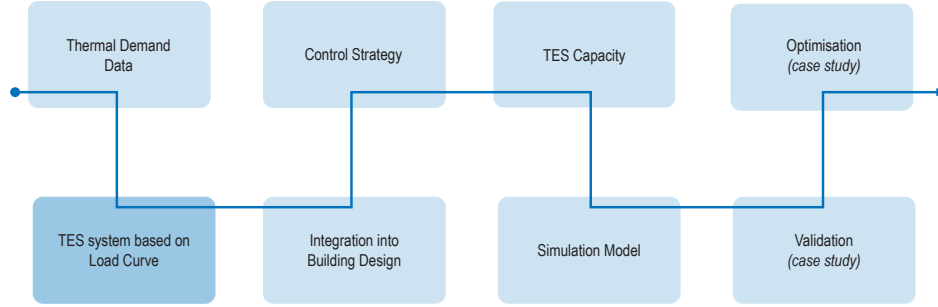


Figure 13: Part 2 of the framework

3.2.1 Load Duration Curve

A Load Duration Curve (LDC) gives insight into a buildings yearly thermal demand. A load model represents a system's energy demand over a given period and is used to assess capacity adequacy. Load models are generally classified as load duration curve (LDC) models or chronological (time-series) models. An LDC is formed by sorting hourly peak loads in descending order. An annual LDC (8760 hours) provides the most accurate representation (Almutairi et al., 2015).

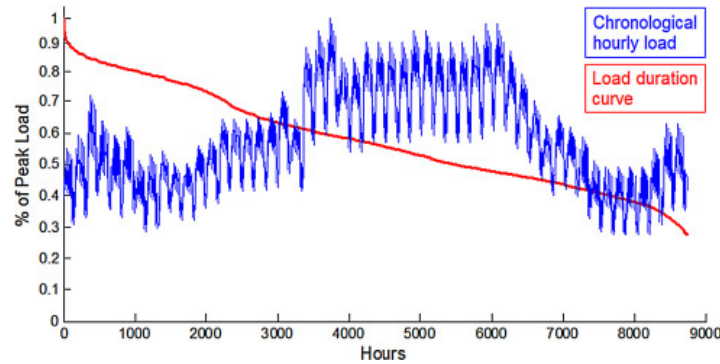


Figure 14: Example of a yearly thermal demand of a building. The Load Duration Curve consists of the chronological hourly load sorted from high to low.

Adapted from Almutairi et al.(2015).

The Load Duration Curve is a statistical tool rather than a chronological schedule. Because it sorts annual demand from highest to lowest, it shows the frequency of a load but removes the context of when it occurred. Consequently, two buildings with entirely different usage patterns, an office peaking at noon and a residence peaking at night, could share an identical curve if their total energy volume and peak magnitudes match.

While this makes the curve unsuitable for daily operational control, a LDC allows for the immediate identification of the maximum power capacity and total energy volume (area under the curve) required to size the physical components of a Thermal Energy Storage system.

3.2.2 Zonal Chronological Hourly Load

While the Load Duration Curve provides a statistical overview of annual demand, it obscures the operational timing necessary for sizing a TES system. To accurately determine the required power capacity and discharge duration, this research utilizes the Chronological Hourly Load (CHL). Unlike the LDC, the CHL preserves the temporal sequence of demand, allowing for a realistic assessment of how a thermal profile fluctuates over time. The CHL is analysed across three distinct temporal scales, with each revealing different requirements for the storage medium:

- **Daily scale:** At a daily scale, the chronological load identifies the intra-day variance and peak-power intensity. This reveals the necessary "thermal responsiveness" of the TES. A thermal profile characterized by high-magnitude, short-duration fluctuations requires a system with high heat-transfer rates to ensure that the discharge power can meet rapid transitions in the demand-side requirements.
- **Weekly scale:** Extending the analysis to a weekly time-frame uncovers periodic occupancy cycles and operational idle periods, such as weekends. This scale is critical for assessing storage requirements and minimizing energy losses during periods of inactivity-e.g., by determining the necessary level of insulation for a water tank to prevent stored thermal energy from dissipating over an idle weekend.
- **Annual scale:** Viewing hourly data over a full year maps the seasonal phase shift between energy generation and peak thermal load. This long-term chronological sequence is the fundamental metric for calculating the required energy-to-power ratio. It determines the transition from short-term buffer solutions to high-capacity seasonal TES, which must bridge multi-month gaps between energy surplus and deficit. ATES and BTES are examples of systems characterized by a high energy-to-power ratio, designed to manage substantial volumes of energy over extended durations.

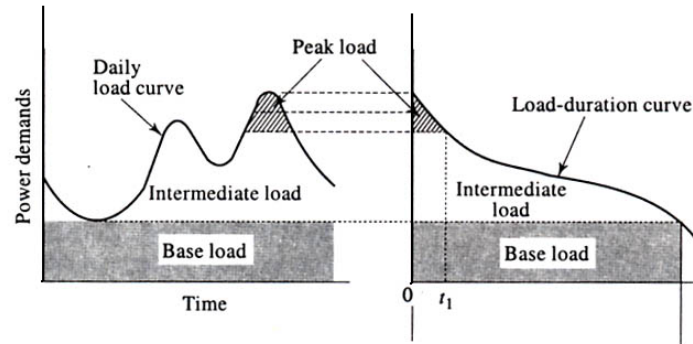


Figure 15: Daily load curve and its LDC

Adapted from Pharos University (2026).

3.2.3 Grid Congestion Time-frame

Grid congestion adds another layer of necessity to the temporal analysis of thermal demand. While traditional TES selection is based on the building's needs, grid-aware TES selection is based on the electrical grid's capacity to supply that energy. This shift moves the focus primarily to the daily and weekly timescales, where grid congestion occurs.

- **Daily scale:** On a daily basis, grid congestion typically occurs during "peak" hours when demand spikes just as solar generation drops. In the Netherlands, morning peaks (7:00-09:00) are often described as "Wake-up" spikes. Residential demand for heat and hot water coincides with office buildings powering up and the start of industrial processes. The evening peak (17:00-21:00) is the most critical window, when the grid is congested the most. By analysing the chronological load, it is possible to identify these congested windows and determine the thermal demand in that period.

- **Weekly scale:** A building's chronological hourly load over a typical week provides a representative demand profile, as it captures the interplay between daily peak power requirements and weekly occupancy rhythms, such as weekend setbacks. This scale is crucial for managing grid congestion, as it identifies the capacity needed to shift loads away from daily "rush hours" while ensuring the system can bridge multi-day periods of high grid stress or low renewable availability.
- **Annual scale:** While daily and weekly scales define operational strategy, the annual scale is critical for identifying the "design day". This is the most extreme period of peak demand and minimum energy availability in a year. By capturing these annual extremes, the TES system can be sized to ensure it remains reliable during the worst-case scenarios, preventing a total depletion of thermal reserves when the building's demand is at its highest and the grid is most congested.

3.2.4 Common Building Load Curve Archetypes

A gap exists in current literature regarding the direct mapping of building-specific demand shapes to TES technology selection. A clear overview of load patterns as a design tool is missing. Even though the literature does present load curves for certain building types, the information is often fragmented and narrowed to specific energy carriers, such as separate heating, cooling, or electricity and gas consumption, rather than providing a cohesive focus on all-electric buildings. Because this data is scrambled across a wide range of research papers without a standardized overview, this thesis proposes a set of typical (daily) load curves and one seasonal load curve illustrated in the figure below.

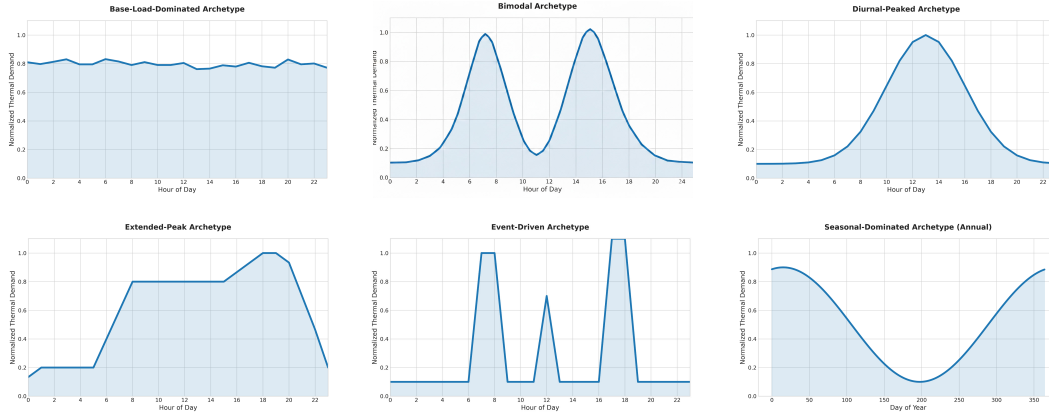


Figure 16: Examples of Archetype Load Curves.

Generated by Gemini (2026).

Due to a lack of existing empirical data for all-electric buildings, this research employs a deductive approach to synthesize building archetypes. Rather than relying on statistical data, these heuristic load curves are mapped directly to occupancy-specific usage intensities. This provides a standardized design tool that bridges the gap between building demand shapes and TES technology selection, though may not be entirely accurate. While these archetypes have a 24-hour time resolution utilized for daily usage sizing of the TES system, long-term seasonal fluctuations are instead captured through the yearly Chronological Hourly Load (CHL) curve.

3.2.5 Load Curve Archetypes and Suitable TES system allocation

- **Base-load dominated** (The Flatline): This curve represents facilities with constant thermal requirements, such as hospitals or data centres. The profile is characterized by minimal fluctuation, where thermal load remains consistently high throughout the day and night without significant peaks or valleys.

– *Suitable TES:* [Stratified Water Tanks](#) | [TABS](#) | [Phase Change Materials \(PCM\)](#)

- **Bimodal** (The M-curve): Typical of residential buildings, this curve shows two distinct peaks in the morning and evening, separated by a midday valley. This archetype requires a TES

capable of daily cycling: charging during the low-demand midday period to discharge during the high-demand peaks.

- *Suitable TES:* [Stratified Water Tanks](#) | [PCM-enhanced Storage](#) | [High-Performance Sensible Tanks](#)
- **Diurnal & Extended peak** (The Plateau): Most common in commercial offices and retail, this profile features a sustained high demand that lasts for the hours of a regular workday. The TES selection for this archetype must prioritize energy capacity to ensure the system does not deplete before the occupancy period ends.
 - *Suitable TES:* [Ice Thermal Storage](#) | [Stratified Water Tanks](#) | [PCM](#) | [TABS](#)
- **Fast-response** (The Needle Peak): This curve is defined by sudden, intense spikes in demand over short durations. This curve is typical for event-driven spaces like theatres. The focus for this archetype is high power delivery during event periods. Recharging of the thermal buffer is done during low demand periods.
 - *Suitable TES:* [Stratified Water Tanks](#) | [High-conductivity PCM](#) | [Short-term Buffer Storage](#)
- **Seasonal** (U-Shape): This profile tracks long-term shifts in demand across months rather than hours, reflecting the transition from winter heating to summer cooling. This archetype requires large-scale storage solutions that can bridge the gap between energy availability in one season and peak demand in another.
 - *Suitable TES:* [ATES](#) | [BTES](#) | [Zeolite Sorption](#) | [Salt-hydrate Storage](#)

3.3 Part 3: Integration into Building Design

This part of the framework establishes the transition from thermal demand analysis and TES selection to a functional climate system design. This section determines the structural configuration of the system. The integration of a TES unit is governed by the building's system topology: centralized, decentralized, or hybrid. This chapter evaluates how these different configurations facilitate energy exchange between zones. The characteristics of the established climatization zones form the technical basis for the integration into the building's climate design. This includes an exploration of the TES as a thermal hub to manage simultaneous heating and cooling demands and its connection to renewable energy sources like PV or PVT panels. The objective is to select an integration strategy that ensures hydraulic flexibility and temperature compatibility for the specific zonal layout of the building.

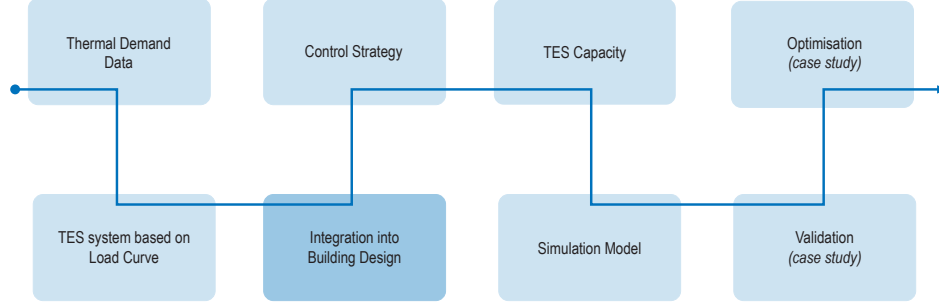


Figure 17: Part 3 of the framework

3.3.1 Zonal Characteristics

In order to successfully integrate a TES system that is compatible with the general climate installation design, the following information per climatization zone is required (see table below). In section 3.4.4 *Thermal mass calculation* the floor area per zone is required to deduce the specific thermal capacity (C_{spec}), based on the *Dutch Energy Performance* table. The emitter of each zone along with its temperature parameters is required to establish the required thermal levels that the TES needs to be able to deliver. The temperature differential is used to calculate flow rates of emitters.

Zone	Floor Area [m ²]	C_{spec} [kJ/(m ² K)]	Emitter type	T_{supply} [°C]	T_{return} [°C]
Z1	—	—	—	—	—
Z2	—	—	—	—	—
ZN	—	—	—	—	—

Table 3: Zone and Emitter Parameters

3.3.2 Centralized TES

In a centralized TES setup, the system acts as a single "thermal vault" that stores the building's energy reserve in one location. By storing thermal energy in a large source tank or thermal battery, the design lowers the cost per unit of energy stored and makes maintenance much simpler (Centralized Vs Distributed Energy Storage Systems: Pros And Cons, 2025). Because the surface area of a single thermal buffer is often less compared to multiple small micro-buffers, the standing heat losses are lower. However, this assumption is only true if the micro-buffers are the same TES medium: PCM buffers have a higher heat density and require less volume compared to a water tank buffer, when storing the same amount of energy.

A centralized TES layout is ideal for load levelling the primary heat source, allowing a boiler or heat pump to run at a steady, high-efficiency rate while the storage handles the building's fluctuating peaks. Since the energy is stored in a central location, a well-designed hydraulic system is needed.

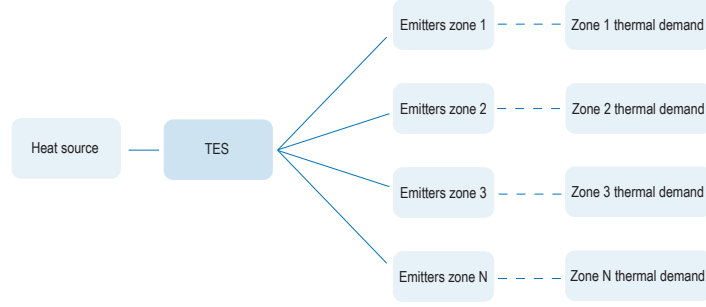


Figure 18: Schematic representation of centralized TES.

3.3.3 Decentralized TES

Instead of a centralized thermal battery, each zone of the building has its own thermal buffer. Zonal TES implementation, also known as micro-buffers, can be subdivided into two categories: partial micro-buffer integration and full micro-buffer integration:

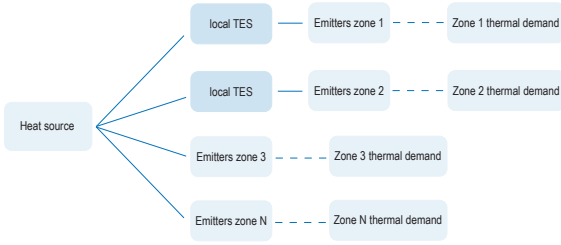


Figure 19: Partial micro-buffer integration.

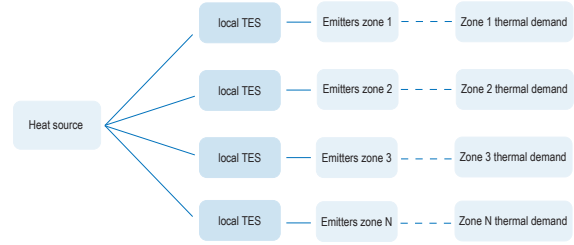


Figure 20: Full micro-buffer integration.

Partial Decentralized TES Configuration.

In this configuration, the system is a hybrid where only specific zones utilize local thermal buffers. This setup is significantly more complex to manage because the heat source must simultaneously handle two different hydraulic behaviours: the charging flow required for local TES units (such as melting PCM modules), and the instant flow required for standard emitters. While only installing buffers in zones where peak-shifting is most needed can be considered cost saving, the disadvantage is the high operational complexity. The control system must prioritize and balance competing flow rates and temperatures. This requires specialized mixing valves to ensure that the instant-heat zones do not different medium temperatures meant for charging TES units.

Full Decentralized TES Configuration.

In this configuration, each zone is provided with its own local TES. The primary advantage is thermodynamic and control consistency; the heat source has a single objective to charge the local thermal buffers whenever they are depleted. This uniformity eliminates the temperature conflict found in the partial micro-buffer configuration. The disadvantage is the increased potential maintenance, as every zone contains mechanical storage and associated valves. However, from a hydraulic standpoint, the system is easier to balance because every branch behaves with similar resistance and flow requirements.

3.3.4 Hybrid of Centralized TES & Decentralized TES

The hybrid configuration integrates a central thermal buffer with decentralized micro-buffers. By utilizing a central reservoir as a hydraulic separator, the heat source can maintain a consistent, lower baseline temperature to satisfy general building demands, thereby improving overall system efficiency. The local TES units provide supplemental storage capacity for specific high-demand zones, allowing these zones to be charged independently during off-peak periods—often utilizing materials with higher

energy density than the central buffer. This enables the local units to provide the high-intensity energy required for peak shifting or specific high-demand climatization zones without requiring the central system to operate at higher temperature set-points or be sized much larger to be able to deliver this high energy demand.

However, this setup requires sophisticated control logic to synchronize the charging of the central thermal buffer and the local micro-buffers without hydraulic interference, which increases the complexity of the operational strategy

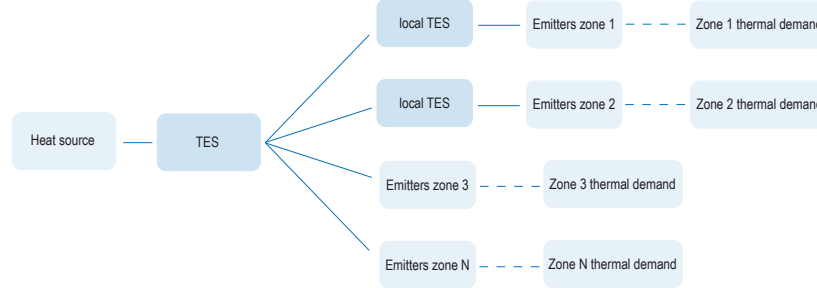


Figure 21: Schematic representation of hybrid TES.

3.3.5 Compatibility of Operating Temperatures

All topologies have to take into consideration that different TES systems as well as standard emitters operate with specific temperatures. Generally it is favourable when the operating temperatures of the systems are within a small temperature range. In an ideal scenario the operating temperatures for all systems is the same. This would be the most efficient and exergy preserving scenario.

- **Central TES:** In case of uniform temperatures among the entire system, $T_{storage} = T_{emitters}$. If the operating temperatures differ among the emitters, the highest required temperature dictates the maximum temperature output of the TES, resulting in $T_{storage} > T_{emitters}$ for lower temperature emitters. This might result in significant thermal efficiency degradation of heat sources due to, in most cases, unnecessary temperature lift. Thermal stratification in sensible heat storage tanks is a way of combatting this by preserving exergy. Nonetheless, this is not a perfect solution.
- **De-central TES:** In case of a fully decentralized TES configuration with uniform temperatures, the heat source can charge the TES (such as PCM-modules) with a steady temperature and treat the building as a giant thermal battery. In case of varying operating temperatures for both fully decentralized TES and partial decentralized TES configurations, the system would have to be able to supply those different temperatures using specialized valves, stratification, temperature mixing strategies or other solutions.
- **Hybrid:** In case of uniform temperatures, the system would be redundant. There is little benefit to having two layers of storage if the temperatures are the same, unless there is little available space in the central storage hub. In case of varying temperatures, the heat source charges the central thermal buffer at a lower temperature for baseline heating. For charging the local thermal buffer units (such as PCM-modules) that might require higher charging temperatures, with a bypass of the central tank, the heat source could directly feed the local units with a temporary higher temperature output. The local TES units provide the extra temperature lift. Disadvantages include complex piping and control systems.

3.3.6 Integration with Renewable Energy

On-site renewable energy generation mitigates grid congestion by decentralizing the electricity supply, allowing a building to satisfy a significant portion of its thermal and electrical demand internally. The added renewable energy can be used to generate and store heat for a building, essentially increasing

the building's total available electricity supply throughout the day. Especially during grid-congested times, this added electricity or heat is very convenient.

Renewable energy sources, PV (photovoltaic) and PVT (photovoltaic-thermal) panels in particular can be well-integrated into a thermal buffer system. PVT panels combine two technologies: solar PV and solar thermal (hot water). Both heat and energy are generated from solar irradiation (Usesolar, n.d.). Over the years these panels have become increasingly popular for buildings. Depending on the type of thermal energy storage, either PV or PVT is a more compatible option for a certain system setup. This chapter will cover the integration of solar collectors with TES systems, however, the possible system configurations are not limited to the examples discussed.

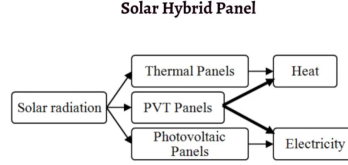


Figure 22: Types of solar panels.
Adapted from Usesolar (n.d.)

Sensible & Latent Heat Storage

The integration of solar collectors for sensible, as well as latent heat storage is well-established in literature. PVT panels are able to supply a heated medium to a thermal buffer. This medium is either directly stored in a thermal buffer, or is lifted in terms of temperature by a heat source in order to be suitable for a thermal buffer. The operating temperatures depend on the TES system. A common heat source is a heat pump, able to lift temperatures, fully or partially on the electricity generated by the PVT panels (Kahana, 2025). The figure below is an overview of examples of system configurations. More setups are possible depending on the installations, TES system, Piping, and design goals. In case of PV integration, only generated electricity, and not thermal energy, is supplied to the system.

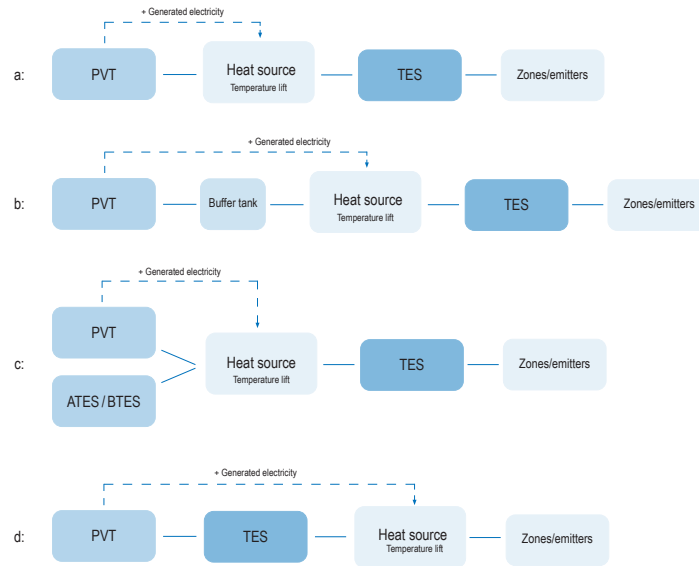


Figure 23: PVT integration examples. Option b illustrates the addition of a buffer tank. This is also possible for option c. Example of a heat source: heat pump.

Configurations (a) and (b) adapted from Chhugani et al. (2022); (c) adapted from Lee et al. (2025); and (d) adapted from Herrando and Ramos (2022).

Thermochemical Heat Storage

According to the review "Applications of low-temperature thermochemical energy storage systems" by Lin et al. (2020), TCES systems can be categorized as open or closed based on operational mode, both systems most compatible with PVT integration for low-temperature sorbents (e.g., Salt Hydrates). High-temperature sorbents (e.g., Zeolites) require an extra temperature lift from a heat source, since the PVT cannot provide these required temperatures.

Closed systems recycle the reactant internally. During storage, vapour is condensed into a liquid and kept in a tank; it is later evaporated to trigger the discharge reaction. While these systems are complex and expensive due to vacuum requirements, they allow for seasonal heating and cooling using a wide range of chemicals. Open systems exchange vapour directly with the surrounding air. These systems are simpler, cheaper, and offer high energy density because they do not need internal gas storage. However, these systems are limited to water-based reactions and require fans and humidifiers to operate, which can affect indoor humidity.

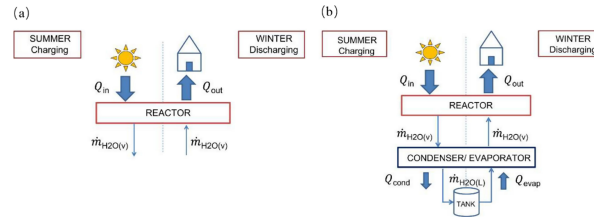


Figure 24: An open system versus a closed system.

Adapted from (Solé et al., 2015)

3.4 Part 4: Control Strategy

This part of the framework defines the operational logic required to manage the interaction between the building's thermal demand, the thermal system, and the selected storage mediums. While the previous step established the physical integration and system topology, this part focuses on the dynamic governance of energy flows. By conceptualizing the system components as discrete functional nodes, a hierarchical priority is established to satisfy specific operational goals.

The following sections evaluate both active and passive control strategies, ranging from specific TES operating modes to the utilization of the building's inherent thermal mass. Central to this analysis is the "switching strategy," which determines the optimal dispatch order based on the available recovery window (time available to recharge the TES) and the characteristic saturation time of each medium. This chapter provides the control strategy necessary to transition from a static building design to a responsive thermal management system. The final capacity of the TES system, determined in part 6 of the framework, is a direct result of the control strategy.

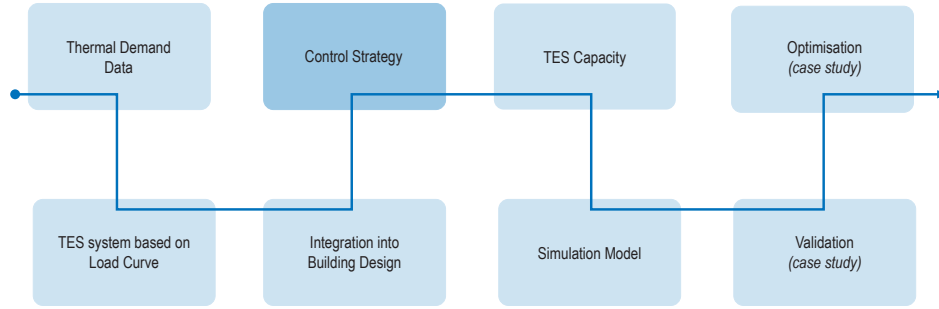


Figure 25: Part 4 of the framework

3.4.1 System Priority Order

To establish a versatile control strategy, this study treats thermal demand, the heat source (the thermal system), the TES system, and thermal mass as discrete functional nodes. However, more nodes can be added if wanted. These nodes serve as the logical basis for defining the system's operational priority, allowing for a tailored energy hierarchy per building that meets specific objectives such as grid-congestion mitigation or cost optimization.

This hierarchical approach allows the energy flow to be tailored to a building by determining which node takes precedence during charging or discharging cycles. The priority order of the nodes are based on type of load profile, system preferences, boundary conditions, or a pre-determined control strategy/climate design. While the fundamental nodal framework remains consistent across different scenarios, the specific sequence of interaction (of the nodes) defines the system's behaviour. Once the main nodal order is established, detailed sub-control layers are implemented to manage the precise operational logic within each individual component.

Figure 26 shows examples of nodal sequences. To provide more contextualization, the following examples compare strategy A and B:

- **Strategy A:** This configuration utilizes a fixed priority sequence starting with, what is always, the thermal demand. During grid congestion, the heat source is deactivated, forcing the system to rely on storage. The thermal mass is dispatched first to provide a high-inertia buffer, while the TES system remains in reserve, activating only after the structural mass is depleted. This maximizes passive energy reduction before utilizing the dedicated buffer.
- **Strategy B:** In this approach, the heat source remains active but is modulated during grid congestion. To maintain high temperature set-point precision, the TES system is prioritized as the primary secondary source to assist the generation equipment. The thermal mass serves as

the last buffer only utilised after the active storage capacity (TES) is exhausted. This strategy prioritizes immediate thermal stability over passive efficiency.

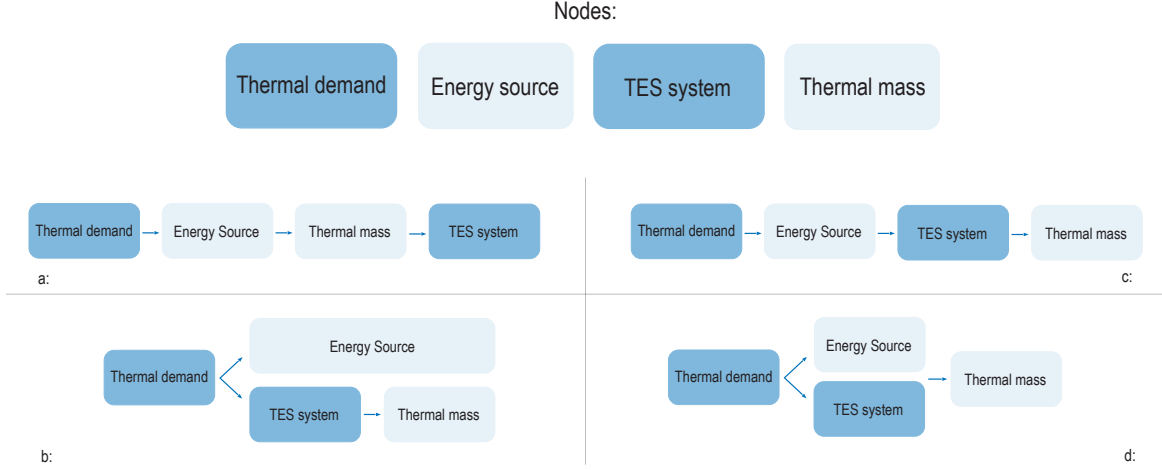


Figure 26: Main (but not limited to) nodes of thermal system setup and example variations of order.

3.4.2 Active Strategy: Operating Modes

Storage performance is inherently tied to its control logic. ASHRAE (2012, p. 822) notes that the specifics of equipment operation, control valve functions, and set-points are all determined by the chosen operation mode. This directly impacts the required energy capacity ($E_{TES\text{capacity}}$) and the resulting TES volume (V_{final}). A combination of operating modes is also possible. In that case, a hierarchy of operating modes needs to be established. This hierarchy will be the control logic that the system follows. Prime examples of operation modes are, but not limited to:

- **Charging with no load:** This mode is generally characterized by a straightforward control sequence where the (heat or cold) generation equipment, such as heat pumps, operates at maximum capacity with constant supply temperature set-points. Charging continuous at a constant flow rate until the storage is fully charged or the available period ends. The scenario assumes that all designated equipment is dedicated solely to storage purposes.
- **Charging while meeting load:** Necessary for buildings with continuous thermal demands, this mode is more complex. The control logic operates the heat or cold generation equipment at maximum capacity, but the load is prioritized. Only the capacity not required to meet the instantaneous demand is diverted to the TES. This necessitates careful consideration of system piping (series or parallel) to ensure both the load and the storage receive adequate thermal energy.
- **Meeting load from discharge only:** Often referred to as a full storage or load shifting, this mode involves deactivating the primary heat or cold generating equipment entirely (decoupling). The entire thermal load is met by the storage system. This strategy is the primary driver for determining the required energy capacity (V_S) for a specific discharge window, as it defines the duration the TES must operate as the sole provider.
- **Meeting load from discharge and direct equipment:** Utilized in partial storage strategies, this mode requires complex control sequences to regulate the proportion of the load met by the TES versus the primary equipment. These sequences must dynamically select equipment operation and capacity. This interaction is best evaluated using a continuous energy balance (V_C) to identify the largest cumulative deficit during peak or constrained periods.
 - **Generation priority control:** The primary heat or cooling source is operated at a constant or optimized capacity, often based on its peak efficiency point. The TES is utilized only to "shave" the remaining peak demand that exceeds the equipment's limit. This minimizes storage cycling but requires larger generation plant capacity.

- **Storage priority control:** The control sequence prioritizes the discharge of the TES to meet as much of the demand as possible. The primary generation equipment remains inactive or operates at a minimum until the storage discharge rate or temperature can no longer satisfy the load. The maximizes the utilization of the stored energy, but carries a higher risk of premature storage depletion.
- **Constant proportion control:** This strategy modulates both the storage discharge and the primary equipment simultaneously to meet the load in a fixed or variable ratio. By dynamically adjusting the contribution to each source, the system ensures that the storage capacity is distributed evenly across the entire discharge window.

3.4.3 Passive Strategy: Thermal Mass

Integrating the thermal mass of a building into its operational strategy provides a more sophisticated thermal management system than relying on active climate control alone. Regarding temperature set-points in combination with thermal mass, the following variables can be distinguished:

- T_{set} : The temperature set-point of zone n
- T_{swing} : The allowed temperature differential compared to T_{set} for zone n (optional)
- T_{min} : The minimum allowed temperature of zone n (also possible: $T_{min} = T_{set}$)
- T_{max} : The maximum allowed temperature of zone n (also possible: $T_{max} = T_{set}$)

1. **Order: Thermal mass $\rightarrow$ TES:** Pre-charging the thermal mass before grid congested periods would reduce the peak energy for the TES system by allowing the building to release heat gradually first:

From Thermal mass T_{max} or $T_{set} \rightarrow T_{min} \rightarrow$ TES sustains T_{min}

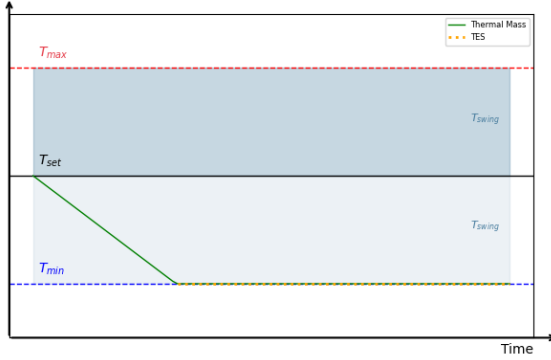


Figure 27: Simplified illustration for heating of strategy T_{set} version.

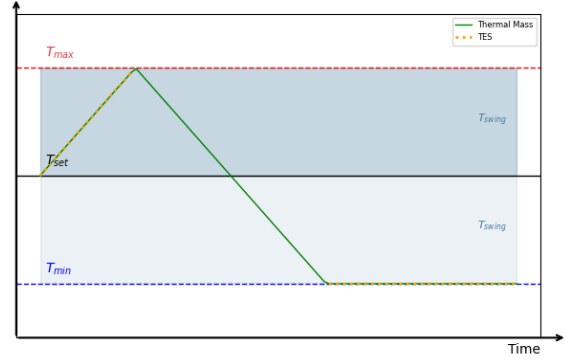


Figure 28: Simplified illustration for heating of strategy T_{max} version.

The TES system only needs to cover the residual demand that exceeds what the precharged structure can provide. This results in a more compact, cost-effective, and efficient system design where the TES acts as a high-responsive reserve rather than a reservoir for bulk energy. This multi-layered approach optimizes performance through two primary engineering principles:

- **Reduction of transmission heat loss:** According to Fourier's law, the rate of heat loss ($Q = U \cdot A \cdot \Delta T$) is directly proportional to the temperature difference between the interior and exterior. By allowing the building temperature to drift within the defined comfort temperature swing during peak periods, the average ΔT is reduced. Thereby lowering the total energy lost to the environment compared to maintaining a constant set-point (using the buffer tank first).

- **Exergy and reserve management:** Structural mass provides high thermal inertia but low discharge flexibility. By utilizing this slow energy source first, the system preserves the high-grade thermal energy within the TES, especially sensible TES, as a high-power reserve. This ensures that the TES remains available to provide a rapid thermal response. Besides supplying thermal energy to stay within the swing temperature limit, saving the buffer for last can serve against unforeseen spikes or extended occupancy.

2. **Order: TES → Thermal mass:** Using TES before activating the building's thermal mass is often driven by a need for precision control and occupant comfort reliability. Initially, the TES sustains the T_{set} temperature for as long as possible. After the TES is depleted, the thermal mass is the remaining buffer and gradually releases heat and drops in temperature:

TES sustains T_{set} → TES depleted → Thermal mass from T_{set} → T_{min} (or lower)

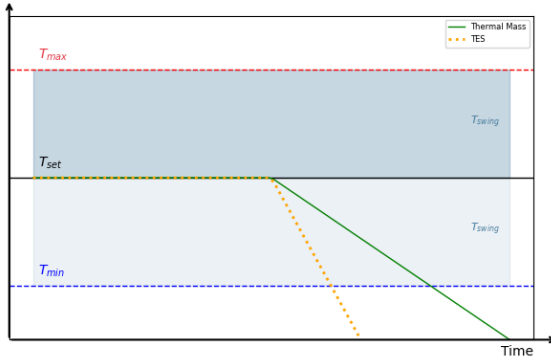


Figure 29: Simplified illustration for heating of strategy T_{set} version.

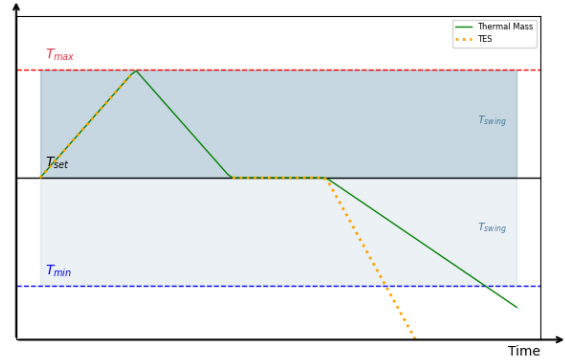


Figure 30: Simplified illustration for heating of strategy T_{max} version.

- **Precision and immediate set-point recovery:** By utilizing the TES first, the system maintains T_{set} with high fidelity. This avoids the early onset of the temperature drift associated with passive thermal mass, making it ideal for zones with low thermal comfort tolerance.
- **Maintenance of thermal potential:** Discharging the TES early ensures that the most flexible energy source is used to meet immediate load spikes. This leaves the structural mass, which has high inertia and low discharge flexibility, to handle the end of the congestion period.
- **Increased transmission loss:** By maintaining a constant T_{set} for longer, the average ΔT between the interior and exterior remains high, leading to a greater total energy loss compared to the "thermal mass first" approach. This is a disadvantage.
- **Exergy degradation:** Using high-grade stored energy for early-stage cooling or heating may be an inefficient use of the buffer if the structural mass could have handled the initial load passively.

3. **Hybrid: Thermal mass & TES:** The hybrid approach involves the simultaneous or zone-specific integration of both storage mediums to balance efficiency with operational constraints.

Thermal mass + TES sustain T_{set} → minimizing T_{swing} → Thermal mass from T_{set} → T_{min} (or lower)

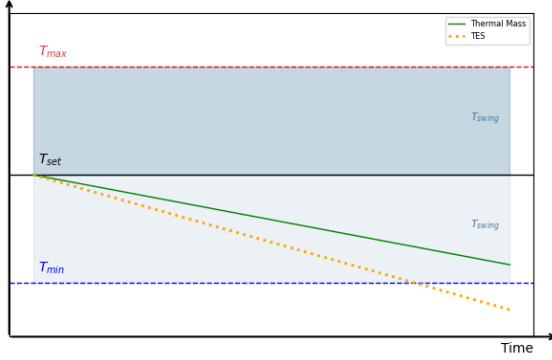


Figure 31: Simplified illustration for heating of strategy T_{set} version.

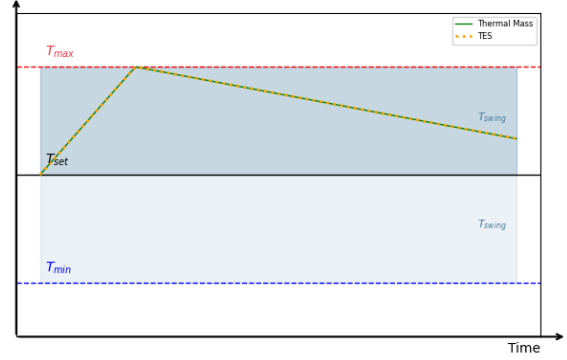


Figure 32: Simplified illustration for heating of strategy T_{max} version.

- **Functional zoning and sensitivity:** In large-scale buildings, a single dispatch order for all zones is often sub-optimal. A hybrid strategy allows high-sensitivity zones to follow a TES → Thermal mass order for stability, while other zones follow a Thermal mass → TES order to maximize energy savings.
- **Dynamic load shaving:** The system can use thermal mass to provide a base cooling/heating effect while using the TES to trim sudden peak demand spikes. This prevents the building from reaching T_{max} (summer) or T_{min} (winter) prematurely, effectively narrowing the operational T_{swing} without depleting the buffer entirely. This system works simultaneously for each zone.
- **Control complexity:** Implementing a hybrid strategy requires a more sophisticated Building Management System (BMS) and predictive modelling to coordinate different dispatch logic across multiple zones. A hybrid strategy risks energy oscillation if the control logic does not synchronize the high-latency thermal mass with the low-latency TES. Over-correction occurs when the active system provides a high-power response to a deviation that the passive mass is already slowly addressing. This results in a temperature overshoot and subsequent "hunting" for the set-point.

3.4.4 Thermal Mass Calculation

Thermal Mass Constant

To quantify the building's inherent energy storage potential, this study employs a methodology based on the specific thermal capacity standards for *Dutch energy performance*. The thermal mass of each zone is estimated by correlating its structural characteristics, in particular the material density of floors and walls and ceilings, with its total floor area. From the provided performance data, the energy required to raise the temperature (or vice versa: the energy released when lowering the temperature) of the internal structure per square meter of floor area can be estimated.

Specific thermal capacity in 1000 J/(m ² K) (m ² refers to floor area)			
		closed or lowered ceiling	no or open ceiling
Floors	Walls		
light	light	55	80
light	heavy	110	180
heavy	light	110	180
very heavy	light	110	180
heavy	heavy	180	360
light	very heavy	180	360
heavy	very heavy	250	450
very heavy	heavy	250	450
very heavy	very heavy	250	450

Floors:	very heavy:	solid concrete floors
	heavy:	steel-concrete floors; concrete hollow-core floors; cassette floors
	light:	other
Walls:	very heavy:	solid concrete walls
	heavy:	concrete column-beam constructions; load-bearing masonry walls
	light:	other

Figure 33: Dutch Energy Performance table

Adapted from Energy performance of buildings – Determination method (NTA 8800:2024), by Netherlands Standardization Institute, 2024.

The specific capacity is converted into a functional thermal mass constant (M_{zone}) expressed in [kWh/K]. This constant allows the TES sizing model to treat the structure as a secondary thermal buffer: absorbing energy during charging, releasing energy during discharge. The conversion is defined as:

$$M_{zone} = \frac{Area_{floor} \cdot C_{spec} \cdot 1000}{3.6 \times 10^6} \quad (4)$$

While utilizing the Dutch Energy Performance table allows for a fast standardized calculation of zonal heat capacity, it introduces some drawbacks:

- **Instantaneous heat exchange:** The model assumes "lumped capacitance", where the entire structural mass reacts to the temperature changes immediately. In reality materials have thermal lag, meaning it takes time to charge or discharge the heat. Concrete for example, depending on the total mass could have a thermal lag of hours. A more realistic estimation of the thermal mass capacity would be to introduce an "Effective Thermal Mass" factor, which would result in a portion of the theoretical mass.

- **Surface area versus volume:** The estimation relies solely on floor area. It fails to distinguish between a thick concrete slab and multiple thin partition walls, which have different heat transfer rates despite having the same total mass.

Zone Share of Heat Source Output

For the (re)charging of the thermal mass of each zone, a second control layer regarding the thermal hunger per zone is present:

- **Sequential recharging of zones:** This strategy allows the zones to be recharged sequentially. If it is adamant that temperatures, and therefore thermal mass, of specific zones are restored to the set-point temperature, a sequence of recharging can be implemented. The high-priority zones would be recharged before lower-priority zones.
- **Proportional recharging of zones:** The proportional division would be based on the "thermal hunger" in [kWh] of each zone. For each zone i :

$$Hunger_i = (T_{max,i} - T_{current,i}) \times M_{zone,i} \quad (5)$$

Where:

- $M_{zone,i}$ is thermal mass constant expressed in [kWh/K] of zone i .
- $T_{max,i}$ is the set-point temperature of zone i .
- $T_{current,i}$ is the current temperature of zone i .

The available surplus power from the heat source is then distributed using a ratio:

$$ZoneShare_i = \left(\frac{Hunger_i}{\sum Hunger} \right) \cdot Q_{surplus} \quad (6)$$

Where:

- $ZoneShare_i$: Power allocated to zone i [kW].
- $Hunger_i$: The energy deficit of zone i , defined as the total thermal energy required to raise the zone temperature to its respective set-point temperature (T_{set}) [kWh].
- $\sum Hunger$: The cumulative energy deficit of all zones in the building [kWh].
- $Q_{surplus}$: The available thermal power from the heat source remaining after satisfying the total instantaneous building demand [kW].

Larger zones require a greater quantity of thermal energy to achieve a 1K temperature rise due to their higher thermal mass. The logic compensates by allocating a higher share of the available thermal power to these zones. Zones with a larger temperature drop have a bigger energy deficit. The logic directs a larger fraction of the thermal power to these areas, prioritizing the zones furthest from their comfort set-points.

3.4.5 Recovery Window: Switching Strategy

Regarding recharging strategy, the selection between structural thermal mass and dedicated TES system is primarily dictated by the available recovery window relative to the characteristic response time of the storage medium. Because heat transfer into the building structure involves significant thermal lag, the structural mass acts as a high-inertia storage asset that requires extended charging durations to achieve meaningful thermal saturation.

Consequently, during extended recovery periods (in between net congested hours), the control strategy prioritizes structural pre-charging to stabilize the Mean Radiant Temperature (MRT) and provide a high-capacity, passive baseload buffer. Conversely, during short windows in between net congestion, the logic shifts to the dedicated TES: its higher power density and optimized heat exchange surfaces, allow it to reach a full State of Charge (SoC) rapidly. This provides a high-grade, low-inertia energy reserve that can be dispatched with minimal delay to meet instantaneous demand when the primary thermal energy generation source is constrained. Switching charging strategy based on the recharge window is necessary when the thermal mass cannot be recharged fast enough.

Temporal Feasibility Check

In the context of thermal management, t_{sat} (Saturation Time) represents the temporal requirement for a specific storage medium to reach its maximum energy capacity or defined temperature set-point under current power constraints. It serves as the speed limit of the storage strategy, accounting for both the available power of the heat source and the physical resistance of the building materials. The relationship between t_{sat} and the recovery window (Δt_{window}) is the primary driver for system efficiency and feasibility:

- If the recovery window is shorter than t_{sat} , the structural mass cannot be meaningfully charged to feel a difference in temperature, making the high-inertia storage an ineffective target for energy.
- By comparing these two values, the control logic can pivot to the medium that provides the best fit: prioritizing the TES system (for example a fast charged sensible buffer tank) when time is scarce and the structural mass when the window is long enough to overcome thermal lag.

The actual durations [hours] required for each zone to absorb the energy, incorporating a utilization factor (η) to account for the thermal lag and surface resistance of the mass:

$$t_{sat,struct_i} = \frac{Hunger_i}{ZoneShare_i \cdot \eta} \quad (7)$$

Where:

- η : The Utilization Factor (e.g., 1.2). It represents the effectiveness of the heat transfer path into the mass.

The system-wide saturation time ($t_{sat,struct}$) is calculated as the duration required for the available surplus thermal power to satisfy the collective energy deficit of all zones:

$$t_{sat,struct} = \frac{\sum Hunger_i}{Q_{surplus} \cdot \eta} \quad (8)$$

The fundamental logic that determines the priority of the charging sequence:

$$\text{Strategy} = \begin{cases} \text{Prioritize Structural Mass} & \text{if } \Delta t_{window} \geq t_{sat,struct} \\ \text{Prioritize Dedicated TES} & \text{if } \Delta t_{window} < t_{sat,struct} \end{cases}$$

The saturation time for the dedicated Thermal Energy Storage tank ($t_{sat,tes}$) is calculated based on the energy required to reach the maximum capacity of the TES:

$$t_{sat,tes} = \frac{E_{tank,gap}}{Q_{surplus}} \quad (9)$$

Where:

- $E_{TES,gap}$ is the remaining energy capacity in the TES (kWh), calculated as $E_{TES,max} - E_{TES,current}$.

3.5 Part 5: TES Sizing Method

While the previous step established the operational priority of the nodes for the control strategy, Step 6 determines the energy storage capacity required to support that logic while maintaining occupant thermal comfort. This stage utilizes the time-series data from part 1 and the control strategy from part 4 of the framework to calculate the necessary Thermal Energy Storage (TES) capacity and the resulting physical dimensions of the storage system. The sizing process evaluates three distinct volumetric requirements: demand-based capacity (V_S), continuous energy balancing (V_C), and hydraulic stability volume (V_H).

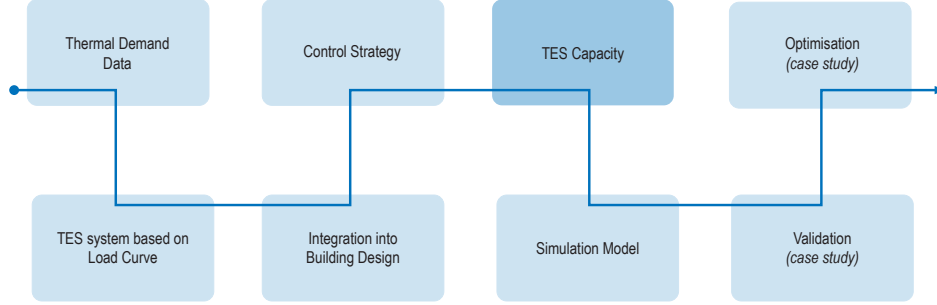


Figure 34: Part 5 of the framework

Determining the correct storage size requires distinguishing between static and dynamic assessments. The static assessment, V_S , functions as a design snapshot. It is calculated based on a single, isolated event, such as a fixed 4-hour grid-constrained window, to establish a baseline capacity for early-stage planning. Because it focuses on one event, it does not account for the influence of preceding days or the variability of an entire year.

In contrast, the dynamic assessment, V_C , evaluates the system performance over an entire operational time-series. Unlike V_S , this approach is highly dependent on the system's state from previous days, ensuring the storage remains functional across consecutive periods where fluctuating energy supply might prevent a full recharge.

Finally, to ensure the system can physically move the stored energy, we calculate V_H . This checks that the storage volume is sufficient to handle the instantaneous power and flow constraints of the hydraulic circuit, bridging the gap between stored energy capacity and real-time delivery requirements. In this case V_H is only relevant for hydraulic systems. It functions as an example for checking if the capacity volume is also compatible with specific system medium and heat source constraints.

3.5.1 Defining the Discharge Window

Step 2: Thermal demand of the workflow described the need for the thermal demand per climatization zone, provided as a time-series dataset. The required span of this dataset (yearly, weekly, daily, or else) depends on the chosen design period that the TES is sized for. This is generally the worst-case scenario with the highest loads, or a typical, most occurring, time-frame.

A critical next step in TES sizing is determining the buffer period. This is the specific duration in which the TES is expected to be the primary heat provider, allowing to decouple the electric heat source. This window is typically defined by the operational strategy, such as shifting the load away from expensive peak-tariff hours or bridging the gap during periods when primary heat sources (such as heat pumps or solar collectors) are inactive due to grid congestion constraints. In case the primary heat source ($\dot{Q}_{supply}$) is modulated down instead of being completely inactive, $E_{TEScapacity}$ should account for: $\dot{Q}_{demand} - \dot{Q}_{supply}$ per zone or as a cumulative:

$$E_{TES\text{capacity}} = \sum_{i=1}^n (|Q_{\text{zone},i}| \cdot t_i) \quad (10)$$

Where:

- $E_{TES\text{capacity}}$ is the total energy demand for a given discharge window [kWh].
- $Q_{\text{zone},i}$ is the absolute thermal demand (both heating and cooling) of zone i [kW].
- t_i is the specific discharge window duration for zone i [hour(s)].

$$E_{TES\text{capacity}} = S \cdot \sum_{i=1}^n (|Q_{\text{zone},i}| \cdot t_i) \quad (11)$$

Where, in case of sensible TES (a tank in particular):

- $S = 1.1$ (10%): Use this if the tank and pipes are extremely well-insulated and located inside the thermal envelope of the building.
- $S = 1.2$ (20%): The standard “safe” engineering margin for typical indoor installations.
- $S = 1.25+$ (25%+): Use this if the tank is located outside or in an unheated plant room to account for higher standing losses.

3.5.2 Volumetric Formulas

The final TES volume V_{final} is determined using the selection function defined in Equation 1. This function selects the governing volume requirement from three independent design criteria, ensuring the system satisfies all operational constraints.

$$V_{\text{final}} = \max(V_S, V_H, V_C) \quad (12)$$

or

$$V_{\text{final}} = \max(V_S, V_C) + V_H \quad (13)$$

Both formula V_S and V_H are quasi-static: demand input data is derived from a dynamic model. However, calculating for a certain design day assumes constant values for ΔT , resulting in a more static calculation. V_S calculates the total capacity needed for a certain discharge window. V_H calculates the volume needed to account for instantaneous power & flow.

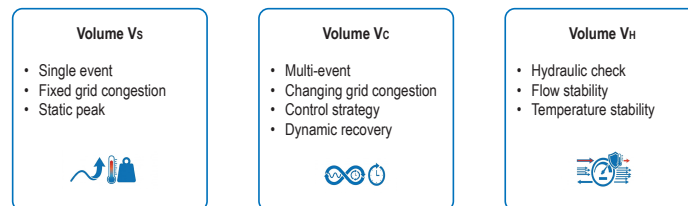


Figure 35: Final volume formula options depending on context, available data, complexity, and TES type.

1. Volume based on Static Demand - V_S

Formula V_S calculates the volume (V_S) required to store the total thermal energy needed for your discharge window (t):

$$V_S = \frac{E_{\text{TEScapacity}} \cdot 3600 \cdot S}{\rho \cdot \Delta u \cdot \eta_{str}} \quad (14)$$

Where:

- V_S is the required storage volume based on energy [m^3 or L].
- $E_{\text{TEScapacity}}$ is the total energy demand [kWh].
- S is the safety factor (e.g., 1.1 – 1.25).
- ρ is the density of the storage medium [kg/m^3].
- Δu is the specific energy density of the medium [kJ/kg].
- η_{str} is the thermal storage efficiency (typically 0.85 – 0.95).

The specific energy density for the following types on thermal energy storage:

1. Sensible Storage

- $\Delta u = c_p \cdot \Delta T_{avg}$
- $\Delta T_{avg} = \frac{\sum(Q_i \cdot \Delta T_i)}{Q_{total}}$
- c_p : Specific heat capacity of the medium.

2. Latent Storage (PCM)

- $\Delta u = (c_{p,s} \cdot \Delta T_s) + L + (c_{p,l} \cdot \Delta T_l)$
- $\Delta T_s, \Delta T_l$: Temperature ranges of solid and liquid phases.
- $c_{p,s}, c_{p,l}$: Specific heat capacities of solid and liquid phases.
- L : Latent heat of fusion.

3. Thermochemical Storage (TCS)

- $\Delta u = \Delta H_r$
- ΔH_r : Enthalpy of reaction or adsorption.

2. Volume based on Continuous Energy Balance - V_C

While V_S focusses on a discrete event, V_C evaluates the system's performance over a continuous time-series (e.g., 1 year - 8760 hours) for a specific selected control strategy. This approach accounts for the zone temperatures and the State of Charge (SoC) of the TES by identifying the largest cumulative deficit between demand and supply ensuring the storage does not deplete during extended periods of low supply.

The hourly demand ($Q_{demand,t}$) used in V_C is defined as the aggregated zonal demand (Q_{zonal}) to ensure the TES capacity accounts for simultaneous heating and cooling requirements across all n zones. $Q_{demand,i}$ is the energy demand resulting from the control strategy. In case thermal mass is utilised first to let the zone temperatures drift, $Q_{demand,t}$ is the energy demand required to maintain the indoor temperature of the zones within the maximum allowed T_{swing} .

In case of a dedicated TES for cooling and a separate TES for heating, calculating the volume for both TES requires two versions of the V_C formula, one for a heating demand and one for a cooling demand.

1. Determine the building-level net energy flow [kW] for every hour (t):

$$Q_{demand,t} = \sum_{i=1}^n Q_{zone,i,t} \quad (15)$$

$$Q_{net,t} = Q_{demand,t} - Q_{supply,t} \quad (16)$$

In case of grid congestion capping the thermal supply ($Grid_Limit_t$ converted from [kVA] to [kW]):

$$Q_{net,t} = Q_{demand,t} - \min(Q_{source,t}, Grid_Limit_t) \quad (17)$$

2. To find the cumulative energy deficit for the building at any time (t) in [kWh], the net energy flow for the current time-step ($Q_{net,t} \cdot \Delta t$) is added to the deficit accumulated in the previous time-step ($E_{cum,t-1}$). To account for the "fully charged" buffer constraint, where the tank is full and cannot store additional surplus energy, $E_{cum,t}$ is reset to 0 whenever a surplus occurs that exceeds the existing debt:

$$E_{cum,t} = \max(0, E_{cum,t-1} + (Q_{net,t} \cdot \Delta t)) \quad (18)$$

3. Find the maximum energy gap in the time-series (e.g., for a year $t = 8760$ hours):

$$E_{max_gap} = \max(E_{cum,1}, E_{cum,2}, \dots, E_{cum,n}) \quad (19)$$

4. Use the maximum energy debt in the volumetric volume formula:

$$V_C = \frac{E_{max_gap} \cdot 3600 \cdot S}{\rho \cdot \Delta u \cdot \eta_{str}} \quad (20)$$

3. Volume based on Hydraulics - V_H

The Case Study of this thesis applies the general TES implementation framework to a sensible heat storage system including heat pumps and stratified buffer tanks. Since these systems are becoming increasingly popular, V_H is included to illustrate a hydraulic check required for hydraulic TES systems. LTS and TCES require different volume checks depending on the mediums. However, this is outside the scope of this research.

Formula (V_H) ensures the storage unit can physically handle the mass flow rates required by the emitters without failing to meet instantaneous demand:

$$V_H = \frac{q_{net} \cdot \tau_{min}}{\eta} \quad (21)$$

Where:

- V_H is the required hydraulic buffer volume [m^3].
- q_{net} : The peak instantaneous flow mismatch between the secondary distribution circuit and the primary generation circuit [m^3/h].
- τ_{min} : The hydraulic stability constant, representing the minimum duration required for the system controls to stabilize during a flow transition (typically 0.25 h).
- η : The volumetric utilization factor, representing the fraction of the storage medium effectively accessible for thermal exchange (typically 0.8 for stratified water tanks).

The flow low mismatch is defined as the maximum absolute difference between the total secondary distribution demand and the primary generation supply across the simulation time-series:

$$q_{net} = \max \left| \sum_{i=1}^n q_{sec,i}(t) - q_{pri}(t) \right| \quad (22)$$

Where:

- q_{pri} is the primary volumetric flow rate provided by the heat source (e.g., heat pump) during the specified operational period [m^3/h].
- $q_{sec,i}$ is the required secondary volumetric flow rate for each individual zone i to satisfy the instantaneous thermal demand [m^3/h].

The required flow rate for each individual zone i is calculated based on the thermal demand $Q_{zone,i}$ (from the Q_{zonal} dataset) and the target temperature differential of the emitter(s) of the zone (ΔT_i :

$$q_{sec,i} = \frac{Q_{zone,i} \cdot 3600}{\rho \cdot c_p \cdot \Delta T_i} \quad (23)$$

Where:

- $Q_{zone,i}$ is the heat demand of zone i [kW].
- 3600 is the conversion factor from seconds to hours.
- ρ is the density of the heat transfer fluid [$\approx 1000 \text{ kg}/m^3$ for water].
- c_p is the specific heat capacity of the fluid [$\approx 4.18 \text{ kJ}/kg \cdot K$ for water].
- ΔT_i is the design temperature difference for the secondary circuit [K].

The primary flow rate provided by the heat source is defined as:

$$q_{pri} = \frac{Q_{supply} \cdot 3600}{\rho \cdot c_p \cdot \Delta T_{pri}} \quad (24)$$

Where:

- Q_{supply} is the actual thermal power output from the primary heat source [kW].
- ΔT_{pri} is the temperature lift across the primary generator (Supply - Return) [K].

3.5.3 Approach Motivation

- **Strategic compliance (V_S):** While dynamic data in V_C fluctuates with weather and other variables, V_S is a quasi-static calculation based on a fixed design objective (e.g., a 4-hour peak-shifting window). It ensures the system meets certain obligations or grid-flexibility policies that must remain valid regardless of whether a specific year was mild or extreme influencing the demand/supply data. This approach establishes a "safety floor" for the storage capacity.
- **Continuity and SoC Integrity (V_C):** This represents the "continuous reality check". Unlike V_S , which assumes a fully charged TES for a single event, V_C evaluates the system over a continuous time-series. It accounts for the State of Charge (SoC) over multiple days for example. This is critical for identifying the cumulative failure, where a system successfully manages a single peak but fails on subsequent days because the available supply (grid-constrained or weather-dependent) was insufficient to fully recharge the medium.
- **Hydraulic and kinetic integrity (V_H):** This represents the "power-to-energy limit". While V_S and V_C focus on total capacity (kWh), V_H ensures that the TES is physically dimensioned to handle peak instantaneous power and mass flow rates (q_{net}). Without this constraint, a system might be energetically sufficient but fail to meet demand because the rate of heat exchange is physically limited. For sensible systems, this prevents the destruction of stratification. For latent and thermochemical systems, it ensures sufficient heat-transfer surface area and reaction (kinetics) to maintain the required output temperature under peak flow conditions.

The final capacity of a TES system is determined by the intersection of two distinct functional requirements: energy capacity (V_C) and operational stability (V_H). The energy volume (V_C) is a derivative of the thermal demand dataset time-step dt , ensuring the medium can meet power demands over a specific duration without exhausting its thermal reserve.

Conversely, the stability volume V_H is governed by the hydraulic or mechanical response time τ_{min} required to protect the primary heat source during rapid load transitions. Depending on the specific control strategy and the sensitivity of the equipment, the total system size is typically established either as the maximum of these two values (*function 12*) (assuming the larger volume can absorb short-term fluctuations) or as their sum (*function 13*) to guarantee a dedicated physical buffer remains intact regardless of the state of charge of the TES system.

3.6 Part 6: Dynamic Simulation Model

While the previous parts of the workflow established the theoretical energy needs, this part implements the actual simulation to find the optimal system dimensions. This stage moves away from static "worst-case" assumptions (formula V_S) and instead uses a dynamic model (V_C) to balance the competing needs of thermal comfort, energy supply constraints, and storage limitations.

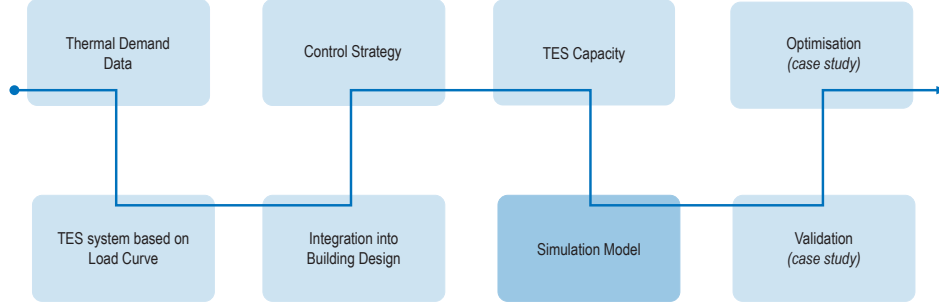


Figure 36: Part 6 of the framework

By treating the building as a series of interacting nodes that make up the control strategy, the simulation can track the state of the system hour-by-hour (or at even finer resolutions depending on the dataset time-step). This allows the framework to determine the precise volume needed to survive periods of grid congestion while accounting for the rechargeability of the storage medium. The method uses an optimization loop to converge on the smallest possible TES capacity that still satisfies all thermal and hydraulic constraints, ensuring the design is efficient rather than oversized.

3.6.1 Simulation Model Architecture

The simulation model is developed in Python and is structured into multiple components: Thermal Data Generator (Multi-zone model or external simulation software), Availability Engine, Simulation Engine, and Optimizer (*see Appendix D, E and F*). This modular approach allows the model to simulate the interaction between grid availability, thermal demand, and storage system behaviour in real-time. Each component is explained below and the accompanying required data and its structure is illustrated in the example tables.

Thermal Dataset

The thermal demand is integrated as a zonal dataset covering a defined series of time-steps, where positive values (+) suggest heating and negative values (−) suggest cooling.

While the raw input is quasi-static, meaning the load profile is pre-calculated and fixed, the simulation engine dynamically corrects this demand in real-time. By applying a thermal mass constant (M_{zone}) derived from the structural design and floor area, the model simulates the building's ability to absorb or release energy. This effectively decouples the immediate building needs from the heat source, allowing the structural mass to (partially) bridge supply-demand gaps during grid-congested events.

Furthermore, directly linking the simulation engine to an external thermal demand model (if possible) enables a fully dynamic exchange. In this configuration, the control logic and the TES state of charge actively influence the building's thermal behaviour in real-time, moving beyond the constraints of a fixed dataset. Moreover, linking the external software or multi-zone model script allows running simulations with different parameters, able to optimize systems and validate its robustness.

Availability Engine

This section calculates per time-step, the PV generation from solar panels, and adds that to the available grid kVA. The available kVA from the grid can either be calculated dynamically per time-step

Time-step	Zone 1 [kW]	Zone 2 [kW]	Zone 3 [kW]	Zone N [kW]
1	—	—	—	—
2	—	—	—	—
3	—	—	—	—
4	—	—	—	—

Table 4: Thermal demand per zone dataset.

Zone	Area [m ²]	C_{spec} [kJ/(m ² K)]
Zone 1	—	—
Zone 2	—	—
Zone 3	—	—
Zone N	—	—

Table 5: Zone heat capacity specifications.

or imported as a fixed schedule dataset. This total electricity supply is multiplied with the COP_{real} . This section simulates a heat pump as the energy generator, however instead of the COP_{real} , any efficiency factor η_{th} of any energy generator that works on electricity can be used as replacement. Finally, the actual available thermal system output is capped by the max capacity of said energy generator, preventing unrealistic theoretical thermal output.

Time-step	Grid [kVA]
1	—
2	—
3	—
N	—

Table 6: Grid availability dataset.

Time-step	Temp [°C]	GG [W m ⁻²]	GD [W m ⁻²]
1	—	—	—
2	—	—	—
3	—	—	—
N	—	—	—

Table 7: Temperature, Global Horizontal Irradiance & Diffuse Horizontal Irradiance for PV energy yield and the external (outside) temperature.

Simulation Engine

This section handles the control logic for both charging and discharging of the heat source and the selected TES. The State of Charge of the TES as well as the temperatures of the zones are a result of the previous hours and the control logic. This part is therefore a dynamic simulation. The input section of the Simulation Engine contains a global parameter section and a section per zone. This way, each climatization zone can set its own control strategy and temperature set-points.

Variable	Unit	Description
Q_{cap}	[kW]	Rated capacity of the primary heat source.
η_{th}	[-]	Thermal efficiency (or conversion factor) of the heat source.
T_{amb}	[K]	Outside temperature to calculate thermal efficiency (COP for heat pump).
$Q_{avail,t}$	[kW]	Available heat source capacity per simulation time-step t .
Output heat source	[choice]	Division of restricted heat source output when thermal supply is lower than thermal demand: sequential or proportional.
Recharging strategy	[choice]	Priority sequence for recharging between the TES unit and thermal mass based on t_{sat} .
ρ, c_p, ν	[varies]	Physical and volumetric constants of the chosen storage medium.
η	[%]	Utilization factor of the storage system capacity.

Table 8: Global input variables for the general implementation workflow.

Variable	Unit	Description
Q_{zone}	[kW]	Specific thermal demand of zone n per simulation time-step.
T_{start}	[°C]	Initial zone temperature at the beginning of the simulation.
T_{set}	[°C]	Target indoor temperature set-point for zone n .
T_{swing}	[°C]	Permissible temperature deviation compared to T_{set} .
T_{min}	[°C]	Minimum allowed temperature boundary ($T_{min} \geq T_{set}$ possible).
T_{max}	[°C]	Maximum allowed temperature boundary ($T_{max} \geq T_{set}$ possible).
Discharging strategy	[choice]	Choice to maintain T_{set} with TES or first allow T_{swing} .
ΔT_{emit}	[K]	Designed temperature differential across the zonal heat emitters.
M_{zone}	[kWh/K]	Functional thermal mass constant.

Table 9: Zonal input variables and thermal comfort boundaries.

Optimizer

To determine the optimal thermal energy storage (TES) capacity, the optimizer employs a binary search algorithm that iteratively divides the search space to converge on the most efficient solution. The simulation engine provides hourly temperature and state-of-charge data, which the optimizer uses to test specific capacity values against defined temperature constraints.

By systematically checking for temperature limit violations, the algorithm identifies the smallest successful capacity, designated as E_{max_gap} , which is then converted into the final volume of the TES system. This volume is directly determined by the energy density of the storage medium, which defines how much energy can be contained per unit of physical space.

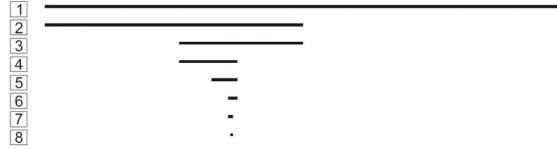


Figure 37: Illustration of the halving interval method.

Adapted from Hasan et al. (2013)

Hydraulic Check

Only applicable for sensible TES systems. This section only runs once: it calculates the volume based on the peak net flow. The final volume of the TES is either a max value of the two volumes or a summation of.

Flowchart of the Simulation Model

The integration of individual components and engines is structured through a modular data pipeline, where each component executes a specific function and passes its results to the next process. This information exchange is visualized in a flowchart using directional arrows that represent the flow of data between discrete process blocks. By mapping these dependencies and input-output relationships, the flowchart provides a representation of how the complete simulation operates as a unified system. The flowchart below is an example of a mostly sequential system.

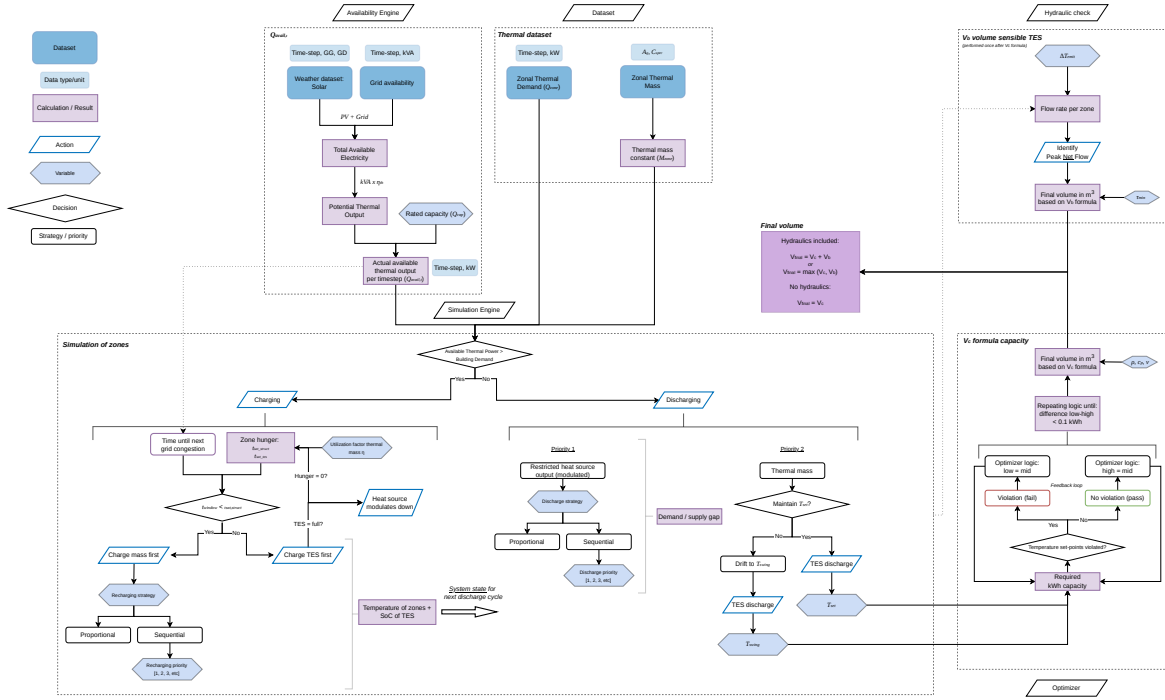


Figure 38: Flowchart
Flowchart of simulation model

3.6.2 Temporal Resolution of Thermal Demand Dataset

The final sizing of the TES tank is a direct result of the time-step scaling. The shorter the time-step, the more accurate the thermal demand data and the resulting required TES tank.

- **Influence on V_C :** The simulation's temporal resolution, defined by the time-step dt , serves as the primary scaling factor for energy-based calculations while functioning as a constraint on the visibility of peak hydraulic demands.

For the tank storage volume (V_C) and zone temperature modelling, the relationship is direct and linear: all power demands (kW) are converted into energy units (kWh) by multiplying the requirements by dt . Consequently, a 1.0 h time-step necessitates that the storage tank bridges sixty-minute intervals of continuous deficit, requiring a larger energy capacity per step than more frequent time-steps, such as 0.5 h or 0.25 h.

- **Influence on V_H :** While large a time-step maintains thermodynamic consistency, the assumption that heating or cooling requirements remain static for a full 1.0 h time-step may omit temperature fluctuations occurring within the zones, affecting the actual thermal demand within that time-step (hour). V_H operates under a different principle, as the core formula is independent of the simulation time-step dt and instead relies upon the fixed hydraulic stability constant τ_{min} . This constant is established to provide sufficient duration for the thermal system (typically 0.25 h for heat pumps) control systems to stabilize during flow transitions.

Although the mathematical structure remains consistent, the use of a 1-hour dt affects the accuracy of the result by averaging the input data. This averaging process potentially masks short-duration flow spikes that would necessitate a larger buffer volume. Therefore, while the 0.25 h constant (for heat pumps) ensures the system meets the minimum physical requirements for control stability, the calculated volume is an estimate based on mean hourly flow rather than the instantaneous peak demand.

4 Case Study: De Broedplaats

While this case study utilizes the methodology established in Chapter 3 as its foundation, the practical application in the case study necessitates a tailored sequence of implementation steps. This adaptation demonstrates the framework's flexibility, as the specific operational requirements and design constraints of the building take precedence over the generalized sequence.

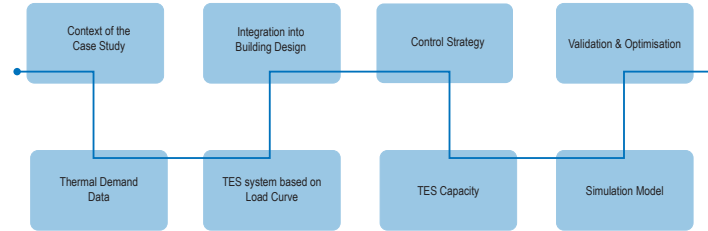


Figure 39: Parts of TES implementation

Furthermore, while the methodology provides a universal workflow, this case study conducts a more in-depth analysis of the selected TES system, moving beyond the framework's high-level sizing logic to develop a highly detailed and technically complete energy storage configuration. The case study is an utility building is located in Breda, the Netherlands, and will function as the new Performing Arts Center in the Havenkwartier area. In terms of scale, the building has a total usable floor area close to 3400 m².

4.1 Climate Design

As a creative hub for performing arts and startups, the site presents a complex thermal profile characterized by intermittent, high-intensity occupancy. A performing arts center could be categorized in the sector of public/institutional category, with standard opening hours. This category would usually lead to a diurnal peak in terms of load profile. However, since the function of this building is to host events, an event-driven load curve is more representative in this case, with multiple potential high thermal peaks throughout the day.

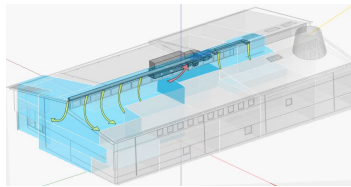


Figure 40: Climate concept with ventilation via central atrium (blue).

Adapted from ABT Adviseurs in bouwtechniek

4.1.1 Climate Concept

The case study features a central atrium that functions as the building's "lungs", serving as the primary air supply for the surrounding zones. This central space is maintained at temperatures ranging from 16°C in winter to 28°C in summer. Utilizing this cascaded air strategy, the atrium pre-conditions fresh air before it is drawn into individual spaces, offering improved efficiency over direct outdoor air intake.

Figure 41 illustrates two systems: a & b. It is a visual representation of the cascaded air strategy. The emitters upgrade the air by using hot or cold water supplied from the buffer tanks.

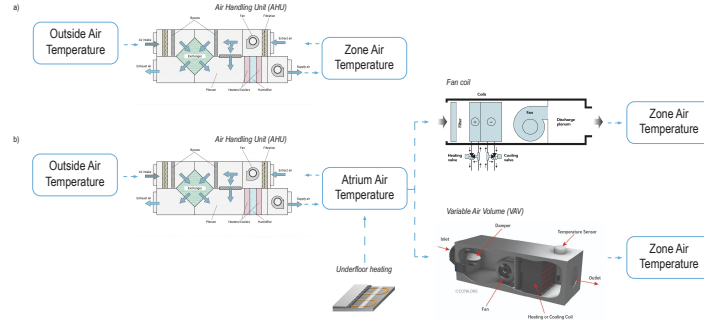


Figure 41: System a: theatre hall zone (Z1) & system b: other zones (Z2, Z3 and Z4).

AHU schematic adapted from Airtechnics (2025); Fan coil schematic adapted from CIBSE Journal (2016); and VAV schematic adapted from InterNACHI (n.d.)

Schematic A: Theatre

The theatre hall is served by a dedicated Air Handling Unit (AHU) that conditions a mixture of outside air and recirculated, heat-recovered, zone air to meet the specific ventilation and thermal requirements of this high-occupancy space. This configuration operates independently of the building's central atrium, focussing on converting the external ambient (outdoor) air conditions and the internal set-point using a high-capacity system.

Schematic B: Cascaded Strategy

Secondary zones utilize a cascaded air strategy where the building atrium serves as a thermal buffer and primary intake source for Fan Coil Units (FCU) and Variable Air Volume (VAV) units. In this setup, the air in the atrium is pre-conditioned by a second AHU and an underfloor heating (UFH) and cooling system. Before this air reaches other zones, the temperature gap is effectively narrowed between incoming air and the zone's target temperature. This pre-conditioned air reduces the temperature lift required from the water-to-air coils in the FCU and VAV units. As a result, the total kilowatt demand is decreased during grid congested periods when the heat pump modulates down and the TES tank has to bridge this period and deliver the kilowatt demand to the zones.

4.1.2 Problem Statement

The Broedplaats is facing a problem regarding grid connection capacity. Due to grid congestion, it is not possible to grant the building a high-capacity grid connection. It is expected that this needed connection is possible in 5 to 10 years time. Before that, the building will have to use the three separate low-capacity housing grid connections (55 KVA each) on site. Therefore, the building is divided into three compartments, each connected to one of the low-capacity connections: theatre, rented spaces, installations.

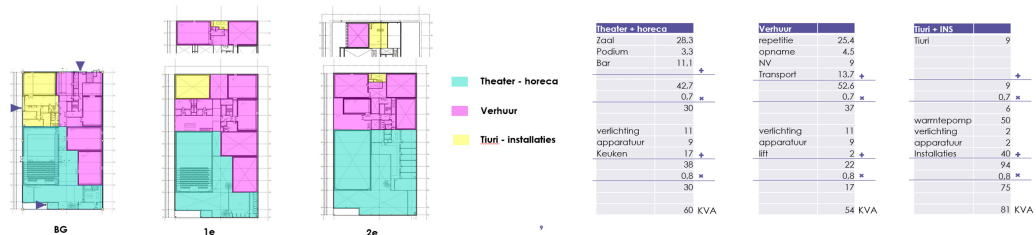


Figure 42: Three zones and respective power allocation.

Adapted from ABT Adviseurs in bouwtechniek

The relationship between real power (P) and apparent power (S) is defined as:

$$P = S \cdot PF \quad (25)$$

Where:

- P : Real Power (kW)
- S : Apparent Power (kVA)
- PF : Power Factor (dimensionless ratio between 0 and 1.0)

Conventional design peak calculations suggest that the power allocation for the cluster *Tiuri + INS* (see figure 42: yellow zones and third column) exceeds the available 55 kVA. Specifically, when the building's mechanical installations and the two all-electric heat pumps are both operating at their estimated design maximums, the cumulative load reaches 81 kVA. Resolving this would require a permanent derating of either the installations or the heat source, potentially compromising climate comfort or heating capacity.

However, this "static" problem assumes a simultaneous peak that rarely occurs in reality. By utilizing a dynamic climate design, the building can leverage the Atrium as a fresh-air reservoir, allowing the Air Handling Units (AHU) and other mechanical installations to modulate based on actual occupancy and air quality. This allows for coordinated capacity sharing, where the heat source utilizes the residual electrical power left by the mechanical installations. During periods of low occupancy or nighttime setback, the electrical capacity freed up by the installations becomes available for the heat pumps to charge the Thermal Energy Storage (TES) system.

To quantify this interaction, the instantaneous power available for the heat pump is no longer treated as a fixed value, but as the residual capacity of the grid connection at any given time-step t :

$$P_{HP_available}(t) = P_{total_limit} - P_{installations}(t) \quad (26)$$

For the case study, this formula translates to:

$$P_{HP,available}(t) = P_{limit} - \sum (P_{light}(t) + P_{equip}(t) + P_{fans}(t) + P_{pumps}(t)) \quad (27)$$

The available heat pump power is based on the operational scenario that the installations are completely off when there is no event. In case the installations (AHU) are modulated down, the available apparent heat pump power reduces slightly. Calculating the thermal output of the heat pump is dependent of the Coefficient of Performance (COP) and can be calculated according to the following formula:

$$Q_{HP,max}(t) = P_{HP_available}(t) \cdot COP \quad (28)$$

4.2 Heat Pump as Heat Source

The initial climate design for the case study equips two all-electric variable-speed heat pumps: one dedicated to cooling, and one dedicated to heating. These heat pumps are air-to-water heat pumps, meaning they extract thermal energy from the outdoor ambient air and transfer it to a hydronic distribution system to heat or cool the building's water-based storage and emitters.

4.2.1 Variable-speed Heat Pump

Currently, variable-speed (modulating) heat pumps account for the vast majority of heat pumps on the market due to their superior efficiency and comfort compared to single-speed heat pumps. A single speed heat pump is only able to operate in two modes: on or off.

“When your heat pump is a modulating one, it means that it can work at 100 percent of its capacity, but also at 70 percent or sometimes even 30 percent. This means that if your building has only a small demand, it can switch on at a much lower power, following the demand of the building more accurately. Therefore, modulating heat pumps have fewer start stops, lower wear on the compressor and are in general more quiet. When a modulating heat pump is working in a part-load regime (that is, at a lower than maximum capacity) there is another great benefit. Since now, strictly speaking, the internal components of the heat pump are oversized relative to the heating demand, its efficiency is also higher. Therefore, modulating heat pumps tend to have a higher efficiency than on-off ones” (Peere, 2025).

4.2.2 Types of Variable-speed Heat Pumps

Among modulating heat pumps, another distinction can be made regarding the ability to handle thermal loads sequentially versus simultaneously. While standard heat pumps are designed to provide either heating or cooling in a single cycle, specialized heat pumps allow for the concurrent delivery of both. The following section discusses these two types of heat pumps and discuss which option is chosen for the case study.

2-pipe Heat Pump

2-pipe heat pumps can only provide either heating or cooling during a cycle. Most 2-pipe heat pumps are reversible, meaning these units can switch roles of the evaporator and condenser, providing heating in winter and active cooling in summer. Switching from cooling to heating (or vice versa) requires the entire volume of water in the pipes to be tempered to the new target, which creates a "lag" time.

The limitation that a single 2-pipe heat pump cannot handle conflicting demands at the same time requires additional operation control strategy: in order to determine the operating mode of the heat pump, a comparison-based decision between heating and cooling demand must be made. A common strategy is switching the heat pump to a mode that is required the most based on the thermal demand.

Because the case study does requires simultaneous cooling and heating, and the chosen TES system does not operate well with a single heat pump that switches between heating and cooling mode, the case study has one 2-pipe heat pump dedicated to cooling and one 2-pipe heat pump for heating, omitting the need for a switching strategy.

4-pipe Heat Pump

Ideally, a 4-pipe heat pump is installed in a building that requires both heating and cooling simultaneously, like in a performing arts center. This saves the need for two separate heat pumps. However, the choice for two 2-pipe heat pumps instead of one 4-pipe heat pump is part of the boundary conditions of the case study.

A 4-pipe system utilizes two independent circuits: one dedicated to chilled water and one to hot water, both available to be sent to emitters simultaneously, or to two separate buffer tanks. This system's highest efficiency occurs during balanced loads. The heat extracted from a zone requiring

cooling is recycled and pumped into the heating circuit instead of being exhausted to the atmosphere (Brent, 2024).

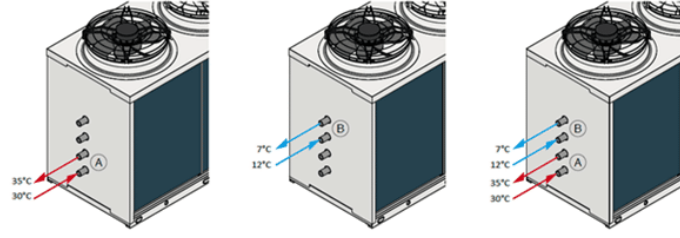


Figure 43: Three operating states of 4-pipe heat pump. The first two states can also be considered a 2-pipe reversible heat pump, but then using the same 2 pipes for both modes.

Adapted from Brent (2024)

4.2.3 Heat Pump Capacity

Both of the heat pumps of the case study have an initial rated power of 75 kW. When total building demand consistently exceeds the peak capacity of the heat source, the system operates beyond its steady-state limits. During periods of grid congestion, the buffer tank functions as the primary energy source to bridge the deficit. However, if this instantaneous peak load is sustained, the finite storage capacity is eventually depleted, leading to a system failure regardless of grid availability. This indicates that the heat source is undersized for the building's absolute peak requirements. In that case, the rated thermal power should be higher of the chosen heat pump. The final simulation will reveal if these rated capacities are sufficient enough.

4.2.4 Coefficient of Performance

The efficiency of the energy conversion process in a heat pump is measured by the Coefficient of Performance (COP), which represents the relationship between the heat energy produced and the electrical power consumed. The COP is defined as the ratio of thermal heat delivered (output) to the electrical power input, and is calculated by:

$$COP = \frac{Q_{hp}}{P_{hp}} \quad (29)$$

Where Q_{hp} denotes the heat output and P_{hp} represents the actual electrical input ($P_{HP,available}(t)$).

COP Carnot

The COP Carnot represents the theoretical maximum efficiency of a heat pump, defined by the temperatures of the heat source and heat sink (T_{source} and T_{sink}). It assumes a perfectly a perfectly reversible cycle with no energy losses, providing the maximum ceiling of performance for any given temperature lift:

$$COP_{Carnot} = \frac{T_{sink}}{T_{sink} - T_{source}} \quad (30)$$

COP Real

The COP Real (or COP_{actual}) is the performance actually achieved by the hardware after accounting for mechanical inefficiencies and thermal energy losses. In energy modelling, the COP real is typically derived by multiplying the Carnot limit by the Lorentz factor (η_{Lo}), which for air-source heat pumps in the Netherlands is often estimated at 0.5 to reflect real-world operation (De Kleijn Energy

Consulting, n.d.):

$$COP_{real,heating} = \eta_{Lo} \times \frac{T_{sink}}{T_{sink} - T_{amb}} \quad (31)$$

$$COP_{real,cooling} = \eta_{Lo} \times \frac{T_{return}}{T_{amb} - T_{return}} \quad (32)$$

Where:

- T_{sink} : Supply temperature to the emission system [K].
- T_{return} : Return water temperature from the emission system [K].
- T_{amb} : Ambient outdoor air temperature [K].
- η_{Lo} : Lorentz efficiency factor (typically 0.5 – 0.7).

4.3 Thermal Demand Data

The general TES implementation framework suggests two distinct pathways for acquiring thermal demand profiles of the building as a whole and for the separate zones. The case study building has been simulated in the external software called *Vabi Elements*. This software has a specialized environment for calculating hourly thermal loads, energy labels, and indoor climate performance. One disadvantage of using this software to obtain the thermal demand datasets per zone is that the software is a black box for its user.

Therefore, this thesis has modelled the case study in the simplified energy balance model in Python: a multi-zone, first-order lumped capacitance model based on the hourly energy balance method of the ISO 13790 / NEN-EN-ISO 52016-1 (*see Appendix C*). Even though this model is may be less accurate than external simulation models, it allows the users to insert their own building in this model and set a list of variables that can be adjusted based on user preferences. This multi-zone lumped capacitance model also allows the users to track all heat flows per zone per time-step to get a better understanding of the dynamic energy balance. Moreover, this multi-zone model can later be linked to the TES simulation, allowing for a range of optimisation and validation possibilities.

4.3.1 Transient Multi-zone First-order Lumped Capacitance Model

The following section briefly explains the multi-zone model and its most important components. However, to see the full logic and equations behind the simulation model, see the appendix.

Lumped Capacitance and Thermal Mass

The thermal behaviour of the building is modelled using a multi-zone, first-order lumped capacitance approach based on the hourly energy balance method prescribed by ISO 52016-1. In this framework, each thermal area of the building is categorised into climatization zones where the combined heat storage capacity of the air, furniture, and internal construction layers is "lumped" into a single thermal mass node. This simplification allows the model to treat each zone as a thermal battery, capturing the physical inertia of the building's structure, such as the high specific capacity of heavy solid concrete floors and walls.

Hourly Energy Balance and Inter-zonal Coupling

The model calculates hourly energy demands by performing a continuous heat balance that accounts for transmission through the building envelope, air infiltration, and controlled ventilation. Internal heat gains from occupants and equipment, along with solar radiation through glazing and opaque facade and roof, are balanced against these losses every hour. Importantly, as a multi-zone network, the simulation calculates the inter-zonal heat exchange across shared internal walls and floors. This link enables the simulation of cascaded air strategies, where the pre-conditioned air of a buffer zone, such as an atrium, influences the temperature of adjacent secondary zones. A simplified formula capturing this hourly balance is defined as follows:

$$Q(t) = [H_{tot} \cdot (\theta_{int} - \theta_{ext}(t))] - [Q_{int}(t) + Q_{sol}(t) + Q_{stor}(t) + Q_{ext_flow}(t)] \quad (33)$$

Where:

- $Q(t)$ is the net thermal demand at hour t [kWh].
- H_{tot} is the total heat loss coefficient, including transmission, infiltration, and ventilation [kW/K].
- θ_{int} is the target internal set-point temperature [$^{\circ}\text{C}$].
- $\theta_{ext}(t)$ is the ambient outdoor temperature at hour t [$^{\circ}\text{C}$].
- $Q_{int}(t)$ represents internal gains from occupants and appliances [kWh].
- $Q_{sol}(t)$ represents solar heat gains through glazing and opaque surfaces [kWh].

- $Q_{stor}(t)$ is the thermal energy stored or released by the building's thermal mass [kWh].
- $Q_{ext_flow}(t)$ is the heat exchanged with adjacent zones via shared internal boundaries [kWh].

Transient Temperature Calculation and Demand Determination

To determine the hourly heating and cooling loads, the simulation employs an exponential solution to solve the transient heat equation. For every time-step, the model identifies an equilibrium temperature, which is the theoretical point the room would reach if external conditions were static. Because the building's thermal mass prevents it from reaching this equilibrium instantly, the exponential formula calculates the actual room temperature transition over each time-step (60-minute) interval. If the resulting "free-floating" temperature falls outside predefined comfort set-points, the model calculates the exact kilowatt demand required from the HVAC system to maintain the target temperature.

4.3.2 Schematic Overview

This multi-zone simulation model uses a "Master and Worker" architecture (*see Appendix D*) to calculate the annual thermal energy demand of a building across 8760 hours. The Orchestrator acts as the master script, managing global weather data, inter-zone heat transfer through shared internal walls and floors, and cascaded ventilation strategies where the Atrium acts as a buffer zone. Within this loop, each individual zone is treated as an instance of the *ZoneModel* class, which functions as the physics engine to calculate hourly heat gains and losses, thermal mass effects, and the mechanical energy needed to meet temperature set-points. The process concludes by aggregating these hourly results into comprehensive annual heating and cooling totals for both individual zones and the entire building.

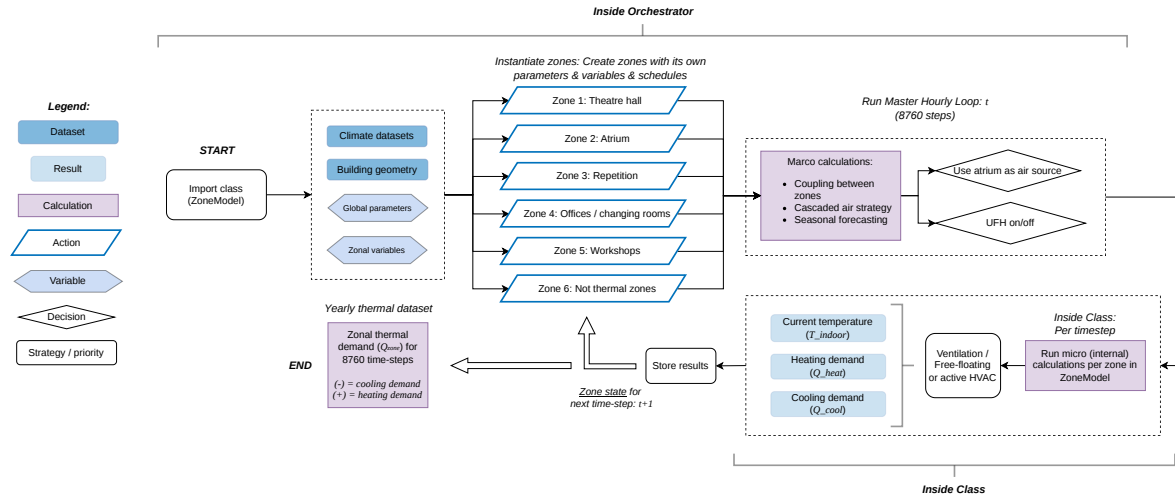


Figure 44: Flowchart of the multi-zone model.

4.3.3 Zonal Variables

Besides the global variables and parameters that all zones share, below are listed the variables per zone. Especially the set-points and schedules heavily influence the thermal demand dataset being generated.

Variable	Unit	Description
Geometry	$[m^2, m^3]$	Dimensional inputs including floor, roof, ground floor area and volume.
Rc-values	$[m^2 K/W]$	Thermal resistance of opaque envelope components (facade, roof, floor, ground) used to determine U-values.
Thermal mass factor	$[J/m^2 K]$	Specific heat capacity per square meter, representing the building's structural inertia.
Facade and glazing areas	$[m^2]$	Orientation-specific surface areas for opaque walls & roof and glass, used for transmission and solar gain calculations.
Shared internal walls & floors	$[m^2]$	Used to calculate the heat exchange between zones.
Internal gains	$[W/m^2]$	Heat flux emitted by lighting and appliances, plus sensible heat from occupants ($W/person$).
UFH	[on / off]	Underfloor heating / cooling activity.
UFH schedule	[0–1]	Hourly profile defining the operational hours in which the UFH is active.
Ventilation set-point	$[^{\circ}C]$	Threshold temperature at which natural ventilation or bypass cooling is activated to reduce internal heat, including a setback set-point.
Cooling set-point	$[^{\circ}C]$	The maximum allowable indoor temperature before mechanical cooling is engaged, including a setback set-point.
Heating set-point	$[^{\circ}C]$	The minimum allowable indoor temperature before mechanical heating is engaged, including a setback set-point.
Occupancy schedule	[0–1]	Hourly profile defining the percentage of maximum occupancy present in the zone.
Equipment schedule	[0–1]	Hourly profile defining the operational load of lighting and electrical appliances.
Ventilation schedule	[0–1]	Hourly profile defining the percentage of maximum mechanical fresh air supply.
System schedule	[0–1]	Hourly profile determining when the HVAC system is active or in setback mode.

Table 10: Zonal input variables and thermal comfort boundaries.

Zone 2: atrium has the option for the activation of the UFH system. It is modelled as a scheduled thermal injection source that utilizes the building's structural mass as a storage medium. The decision to heat or cool is determined by a seasonal forecast logic that calculates the average outdoor temperature for the upcoming 24 hours. Based on the forecasted outdoor temperatures and set boundary temperatures, the UFH is set to heating mode or cooling mode. There is also a temperature limit for the UFH after which the UFH turns off when the zone's temperature is achieved.

4.3.4 Results: Multi-zone Model with Temperature Set-point Ranges

The model utilizes a hierarchy of temperature thresholds including heating, ventilation, and cooling set-points, to optimize energy use by maximizing the periods when the building can free-float. The Orchestrator defines these set-points through weekly profiles that transition between high-precision "Comfort" targets during occupied hours and wider "Setback" ranges during nights and weekends. Within the physics engine, active HVAC is only engaged if the zone temperature falls below the heating set-point or rises above the cooling set-point. Between these limits, the model first attempts to maintain comfort via the ventilation set-point, which triggers low-energy natural cooling (like opening windows or using a bypass) whenever external conditions are favourable.

By allowing the temperature to drift within this multi-layered deadband, the model leverages the building's thermal mass to absorb internal and solar gains, effectively delaying or entirely mitigating the need for active mechanical systems. This is the method results in a realistic demand profile for the case study.

The following graphs visualize the results from the multi-zone model for the case study: de Broedplaats. The multi-zone simulation is run with the NEN 5060-B2 1% climate dataset, and no heat recovery, TES or UFH implementation. Zones that are not part of the thermal zones and therefore not the climatization zones, have free-floating temperatures and are dependent on the external temperature as well as the adjacent zones for internal zonal coupling.

Disclaimer: these results are based on certain global and zonal parameters. By changing these parameters and variables, the thermal demand results will also change. The settings for the parameters for the case study are based on provided technical documents and software.

Annual & Peak Demand

The following table lists the annual heating and cooling demand per climatization zone. The peak demands per zone are also shown. Note: the total peak heating and cooling demands are not a sum of the individual peaks per zone, but is the peak demand that occurs for a single time-step within the simulation.

Zone	Ann. Heating [kWh]	Ann. Cooling [kWh]	Peak Heating [kW]	Peak Cooling [kW]
Zone 1: Theatre	42,989.05	-9,223.77	49.48	-58.79
Zone 2: Atrium	28,097.24	-11.85	46.52	-17.05
Zone 3: Repetition	34,201.80	-17,798.05	68.68	-55.07
Zone 4: Offices	27,962.75	-8,435.07	65.30	-62.62
Zone 5: Workshops	23,348.01	-4,061.81	44.98	-39.77
Total Building	sum: 156,598.85	-39,530.55	max: 251.60	-145.28

Table 11: Summary of annual thermal energy demands and peak loads per zone (NEN 5060-B2 1% extreme year).

Variables Used

Some of the most influential variables per zone are the temperature- and ventilation set-points. These parameters directly dictate when the HVAC system supplies heat or cold to the zones and when natural ventilation is used before mechanical ventilation.

Zone	Comfort set-points			Setback set-points			Description
	Heat	Cool	Vent	Heat	Cool	Vent	
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	
Zone 1: Theatre	20.0	24.0	23.9	18.0	26.0	25.9	Based on schedules: 4 days in week active.
Zone 2: Atrium	16.0	28.0	27.0	16.0	28.0	27.0	Based on schedules: all week active.
Zone 3: Repetition	20.0	24.0	23.9	18.0	26.0	25.9	Based on schedules: all week active.
Zone 4: Offices	20.0	24.0	23.9	18.0	26.0	25.9	Based on schedules: 5 days in week active.
Zone 5: Workshops	20.0	24.0	23.9	18.0	26.0	25.9	Based on schedules: 5 days in week active.

Table 12: Operational thermal set-points for comfort and setback modes used for results.

Annual Demand Profile

The annual energy balance reveals a significantly heating-dominated building profile, with a total thermal demand of 156.6 MWh for heating compared to 39.5 MWh for cooling. While Zone 1 (Theatre) and Zone 3 (Repetition) are the largest absolute heating consumers, the Atrium (Zone 2) demonstrates a unique thermal signature where it requires 28.1 MWh of heating yet effectively zero mechanical cooling. This is due to the temperature climate strategy for the atrium.

The Load Duration Curve (LDC) validates the building's operational efficiency by illustrating that while the system must be sized for a 251.6 kW peak, the building operates at less than 20% of this capacity for over 6,000 hours of the year. The curve's steep initial slope represents the rare, extreme morning warm-up periods, while the central plateau highlights an extensive "deadband" period where the building's thermal mass and set-points (particularly the 16–28°C range in the Atrium) allow for passive operation without mechanical intervention.

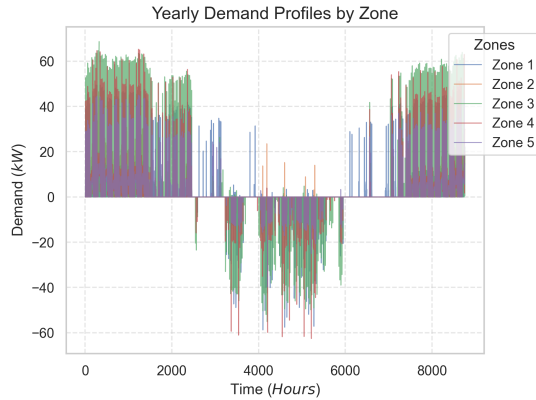


Figure 45: Annual Chronological Hourly Load (CHL) curve of the case study.

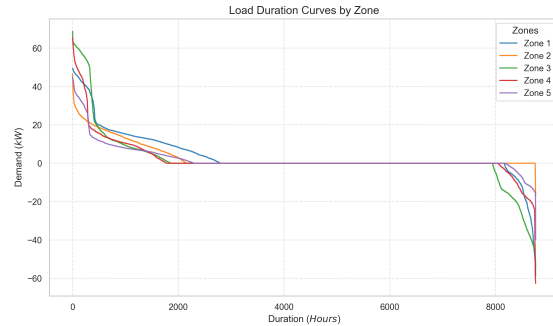


Figure 46: Annual Load Duration Curve (LDC) of the case study.

Peak Demands

The building-wide heating peak of 251.6 kW occurs during Week 8 (February 19–25), coinciding with the extreme cold wave from the NEN 5060-B2 dataset. The demand profile is characterized by sharp

morning spikes triggered when the 100% ventilation schedule initiates against outdoor temperatures as low as -14.5°C .

The maximum cooling demand is reached during Week 26 (June 25–July 1), driven by the simultaneous peak of solar radiation and full building occupancy. The data indicates that cooling demand is highly coincident; the absolute peak occurs on a workday when internal gains from equipment, lighting, and occupants are at their maximum, rather than on the absolute hottest weekend day.

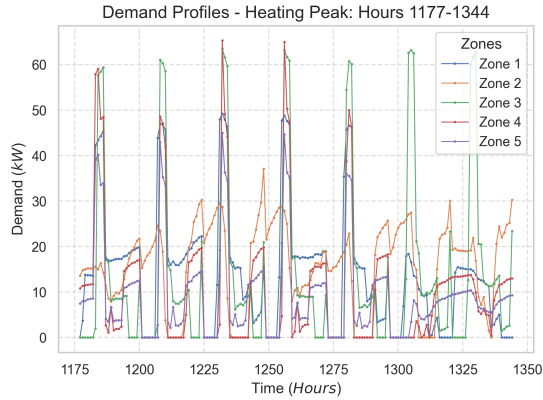


Figure 47: Peak heating week occurring from February 19 to February 25.

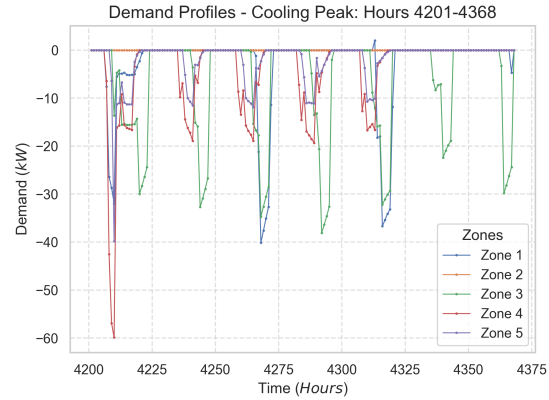


Figure 48: Peak cooling week occurring from June 25 to July 1.

4.3.5 Results: Multi-zone Model with Fixed Temperature Set-points

By setting the heating, cooling, and ventilation set-points to a single, identical value, the model effectively eliminates the "deadband" and prevents the zones from free-floating. In this configuration, the physics engine forces the indoor temperature to remain static across every time-step, meaning the resulting demand reflects the absolute energy required to perfectly neutralize all solar gains, internal heat, and transmission losses to maintain that exact temperature.

Since the temperature is no longer permitted to drift, the building's thermal mass is not actively used within the class logic to buffer shifts; instead, the model outputs a "raw" hourly energy profile. This provides a clean baseline demand for your TES script, which can then apply its own thermal storage strategy to this load while ensuring the buffering work of the building's mass is only calculated once in the downstream logic.

In hindsight, a live connection between the multi-zone model and the Simulation Engine would allow the user to define temperature dead band zones and integrate natural ventilation. Rather than defining the allowed drift temperatures inside the Simulation Engine, the multi-zone model could more accurately calculate demands outside of these comfort boundaries, and feed this thermal demand and the updated zone temperatures into the Simulation Engine, describing a constant exchange of information per time-step. Currently, the connection is purely sequential, where the Simulation Engine calculates the new temperatures and corrected thermal demands by itself, although less accurate. This is further discussed in the limitations and further research recommendations section of this thesis.

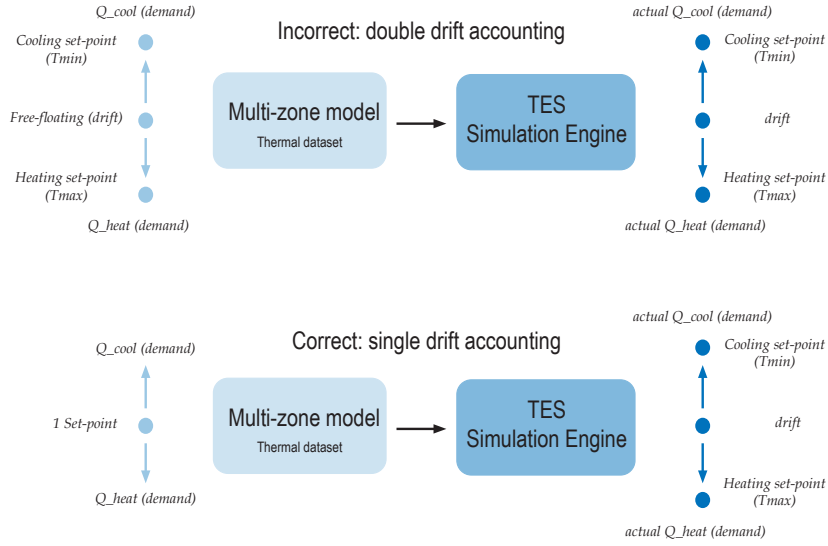


Figure 49: Schematic illustration of single set-point importance for compatibility with TES simulation.

Annual & Peak Demand

The following table lists the annual heating and cooling demand per climatization zone for a fixed temperature set-point scenario with no allowed temperature range. The only zone with active HVAC and an allowed free-floating temperature range is zone 2: atrium. The reason is that without this temperature range, the cascaded air strategy is neutralized. This would not be a representative translation of the climate design for this specific building.

In order to prevent the double utilisation of thermal mass for zone 2, the TES simulation script that uses this thermal demand dataset will set the allowed temperature swing for zone 2 to zero. The TES simulation will not try to calculate temperature drifts for this zone, since that is already done in the multi-zone model. The demand for zone 2 will indicate zone 2 is already at its limit, and needs the energy supply immediately.

Moreover, a fixed set-point for zones 1, 3, 4, and 5 will not include any natural ventilation cooling capabilities. This approach assumes the worst-case design scenario, where the HVAC system must be sized to handle the full thermal load independently. This is necessary because natural ventilation is not a reliable source of cooling due to fluctuating external wind speeds and variable ambient conditions, except for the large atrium.

Zone	Set-points [°C]			Annual Demand [kWh]		Peak [kW]
	Heat	Cool	Vent	Heating	Cooling	Heat / Cool
Zone 1: Theatre	21.0	21.0	none	69,328.96	-29097.37	26.53 / -56.51
Zone 2: Atrium	16.0	28.0	27.0	16,218.47	0.00	39.74 / 0.00
Zone 3: Repetition	21.0	21.0	none	53,017.84	-42530.43	25.77 / -43.62
Zone 4: Offices	21.0	21.0	none	52,166.96	-22365.59	23.08 / -27.80
Zone 5: Workshops	21.0	21.0	none	39,199.22	-13125.65	17.09 / -17.48
Total Building				sum: 229,931.45	-107,119.04	max: 124.26 / -109.75

Table 13: Operational thermal set-points and annual simulation results for the multi-zone model.

Annual Demand Profile

The annual demand illustrates that almost all time-steps for all zones require a heating or cooling demand. Due to the strict set-point maintenance, the zone temperatures are not able to free-float, and therefore not register a zero thermal demand. The LDC graph clearly shows that the atrium is the exception: for more than 6000 hours, the temperature inside the atrium is free-floating within the set comfort bounds, resulting in zero thermal demand for those hours.

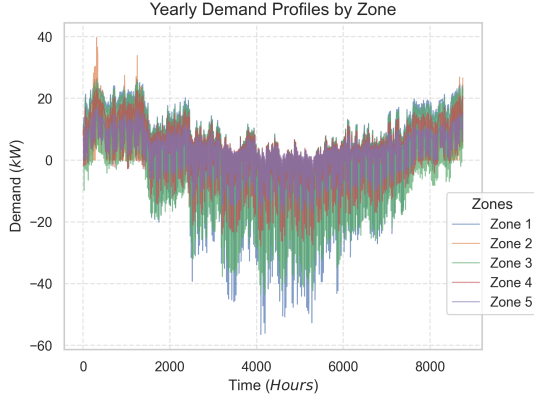


Figure 50: Annual Chronological Hourly Load (CHL) curve of the case study.

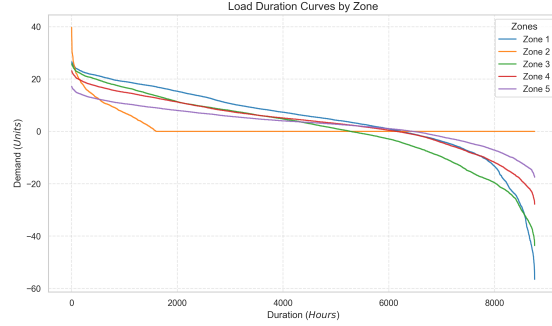


Figure 51: Annual Load Duration Curve (LDC) of the case study.

Peak Demands

Noticeably, the peak heating hours for heating occur at an earlier period in the year, compared to the peak heating hours of the multi-zone model with temperature set-point ranges. The reason being the slightly higher heating set-point of 21°C instead of 20°C combined with the colder outdoor temperatures in this period, resulting in a higher heat loss to the environment and therefore requiring a higher heating demand.

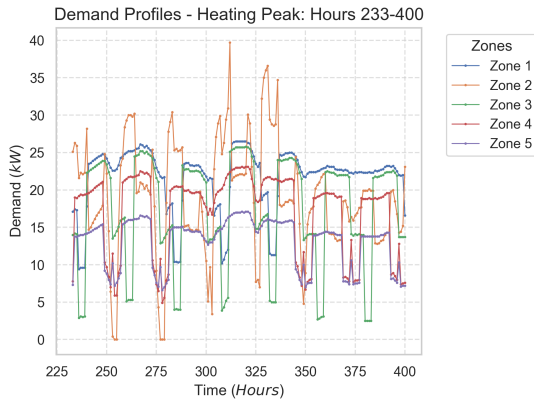


Figure 52: Peak heating week occurring from January 10 to January 17.

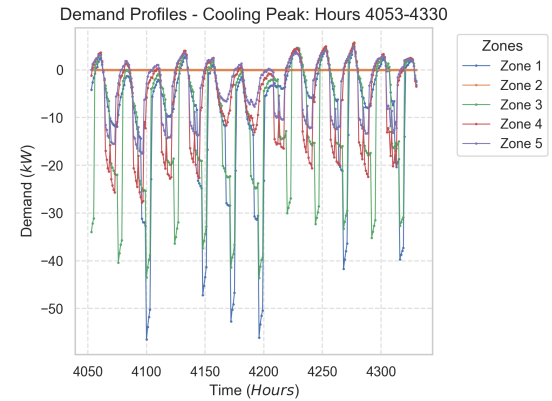


Figure 53: Peak cooling week occurring from June 18 to June 25.

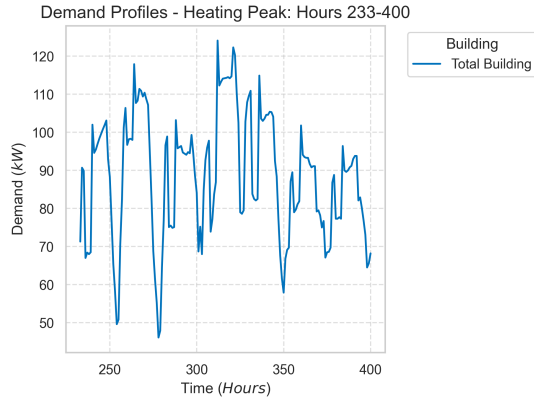


Figure 54: Total building (sum of all zones) peak heating.

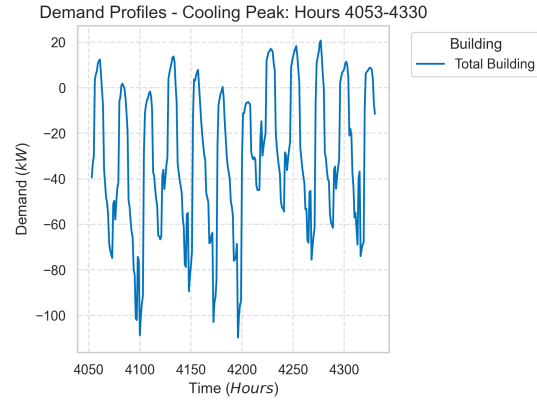


Figure 55: Total building (sum of all zones) peak cooling.

4.4 TES System Selection

This chapter will cover the motivation for the chosen TES system: two stratified buffer tanks. Moreover, the principle behind a stratified buffer tank is explained and the types of available tanks are discussed.

4.4.1 System Choice

For event-driven peaks, a stratified buffer tank is selected due to its high power density and low thermal lag. While other TES media may offer higher energy density, the water-based buffer tank excels in its ability to meet rapid discharge requirements without the heat-transfer bottlenecks associated with solid-state or phase-change systems. Moreover, design principles leading to this choice of TES include: energy-efficient and environmentally friendly, low-maintenance, low operating costs, and compatible with fully electric heat pumps. The stratified buffer tanks are the centralized TES units supplied by heat pumps, and providing the emitter of the zones with thermal energy.

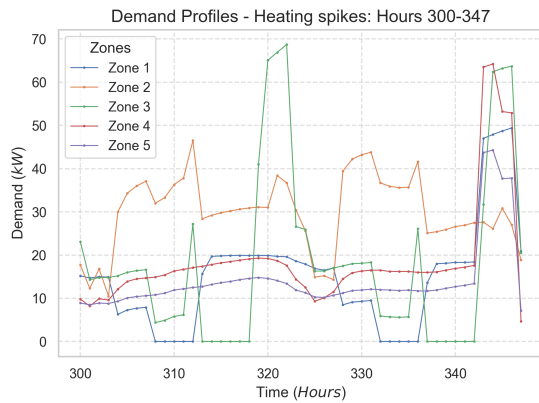


Figure 56: Example of heating spikes for a 48-hour window.

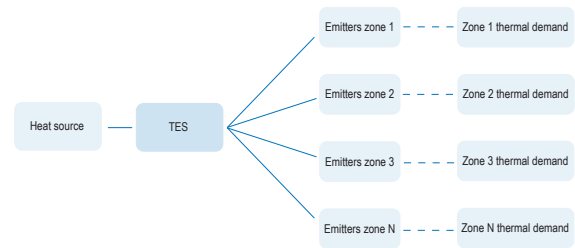


Figure 57: Schematic representation of centralized TES from the general framework.

Fast-response (The Needle Peak): This curve is defined by sudden, intense spikes in demand over short durations. This curve is typical for event-driven or sudden high-occupancy spaces. The focus for this archetype is high power delivery during occupancy and start-up periods. Recharging of the thermal buffer is done during low demand periods.

4.4.2 Stratified Buffer Tank

Effective TES operation utilizes the inherent density differences of water to maintain thermal layers. This results in a vertical temperature profile where hot water remains at the top and cold water at the bottom, separated by a mid-level thermocline. Research indicates that maximizing the temperature difference and optimizing the tank's aspect ratio are primary drivers for maintaining high stratification quality (Bahnfleth & Musser, 1998). Stratification is reduced through fluid mixing caused by convection and through thermocline movement resulting from load imbalances (Haller et al., 2009).

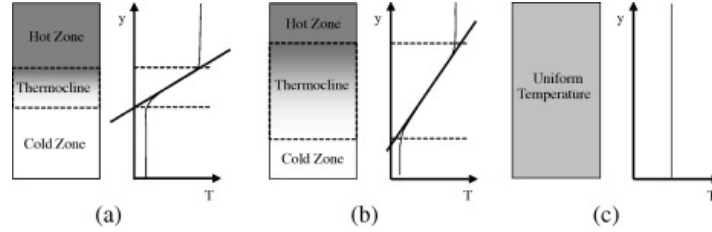


Figure 58: Differing degrees of stratification within a storage tank with the same amount of stored heat: (a) highly stratified, (b) moderately stratified, and (c) fully mixed, unstratified storage.

Adapted from Haller et al. (2009)

4.4.3 Hydronic Piping of Stratified Buffer Tank

Connecting a heat pump (HP) to a sensible heat storage tank is a critical design choice that dictates system efficiency, thermal stratification, and operational flexibility. The integration typically follows one of three primary piping architectures, each offering a different trade-off between hydraulic complexity and thermal performance. These piping variations are not to be confused with the 2-pipe versus 4-pipe heat pump types discussed in section 4.2.2; while the latter refers to the machine's ability to generate heating and cooling, these tank-side variations represent the primary hydraulic interaction between the heat source (heat pump), the storage volume, and the zone emitters. These configurations determine the fluid dynamics between the heat pump, the storage (tank) volume, and emitters, specifically governing how mass flow is managed to preserve thermal stratification and achieve hydraulic independence.

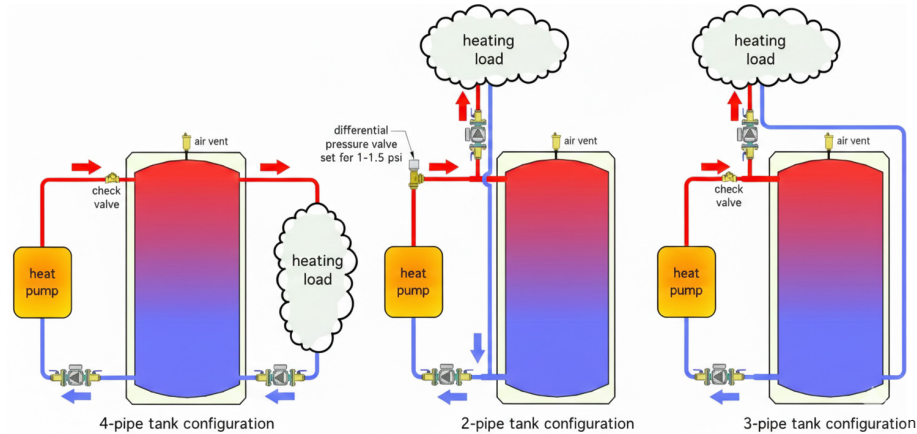


Figure 59: Piping configurations for single tank to heat pump: “4-pipe”, “3-pipe” and “2-pipe”.

Adapted from (Siegenthaler, 2015)

4-pipe Tank Configuration (*Parallel*)

For a multi-zone building with n zones, heterogeneous emitters, with varying ΔT , the 4-pipe parallel configuration is the most robust architecture and is therefore chosen for the case study. By providing

total hydraulic and thermal decoupling, it ensures the system remains functional regardless of varying zone requirements or grid-induced modulation (Siegenthaler, 2024). This setup is comprised of two loops: primary loop (ASHP and tank), and the secondary loop (tank and zones). A secondary system offers superior efficiency and flexibility, particularly in projects with multiple zones with varying heating/cooling loads (Plastpump, n.d.).

- **Hydraulic decoupling:** Isolates the ASHP from variable flow rates of n zones, preventing "low-flow" errors and protecting the compressor.
- **Thermal layering:** Utilizes natural buoyancy to manage differing return temperatures, preserving high-grade heat at the top of the tank to serve as a reliable "thermal battery" during grid congestion.
- **Operational flexibility:** Supports mixed-emitter scenarios, allowing high-temperature zones (e.g., fan coils) and low-temperature zones (e.g., floor heating) to coexist without thermal interference.

2-pipe Tank Configuration (*Series*)

This setup is less suitable due to hydraulic risk. In a multi-zone system, the ASHP becomes very dependent on zone flow. If multiple zones close, the resulting flow drop can trigger high-pressure faults and system shutdowns. Furthermore, it lacks the storage exergy needed for long-term grid-load shifting. This setup is more suitable for a single-zone configuration.

3-pipe Tank Configuration (*Hybrid*)

This setup is less suitable due to thermal dilution. The shared return pipe (manifold) forces return water from all n zones into a single entry point. This creates significant internal turbulence and "smears" the thermocline, quickly degrading the tank's thermal stratification and reducing the autonomy of the building during grid congested periods.

4.4.4 Stratification Maintenance

Thermal stratification in parallel buffer configurations is fundamentally dependent on the maintenance of a stable thermocline. When inlet velocities are low, gravitational buoyancy successfully separates water by density, preserving the high-grade thermal energy required for the emission system. Excessive flow velocities trigger turbulent mixing within the tank, 'smearing' the temperature gradient. This prevents the maintenance of distinct hot and cold layers. As a result, the temperature inside the tank drops to a lukewarm level. While the total amount of energy remains the same, the water is no longer hot enough to heat the building effectively (loss of exergy).

Sizing for low velocity, flow matching, diffusers and internal baffles, strategically placed sensors monitoring the temperature, and proper height-to-width ratio of tank mitigate the loss of stratification inside the tank. The stratification efficiency factor (η_{str}) accounts for how much extra volume is needed to compensate for these effects.

Additionally, this thesis implements a minimum modulation threshold for the heat pumps to preserve thermal stratification within the storage tanks. During grid congestion or periods of zero thermal demand, this threshold ensures that the heat pumps do not operate at sub-optimal power levels, which would result in a low temperature lift and cause the thermocline to smear through convective mixing. By reserving a small, dedicated electrical power floor for both heat pumps, the system ensures that any energy injected into the tanks maintains the necessary buoyancy to support a distinct thermal gradient at all times. This prevents the tanks from drifting too far from the desired temperatures.

4.5 Integration into Building Design

The first step in integrating the TES system in the building's climate design is to identify the climatization zones. Section 3.1.2 of the general TES implementation workflow describes how a building's spaces can be sorted into climatization zones. The case study is a multi-function building that has five climatization zones in total; Zone 1: theatre hall, Zone 2: atrium, Zone 3: repetition spaces, Zone 4: office & changing rooms, and Zone 5: workshop spaces.

4.5.1 Zonal Characteristics

Each thermal zone within the building has its own type of emitter system, geometry characteristics, specific heat capacity, and temperature set-points. The first eight columns are fixed input for the TES sizing simulation model. The last four columns are temperature input variables that can be set based on control strategy or preferences. The values in light grey represent realistic default temperature set-points for the case study.

Zone	Floor Area [m ²]	C_{spec} [kJ/(m ² K)]	Emitter type	$T_{sup,H}$ [°C]	$T_{ret,H}$ [°C]	$T_{sup,C}$ [°C]	$T_{ret,C}$ [°C]	T_{set} [°C]	T_{max} [°C]	T_{min} [°C]	T_{swing} [°C]
Z1	455	450	AHU	45	35	10	18	21	23	19	2
Z2	565	450	AHU	45	35	10	18	22	28	16	6
			UFH	35	25	18	22				
Z3	685	450	VAV	45	35	10	18	21	23	19	2
Z4	730	450	FCU	45	35	10	18	21	23	19	2
Z5	480	450	FCU	45	35	10	18	21	23	19	2

Table 14: Zone and emitter parameters.

4.5.2 Climate System Piping

The building's hydronic architecture employs a hybrid distribution strategy where high-capacity Air Handling Units (AHUs) utilize a four-pipe configuration for instantaneous mode switching, while Fan Coil Units (FCUs) and Underfloor heating (UFH) are constrained by a two-pipe seasonal changeover logic. This physical limitation creates a significant discrepancy with the TES sizing algorithm, which assumes four-pipe agility and instantaneous response across all terminal units.

To align this physical piping infrastructure with the simulation's logic, each zone and its emitter is modelled as a 4-pipe system. This set-up is the most industry standard, though more expensive and complex to construct. Even in a 2-pipe system, usually the thermal demand per season consists of either cooling or heating, effectively minimizing their demand variability within a short timespan.

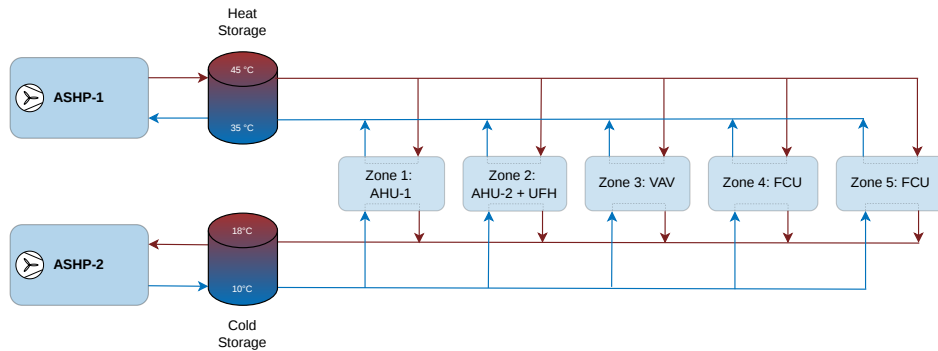


Figure 60: Piping architecture of the case study: manifolds with headers to zones.

4.5.3 Importance of Constant Temperatures

The primary objective of modulating the flow rate of each zone (q_i) to maintain a constant T_{return} is to preserve the tank's thermal stratification. By returning water at a consistent 35°C (see table 14), the system ensures that the return flow enters the tank at a temperature that matches the lower, cooler zone, preventing turbulence and the mixing of the high-grade 45°C supply water.

The utilization of the atrium as a cascaded air source further optimizes this process by moderating the temperature lift required at the plant level. For example, as the atrium air temperature ($T_{air,in}$) is increased by internal gains and solar radiation, and even the UFH, the fan coils and VAV units can satisfy zone set-points with reduced thermal energy (in case of a heating demand). The fundamental thermodynamic principles for heat exchangers can be derived from the following formula:

$$Q_{delivered,i} = UA \cdot \Delta T_{lm} \quad (34)$$

Where:

- $Q_{delivered,i}$ is actual the thermal power delivered to zone i [kW]. If demand and supply per zone match, then $Q_{delivered,i} = Q_{zone,i}$.
- UA is the thermal conductance, representing the product of the overall heat transfer coefficient (U) and the surface area (A) of the coil [W/K];
- ΔT_{lm} is the Log Mean Temperature Difference between the water and air streams [K or °C].

The formula for the Log Mean Temperature:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)} \quad (35)$$

Where:

- ΔT_1 : The temperature difference between the hot and cold fluids at Side 1 (one end of the exchanger).
- ΔT_2 : The temperature difference between the hot and cold fluids at Side 2 (the other end of the exchanger).

A higher $T_{air,in}$ reduces the Log Mean Temperature difference (ΔT_{lm}), lowering the thermal demand ($P_{delivered,i}$) pulled from the stratified tank (Gönce, 2012). This reduction in load allows the tank to maintain its charge for longer periods. Simultaneously, the flow rate formula of each zone:

$$q_i = \frac{Q_{delivered,i} \cdot 3600}{\rho \cdot c_p \cdot \Delta T_i} \quad (36)$$

ensures that, regardless of the atrium's air temperature changes, the return water never smears the tank's thermocline with varying return temperatures. By stabilizing the return at 35°C, exergy efficiency is maximised.

Beyond operational efficiency, maintaining a fixed ΔT for the tank significantly simplifies the 8760-hour simulation and the subsequent sizing of the buffer tank. From a modelling perspective, keeping T_{supply} and T_{return} as quasi-steady state variables, reduces the number of interdependent

iterations required at each time step of the simulation.

Furthermore, this stability for the temperatures is essential for the accurate sizing of the stratified tank. By ensuring a consistent 35°C return, the cold volume of the tank remains mostly predictable, preventing the thermocline from fluctuating wildly. This allows for a more precise calculation of the tank's effective storage capacity using the standard energy equation:

$$V_C = \frac{E_{max_gap} \cdot 3600 \cdot S}{\rho \cdot \Delta u \cdot \eta_{str}} \quad (37)$$

Where $\Delta u (=c_p \cdot \Delta T_{avg})$ is the reliable 10°C difference maintained by the hydraulic modulation. Without this stability, the tank would require significant over-sizing to account for "low ΔT syndrome", where mixed return temperatures would prematurely degrade the available heat at the top of the tank (Karim et al., 2018).

4.5.4 Underfloor Heating

The atrium of the case study is partially equipped with underfloor heating and cooling. This system plays a critical role in the cascaded air strategy by acting as the primary thermal engine for the atrium's buffer volume, besides the AHU. By conditioning the floor slab, the UFH stabilizes the atrium air temperature (lifting or lowering), which in turn narrows the temperature lift required by the downstream FCUs and VAV units in other zones. The underfloor heating is the only component that does not have the same supply and return temperatures in heating and cooling mode as the other emitters.

In a manifold system, the return temperature ($T_{ret,mix}$) is not just an average of the temperatures, it is a weighted average based on flow rates. A mismatch in supply and return temperatures, as well as its ΔT , and the resulting flow rate, can cause the return temperature to be higher or lower than anticipated. The following formula illustrates this:

$$T_{ret,mix} = \frac{(\dot{V}_{FCU} \cdot T_{r,FCU}) + (\dot{V}_{UFH} \cdot T_{r,UFH}) + (\dot{V}_{LBK} \cdot T_{r,LBK}) + (\dot{V}_{VAV} \cdot T_{r,VAV})}{\dot{V}_{total}} \quad (38)$$

Where:

- $\dot{V}_{total} = \dot{V}_{FCU} + \dot{V}_{UFH} + \dot{V}_{LBK} + \dot{V}_{VAV}$
- $T_{r,i}$ is the return temperature of each specific branch.

This thesis is primarily focussed on the energy balance of a building with the help of thermal energy storage. The State of Charge of the stratified buffer tank is tracked in terms of energy (kWh), but not in terms of actual volume of water at different temperature levels. Due to mixing and varying flow rates from and to the TES tank, the thermocline and therefore the specific temperature volumes are moving up and down. A stratification correction factor is applied to estimate the actual usable energy inside the tank. Because the floor heating can cause temperature degradation inside the tank due to different operating temperatures, the following solutions are suggested:

Solution 1: Mixing Valves

The ISSO 43 & 44 provide system solutions with specialized valves that mix the supply and return temperatures of the UFH without much temperature degradation. These special three-way mixing valves and bypass loops maintain thermal consistency by modulating the flow inside the system to meet specific temperature set-points instead of dumping water of varying temperatures directly in the main return manifold.

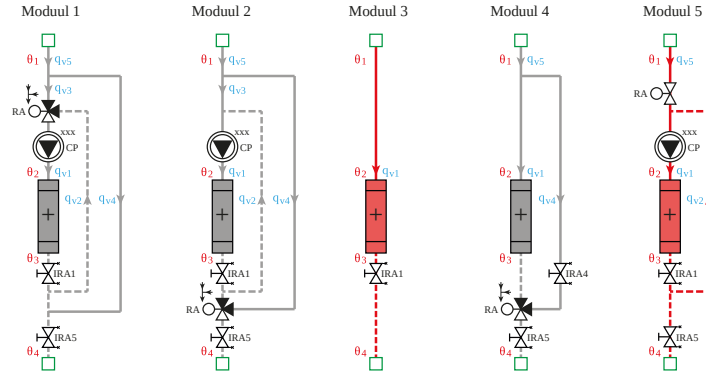


Figure 61: Heat Interface Unit (HIU) without PICV—Pressure Independent Control Valve, where modules 1,2 and 5 are applicable to UFH systems.

Adapted from ISSO 44.

Moreover, solutions such as flow limitations, variable speed pumps, or even separate manifolds can mitigate this imbalance. Flow limitations mean the flow would be capped, resulting in a forced larger ΔT . Variable speed pumps would modulate the UFH floor pumps to stabilize the return temperature. In high-end designs, the UFH and FCU returns are sometimes kept separate, so that the UFH returns to the very bottom of the tank, and the FCUs return to the middle of the tank. This is the multi-port tank setup.

Solution 2: Scheduled UFH Activity

Another approach to maximize the effectiveness of the TES is to restrict the active operation of the Underfloor Heating (UFH) to nighttime hours. In this strategy, the UFH serves as a thermal baseload, "pre-charging" the atrium's significant thermal mass before high-occupancy hours begin. By utilizing the UFH during these low-occupancy periods, the system leverages the building's structural capacity to store energy, effectively reducing the peak thermal demand required during the day.

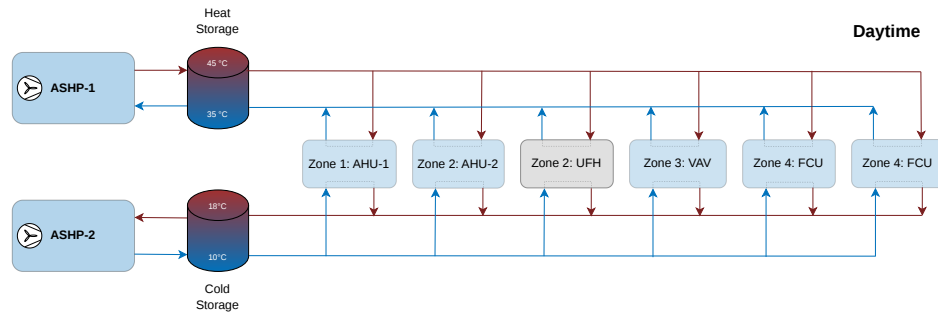


Figure 62: Daytime versus nighttime tank temperatures and active emitters.

To maintain the system's ability to meet daytime peaks, the UFH is deactivated during high-occupancy hours (daytime). This prevents the underfloor loops from competing for energy with standard emitters, such as AHUs and FCUs, which require higher supply temperatures and immediate capacity. Deactivating the UFH during the day ensures that the TES tank's State of Charge (SoC) is not prematurely depleted by the slow-reacting floor load, preserving the stored high-grade heat for the fast-acting emitters that maintain indoor comfort during peak demand periods.

4.5.5 UFH Parameters and Variables

In the table below are the variables and parameters listed for the UFH system for the case study. The UFH is able to provide cooling and heating. The Winter/Summer logic acts as a master switch that uses a weather forecast to decide if the building should be in heating or cooling mode. By looking at the average outside temperature for the coming day (= winter (cooling mode) $< 15.5\text{ }^{\circ}\text{C} < \text{summer}$ (heating mode)), the system automatically swaps between hot and cold supply water and adjusts the floor's heating efficiency. The floor limit temperatures match standard radiant floor safety limits.

Parameter	Symbol	Value	Unit	Limit / Mode	
				Min	Max
Heat Transfer (Heating)	U_h	11.0	W/m ² K	—	24.0 °C
Heat Transfer (Cooling)	U_c	7.0	W/m ² K	18.0 °C	—
Active Floor Area	A_{fl}	200.0	m ²	Atrium Only	
Supply Water (Heating)	$T_{w,h}$	35.0	°C	—	—
Supply Water (Cooling)	$T_{w,c}$	18.0	°C	—	—
Initial Temp (Neutral)	T_{start}	21.0	°C	All Zones	
Cascaded Coupling ($Q_{delivered,i}$)	$UA_{emitter}$	0.5	W/K	Atrium Air	

Table 15: Underfloor Heating (UFH) and zone emitter physical and operational parameters.

4.5.6 Integration of Renewable Energy

The case study includes the addition of PV panels on the roof. This extra generation of electricity increases the total electrical power for those time-steps, alleviating some of the grid congested periods. The available thermal capacity of the ASHP during grid congested periods (events) can be calculated according to the following formula, where the solar energy is converted to thermal energy [kW] per time step:

$$\dot{Q}_{HP,max}(t) = \min(Q_{cap}, [(Grid_Limit_kVA(t) + PV_kVA(t)) \times PF] \times COP(t)) \quad (39)$$

Where:

- Q_{cap} = ASHP rated thermal capacity [kW].
- $PV_kVA(t)$ = Apparent power generated by photovoltaic panels [kVA].
- $Grid_Limit_kVA(t)$ = Electrical input limited during grid congestion (event) [kVA].
- Power Factor (PF) = 0.9 - 0.95
- COP = Coefficient of Performance of the heat pump at time (i).

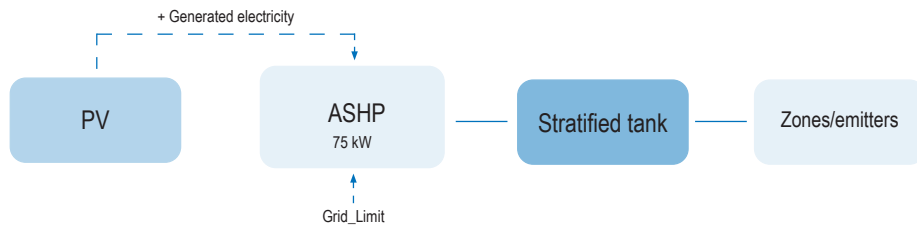


Figure 63: Photovoltaic panels integration with instance of $Q_{cap} = 75\text{ kW}$.

To determine the heat pump's thermal output, $Q_{source,t}$, the PV panels' apparent power must be estimated at each hourly time-step to quantify the total electrical energy available for heat pump operation. Given the available data regarding the PV panels, location, and solar irradiance, the following formula's are used to calculate PV_kVA_i :

1. The Solar Irradiance Formula (Isotropic Sky Model) ($I_{poa,t}$) calculates the *Plane of Array* irradiance (Perry, 2018) per time-step. It tilts the horizontal solar data from the climate dataset to the specific $\cos(7^\circ)$ angle of the PV panels of the case study:

$$I_{poa}(t) = (GG(t) - GD(t)) \cdot \cos(7^\circ) + GD(t) \cdot \frac{1 + \cos(7^\circ)}{2} \quad (40)$$

Where:

- GG is the Global Horizontal Irradiance adapted from NEN5060-B2 climate dataset.
- GD is the Diffuse Horizontal Irradiance adapted from NEN5060-B2 climate dataset.
- Tilt in $\cos(7^\circ)$ is the angle of the PV panels. *Note: While the tilt is defined as 7° , trigonometric functions in computational environments typically require this value to be converted to radians (0.122 rad) to return the correct cosine ratio.*

2. The following formula for PV_kVA_i converts the direct light onto the PV panels into the electrical capacity produced by the (300 m^2) PV system (NEN-EN-IEC, 2021):

$$PV_kVA(t) = \frac{I_{poa}(t) \cdot A \cdot \eta \cdot PR \cdot (1 - D)}{1000} \quad (41)$$

Where:

- A: Total surface area of 300 m^2
- η : Efficiency (0.20), based on the 200 Wp/m^2 ($200/1000$, according to STC by (IEC, 2020))
- PR: Performance Ratio (0.78), accounting for the "moderate ventilation" and inverter losses.
- Degradation factor (0.995), accounting for the 0.50% annual ageing
- 1000: The divisor to convert the result from Watts to kilo-Volt-Amperes (kVA).

4.6 Control Strategy

The effectiveness of a TES system is largely determined by the underlying control logic, which dictates how and when energy is stored or released. For this case study, a priority-based strategy is used to stay within the 61.25 kVA grid limit while maintaining occupant comfort.

The control strategy identifies two systems: the TES system entails the heat pump and stratified buffer tank, and a separate control strategy for the UFH, which is not an active component in the TES Simulation Engine, but part of the Multi-zone thermal model. Therefore, this section also includes the control strategy for the UFH in the Multi-zone model since its effects will influence the thermal demand dataset that is eventually used as input for the TES Simulation Engine.

4.6.1 TES Charging Strategy

When auxiliary installations are inactive and the heat pump has electrical headroom, the system follows a hierarchical (re)charging sequence. This sequence is dynamically adjusted based on the available time between high thermal load events:

Scenario A: Sufficient recovery window ($\Delta t_{\text{window}} \geq t_{\text{sat,struct}}$):

1. **Primary priority: set-point maintenance:** The heat pump first satisfies the instantaneous heating demand of each zone to maintain the baseline comfort temperature (T_{set}).
2. **Secondary priority: structural pre-charging.** Any residual surplus power is utilized to charge the building's thermal mass, raising the zone temperature toward the maximum allowable limit (T_{max}).
3. **Tertiary priority: active TES charging.** Only once the building structure is thermally saturated does the system direct surplus energy to charge the water buffer tank to its maximum capacity.

Scenario B: Immediate constraint window ($\Delta t_{\text{window}} < t_{\text{sat,struct}}$):

1. **Primary priority: set-point maintenance.** Instantaneous demand is satisfied first.
2. **Secondary priority: active TES charging.** Because the water buffer provides a higher power density, faster response, and is much quicker to recharge, it is prioritized to reach a full State of Charge (SoC) quickly.
3. **Tertiary priority: structural pre-charging.** Any remaining energy is diverted to the structural mass, acknowledging that full thermal saturation may not be achieved before the next event.

Within the structural charging phase, a secondary control layer manages the distribution of energy across multiple zones:

- **Sequential recharging of zones:** Zones are addressed based on a pre-defined priority list (e.g., Zone 1 (main stage) first, Zone 2, 3, and 4 after). High priority zones are restored to T_{max} (or T_{set}) before lower priority zones receive surplus energy.
- **Proportional recharging of zones:** The proportional division would be based on the "thermal hunger" of each zone, as described in the general workflow *Part 4: Control strategy*. This logic ensures that larger zones with higher thermal inertia or zones that have drifted furthest from their set-points receive a mathematically fair share of the available energy. For each zone i :

$$\text{Hunger}_i = (T_{\text{max},i} - T_{\text{current},i}) \times M_{\text{zone},i}$$

&

$$\text{ZoneShare}_i = \left(\frac{\text{Hunger}_i}{\sum \text{Hunger}} \right) \cdot P_{\text{surplus}}$$

4.6.2 TES Discharging Strategy

During events when grid availability is restricted or the demand supply outweighs the supply, and the heat pump is forced to modulate down, the system transitions to a hierarchical discharge sequence:

Long-duration event (high inertia focus):

1. **Primary priority: modulated heat pump output:** The heat pump operates at its maximum constrained capacity ($Q_{HP,max}(t)$, see section 4.1.2 *Problem Statement*) to meet as much demand as possible.
2. **Secondary priority: passive structural discharge.** The zones are allowed to drift naturally from T_{set} (or $T_{current}$ when not fully charged) toward the minimum allowed "swing" temperature T_{min} . The building's thermal inertia acts as the primary buffer.
3. **Tertiary priority: active TES discharge:** The sensible buffer tank acts as a tactical reserve, injecting heat only when the structural temperature threatens to breach the T_{min} threshold.
4. **Deficit tracking:** If the combined capacity of the thermal mass and the tank is exhausted, the resulting unmet demand is logged to determine the required volume of the TES (V_C).

Within the primary priority: *modulated heat pump output*, a secondary control layer manages the distribution of energy across multiple zones:

- **Sequential HP output division:** Zones are addressed based on a pre-defined priority list (e.g., Zone 1 (main stage) first, Zone 2, 3, and 4 after). High priority zones receive the HP modulated output first to meet try to meet the instantaneous demand before lower priority zones receive output energy (if there is any left).
- **Proportional HP output division:** The proportional division would be based on the thermal demand share of the total modulated heat pump output. For each zone i :

$$ZoneShare_i = \left(\frac{Demand_i}{\sum Demand} \right) \cdot Q_{HP,max}(t)$$

4.6.3 UFH Control Strategy

The primary goal of the Underfloor Heating (UFH) system is to minimize the governing cumulative annual energy deficit (E_{cum}), which acts as the core stress metric representing any heating and/or cooling load that exceeds the heat pump's dynamic capacity ceiling and must be covered by the storage (buffer tank) system.

By utilizing the Atrium's massive concrete floor slab as a structural thermal battery pre-charged during high-efficiency solar or off-peak windows, the system slowly radiates heat to adjacent zones via internal wall connections. This peak-shifting strategy prevents the premature depletion of the TES buffet tank and directly minimizing the final required physical buffer tank volume (m^3).

Fixed versus Dynamic Scheduling

The UFH is part of the multi-zone thermal model. The control strategy must be defined within that simulation. The TES Simulation Engine will only see the required energy demand per time-step for the UFH based on the chosen control strategy. There are two options regarding the control strategy for the UFH: a fixed daily schedule for the entire year, or a dynamic schedule varying from day to day. The following section proposes a stepwise optimisation framework for both strategies:

1. **Dynamic capacity boundary mapping:** The optimisation method starts with evaluating the electrical constraints by calculating the real-time building base loads and available grid capacity. Within the Availability Engine, the maximum thermal output potentials for the heat pumps are dynamically determined as an hourly capacity ceiling (based on COP, available kVA headrooms, solar PV yields and power split between the heat pumps).

2. **Thermal fighting penalization:** Multi-zone thermal fighting is explicitly penalized to prevent systemic inefficiencies. For instance, if an aggressive UFH schedule overcharges the atrium (zone 2), excessive heat conducts through shared internal walls into adjacent zones. This could trigger concurrent cooling demands in these adjacent zones. Consequently, the simultaneous cooling load then affects the power split between the heat pumps, if set to *proportional split*, shrinking the heating capacity headroom. Besides a lower heating capacity, the extra cooling demand turns the UFH into an energetic liability rather than a strategic buffer. Therefore, a severe penalty is imposed on the schedule that causes this situation.
3. **Optimisation indicators:** To optimise both schedule control strategies, the hourly capacity deficits are calculated: any hour where the building's total load exceeds the heat pump's capacity ceiling. These deficits are processed through a squared cost function, $\sum(\text{deficit}_t)^2$, which heavily penalizes and flattens large demand spikes, where a linear function would have treated massive deficit spikes the exact same as several tiny, harmless deficits spread over a long time.

Finally, the physical water tanks are not sized by the total annual sum of these deficits, but by the single worst-case continuous energy deficit window ($E_{\max_gap}$). Tracked chronologically over all 8,760 hours of the year, this peak depletion sequence reveals the exact moment the heat pump is most overwhelmed, directly dictating the absolute storage volume (V_c) required for the hot and cold water tanks.

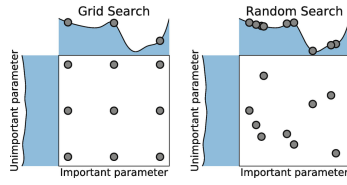


Figure 64: Fixed schedule: Grid Search Optimisation visual representation.

Image adapted from Bergstra & Bengio (2012).

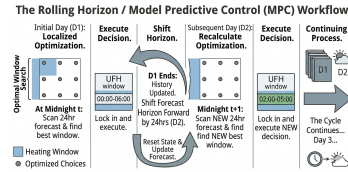


Figure 65: Dynamic schedule: Model Predictive Control with Rolling Horizon.

Image generated by Gemini.

Fixed Schedule Optimisation.

- **Mechanism:** Simulates the 8,760-hour year 24 separate times in the multi-zone model, executing a parametric grid search that shifts a rigid 6-hour UFH block by 1-hour increments each run (e.g., 00:00–06:00, then 01:00–07:00). This automated optimization method is significantly more efficient than a manual or random schedule search.
- **Criterion:** Adds up the total annual energy debt for each iteration and feeds this schedule in the Simulation Engine, scanning this chosen profile to find the single worst continuous energy deficit window ($E_{\max_gap}$).
- **Completely static:** It locks in one daily schedule for the entire year and cannot adjust to daily weather changes.

Dynamic Schedule Optimisation.

- **Mechanism:** Pauses the main chronological simulation every midnight to run a quick local check testing 264 combinations of different start hours (0 to 23) and operational lengths (*selected range: 0 - 8 hours to save computational power*) for the next day, also based on the state of the day prior (N+1).
- **Criterion:** Scores each combination against a 24-hour weather and solar forecast, instantly locking in the specific schedule length and timing that minimizes tomorrow's predicted deficit sum.
- **Flexibility:** Fully adaptive as it automatically extends floor charging times during extreme multi-day cold snaps or shortens runtime on mild days to avoid thermal fighting penalties.

Strategy Selection

There are three possible strategies for the UFH in the simulations models: no UFH, active UFH with optimised a fixed schedule or active UFH with dynamic a schedule. The selection between the strategies is determined by balancing physical hardware savings and peak-shifting against operational complexity:

1. **Physical TES Volume (m^3):** Each optimized thermal dataset with or without UFH is processed through the optimizer section of the main TES Simulation Engine, to isolate its single worst-case continuous energy deficit window. The UFH strategy that yields the smallest required physical water storage tank wins the primary advantage by minimizing installation costs and structural footprint.
2. **Operational complexity:** The Fixed schedule carries zero infrastructure overhead, providing a static daily timeline easily hardcoded into standard building controls. The Rolling Horizon method introduces high operational complexity, requiring continuous internet access for live 24-hour weather forecasts and a local processor to solve a 264-iteration loop every midnight.
3. **Performance Margin:** The system defaults to the simpler optimised fixed UFH schedule if the dynamic method yields negligible tank reductions. The Rolling Horizon MPC is only selected if its forecast-adaptive logic achieves a high-value drop in tank volume, proving that its daily flexibility is necessary to handle extreme seasonal anomalies.

Chapter 8.8 *Simulation model* will experiment with different UFH strategies and see which strategy has the most significant outcome: maintaining occupant thermal comfort under grid congestion- and equipment restraints with the smallest possible stratified buffer tanks.

4.7 TES Capacity Sizing Method

4.7.1 Volumetric Formula for Single-node Model (V_C)

The V_C calculation utilizes a single-node energy balance to identify the E_{max_gap} . However, to bridge the gap between this idealized 'energy bucket' and real-world thermal performance, a total efficiency factor (ϵ) is applied. This approach accounts for the fact that a tank is never 'empty' of water, but rather 'empty' of usable exergy once thermal degradation and mixing occur. By applying η_{str} and the $dead_zone$ factor, the model effectively transforms the theoretical energy volume into a realistic practical volume.

From the simulation model, the optimizer delivers a flattened net energy profile, allowing a secondary bisection search method to isolate the governing continuous deficit window. This bisection loop calculates E_{max_gap} , which represents the absolute minimum energy capacity required from the TES tank to survive that critical window without draining to empty. This approach significantly minimizes the physical water volume needed by first fully exhausting the storage capacity of the building's own thermal mass.

Use E_{max_gap} in the volumetric volume formula for stratified buffer tanks:

$$V_C = \frac{E_{max_gap} \cdot 3600 \cdot 1.2}{1000 \cdot \Delta u \cdot \epsilon} \quad (42)$$

Where:

- V_C is the required storage volume based on energy [m^3 or L].
- E_{max_gap} is the size-dictating total energy demand [kWh].
- S is the safety factor (e.g., 1.1 – 1.25).
- $\rho \approx 1000$ (kg/m^3).
- Δu is the specific energy density of the medium [kJ/kg].
- ϵ is total efficiency accounting for exergy loss.

The specific energy density for the following type on thermal energy storage:

1. Sensible Storage (water)

- $\Delta u = c_p \cdot \Delta T_{avg}$
- For the hot tank: $\Delta T_{avg} = 4$ °C
- For the cold tank: $\Delta T_{avg} = 8$ °C
- $c_p \approx 4,18$ kJ/(kg · K)

To calculate the required storage volume based on usable exergy without the computational overhead of multi-node numerical simulation, a total efficiency factor (ϵ) is applied. This factor bridges the gap between idealized energy-balance model and real-world thermal performance by acknowledging that a tank is never "empty" of water, but rather "empty" of useful heat once the thermocline reaches the supply outlet.

The total efficiency (ϵ) is derived as the product of the stratification efficiency (η_{str}) and the hydraulic effective volume ($1 - dead_zone$). While η_{str} accounts for the thermal degradation and conduction cross the thermocline, the dead zone factor represents the volumetric loss due to kinetic mixing and turbulence at the diffusers. By multiplying these factors, the formula effectively penalizes the theoretical volume twice: once for the physical space occupied by the mixing layer, and once for the thermal smearing that causes the last portion of the stored energy unusable at the design supply

temperature for the emitters.

$$\epsilon = \eta_{str} \cdot (1 - \text{dead_zone}) \quad (43)$$

Where:

- η_{str} is the stratification efficiency (typically 0.85 – 0.95) depending on the quality of the diffusers.
- dead_zone is the unusable volume fraction due to mixing (typically 0.1 – 0.2).

4.7.2 Volume Check based on Hydraulics (V_H)

The required hydraulic buffer volume (V_H) is determined by the peak instantaneous flow mismatch between the generation (heat pump) and distribution circuits (zone demand). Here, q_{net} is the supplemental flow rate [m^3/h] discharged from the buffer tank to bridge the deficit between the peak zone demand and the limited heat pump supply. Unlike static sizing methods that often assume a fixed-speed heat pump, this methodology accounts for inverter-driven modulation of the heat pump during grid-congested events.

$$V_H = \frac{q_{net} \cdot \tau_{min}}{1 - \text{dead_zone}} \quad (44)$$

Where:

- V_H is the required hydraulic buffer volume [m^3].
- q_{net} is the peak instantaneous flow mismatch value across the dataset (worst-scenario) between the emitter demand and the modulated heat pump supply [m^3/h].
- τ_{min} is the hydraulic stability constant (typically 0.25 h or 15 min).
- dead_zone is the unusable volume fraction due to mixing (typically 0.1 – 0.2).

"While the net flow logic assumes a linear displacement of the thermocline, a dead_zone fraction is applied to account for the kinetic energy of the incoming primary and secondary flows" (Chandra & Matuska, 2019). This additional volume ensures that when the storage tank discharges q_{net} to bridge the supply-demand gap, localized turbulence at the inlet diffusers does not compromise the thermal stratification or the temperature stability of the water delivered to the zones.

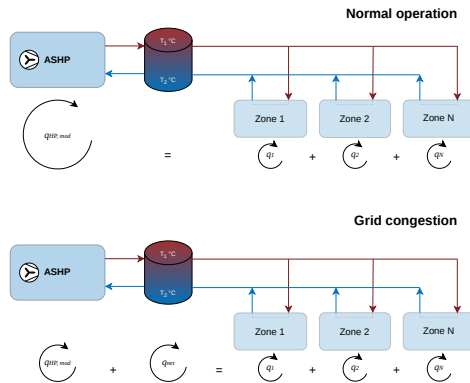


Figure 66: Schematic illustration of flow balancing.

Hydraulic flow balance during normal operation (top) and grid-congested events (bottom), where the storage tank provides the balancing flow q_{net} .

The flow low mismatch per time-step is defined as:

$$q_{net} = \max \left(\sum_{i=1}^n q_i - q_{HP,mod} \right) \quad (45)$$

Where:

- q_i is the required flow rate for zone i to meet its thermal load.
- $q_{HP,mod}$ is the primary flow rate provided by the heat pump while operating under grid constraints.

The required flow rate for each individual zone i is calculated hourly based on the thermal power delivered and the target temperature differential (ΔT):

$$q_i = \frac{Q_{delivered,i} \cdot 3600}{\rho \cdot c_p \cdot \Delta T_i} \quad (46)$$

Where:

- $Q_{delivered,i}$ is the total thermal power delivered to the zone (kW) ($= Q_{zone,i}$ if thermal demand can always be met by the supply), comprised of the following (or a combination of) depending on the situation:
 - $ZoneShare_i$
 - $Demand_i$
 - $TankSupply_i$
- 3600 is the conversion factor from seconds to hours.
- ρ is the density of the heat transfer fluid (typically 1000 kg/m^3 for water).
- c_p is the specific heat capacity of the fluid (typically $4.18 \text{ kJ/kg} \cdot K$).
- ΔT_i is the design temperature difference between the supply and return pipes for Zone i (K).

The modulated primary flow rate between stratified tank and heat pump is calculated as:

$$q_{HP,mod} = \frac{Q_{HP,max}(t) \cdot 3600}{\rho \cdot c_p \cdot \Delta T_{HP}} \quad (47)$$

Where:

- $Q_{HP,max}(t)$ is the actual thermal power output from the heat pump under grid-limited modulation [kW].
- 3600 is the conversion factor from seconds to hours.
- ρ is the density of the heat transfer fluid (water) [$\approx 1000 \text{ kg/m}^3$].
- c_p is the specific heat capacity of water [$\approx 4.18 \text{ kJ/kg} \cdot K$].
- ΔT_{HP} is the temperature lift across the heat pump (Supply - Return) [K].

4.8 Simulation Model

The following inputs are variable in the script and can be adjusted based on system specs or preferences.

4.8.1 Climate Datasets

The NEN 5060 standard defines reference climate data for the Netherlands, providing specialized datasets based on specific engineering requirements. While the NEN 5060-A2 dataset provides a statistically "typical" year for calculating annual energy consumption and performance (kWh), it is explicitly unsuitable for extreme weather simulations.

For simulating extreme weather and assessing thermal comfort, the NEN 5060-B2 dataset is utilized. This dataset provides three probability levels-5%, 2%, and 1%-to account for sustained extreme periods. The 1% exceedance dataset represents the most extreme scenario, containing documented heatwaves and cold waves to ensure safety margins in HVAC sizing and risk mitigation. Since this thesis is focussed on HVAC sizing and thermal comfort maintenance, the NEN 5060-B2 1% dataset will be used.

NEN 5060-B2 1%: temperatures and solar irradiation

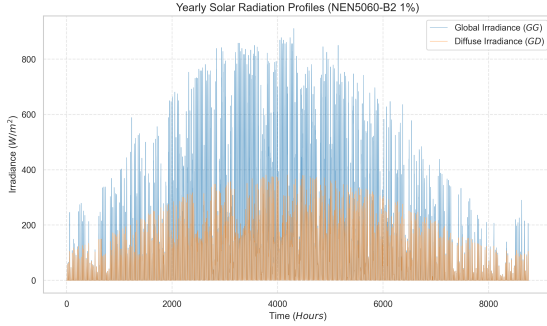


Figure 67: Solar irradiation from NEN5060-B2 1% for calculating cooling loads.

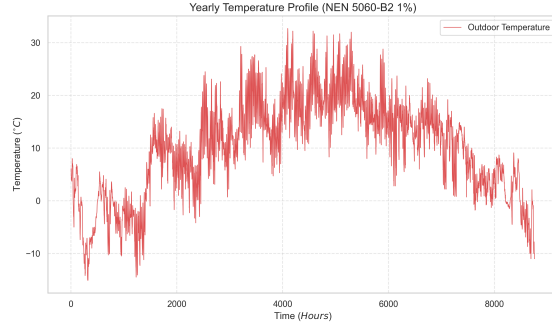


Figure 68: Solar irradiation from NEN5060-A2 for calculating heating loads.

Data Format

The climate data is required to be in a DataFrame format for the simulation engines. The following tables illustrate this format:

Time-step	Temperature [°C]
1	—
2	—
3	—
N	—

Table 16: Hourly Temperature Data

Time-step	GG [W m^{-2}]	GD [W m^{-2}]
1	—	—
2	—	—
3	—	—
N	—	—

Table 17: Global Horizontal Irradiance & Diffuse Horizontal Irradiance.

4.8.2 Availability Engine

The Availability Engine is a separate script that functions as the central processing logic for thermal power output calculation and distribution, translating external environmental and grid-based data into instantaneous operational constraints for the simulation. By aggregating on-site PV generation with grid capacity, the engine establishes a total hourly electrical pool that is divided between the heating and cooling heat pumps using either fixed or demand-proportional allocation modes.

This engine ensures mechanical stability by enforcing a minimum 1.5 kVA electrical floor for each unit while dynamically calculating COPs and free-cooling potentials based on ambient conditions. Ultimately, these calculated thermal potentials are passed to the Simulation Engine.

PV Settings

The following variables are part of the Availability Engine to calculate the electricity generated by the PV panels on the roof of the building of the case study. Per time-step, with the global horizontal irradiance & diffuse horizontal irradiance as input, the extra electricity for the heat pump is system is calculated and added to the available grid kVA supply.

Variable	Unit	Description
AREA	[300 m ²]	Total surface area of PV panels.
Tilt_DEG	[7°]	Tilt in cos(7°) is the angle of the PV panels.
EFF	[0.2]	Efficiency, based on the 200 Wp/m ² (200/1000, according to STC by (IEC, 2020))
PR	[0.78]	Performance Ratio, accounting for the "moderate ventilation" and inverter losses.
D	[0.005]	Degradation factor (0.995), accounting for the 0.50% annual ageing

Table 18: PV calculation data from the case study.

COP Methodology

The simulation model determines the COP using the Lorentz formula rather than static manufacturer performance curves. While fixed performance curves provide empirical data for specific heat pumps, the Lorentz approach ensures theoretical consistency across a wide temperature range. this method allows the simulation to adapt dynamically to varying source and sink temperatures by calculating the maximum thermodynamic potential of a cycle.

To reflect advanced hardware, the model uses a three-stage cooling logic based on the difference between the outside air temperature (T_{amb}) and the chilled water set-point ($T_{source} = 10^{\circ}\text{C}$). A multi-stage heating logic is not necessary since the temperatures in the Netherlands do not exceed those of the supply temperatures for heating throughout the year.

Normally, when the outside air is cooler than your cold supply temperature, one would open windows to let in the cold air. However, in case that is not possible due to noise constraints or there not being any windows to open, another method is used: if T_{amb} is lower than T_{source} , the system uses a so-called *dry cooler* to bypass the compressor entirely. During this Free Cooling mode, the compressor is turned off. Electrical use is then restricted to the small amount of power needed for fans and pumps, and the cold outside air is used directly for cooling (Delta T Systems, 2025). Because of this, the system reaches an "Equivalent COP" between 10.0 and 20.0. These high values are much better than standard mechanical cooling because the system uses the cold outside air as a natural energy sink.

Mode	Condition	Description	COP
Mechanical	$T_{amb} > T_{source}$	Compressor runs hard to push heat against warm outside air.	1.5 – 4.5
Partial free cooling	$T_{amb} \approx T_{source}$	Compressor at low speed to bridge the gap; fans do most work.	5.0 – 8.0
Total free cooling	$T_{amb} < (T_{source} - 2)$	Compressor OFF. Only fans and pumps are running.	15.0+

Table 19: The three phases of real-life cooling for high-end systems.

Partial free cooling COP adapted from Zhang et al. (2023); Total free cooling COP adapted from Jia et al. (2021)

Heat Pump Performance

The following variables are part of the Availability Engine to calculate the COP of both heat pumps. Because the COP is calculated according to the Lorentz formula, the supply temperatures of both heat pumps are required. A max COP is added to reflect real world mechanical limits. In case of partial or free cooling, the COP can achieve higher values.

Variable	Unit	Description
ETA_LO	[0.5]	Lorentz Factor (η_{Lo}), representing the ratio between the actual COP and the theoretical Carnot COP.
T_SINK_H	[45°C]	The fixed temperature (sink) used for the heating supply (T_{sink}).
MAX_COP_H	[5.0]	Maximum allowed Coefficient of Performance (COP) for the heating cycle to prevent unrealistic efficiency peaks.
T_SOURCE_C	[10°C]	The fixed temperature (source) used during the cooling cycle (T_{source}).
MAX_COP_C	[4.5]	Maximum allowed Coefficient of Performance (COP) for the cooling cycle (EER equivalent) during thermal extraction.

Table 20: Heat pump configuration settings and thermodynamic boundary conditions for the simulation.

Thermal Stability and Hardware Constraints

The simulation framework incorporates an integrated Availability Engine to regulate the concurrent electrical demands of two separate heat pump units, each dedicated to its own thermal energy storage (TES) tank. To prevent electrical overloading of the building's electricity connection, the total available electrical power, derived from grid capacity and photovoltaic generation, is partitioned based on a user-defined *heating share input*.

Each unit's control architecture accounts for real-world hardware limitations by enforcing a 1.5 kVA mechanical minimum, representing approximately 5% of a standard 30 kVA compressor capacity. This floor is critical for thermocline maintenance, ensuring that even during low-demand periods, the heat pumps operate at a baseline level to stabilize the tank's temperature gradient and offset continuous thermal drift (*drift-rate*).

Any surplus energy generated at this modulation floor is injected into the respective TES or building mass, effectively performing "maintenance" on the thermal state rather than resulting in theoretical wastage.

Mode	Description
Fixed kVA split	Uses the <i>HEATING_SHARE_INPUT</i> as a rigid percentage (e.g., 50/50 or 70/30) regardless of the instantaneous demand in individual zones (<i>KVA_SPLIT_MODE</i>).
Proportional split	Dynamically evaluates the actual kW demand of the zones in each specific hour and partitions the building's electrical capacity based on thermal stress (<i>KVA_SPLIT_MODE</i>).
Mechanical floor	Enforces a 1.5 kVA (approx. 5%) modulation minimum to maintain the thermocline and operational stability of the compressor, diverting surplus energy to the TES (<i>HP_MIN_MOD_KVA</i>).
Thermal drift	Simulates continuous hourly energy degradation to the environment to prevent the TES from acting as a loss-free reservoir, ensuring realistic storage behaviour (<i>DRIFT_RATE</i>).

Table 21: Control logic methodologies and hardware constraints for parallel heat pump operations.

4.8.3 Simulation Engine

The Simulation Engine script serves as the primary integration layer, managing the parallel operation of heating and cooling heat pumps while interacting with external grid constraints. It processes the hourly building demands through a hierarchical logic. Users can define the operational limits and control strategies in the input section to observe how different hydraulic and control configurations affect overall system performance and comfort maintenance.

Heating Side Parameters

The table below outlines the variables governing the heating system and its dedicated TES tank. These settings define the rated output of the heating heat pump and the logic used to charge the thermal mass or discharge the hot tank during periods of limited electrical availability.

Variable	Unit	Description
HP_MAX_CAPACITY_H	[75 kW]	Rated capacity of the Air-Source Heat Pump (Q_{cap}).
REHEAT_STRATEGY_H	[sequential or proportional]	Strategy for Thermal Mass charging surplus.
DISCHARGE_STRATEGY_H	[sequential or proportional]	Strategy for modulated heat pump distribution during grid congestion ($Q_{HP,max}(t)$).
ZONE_TES_FIRST_H	[True or False]	Determines if the TES is used immediately to maintain set-point or after drifting to minimum.
ZONES_DELTA_T_H	[10 K heat, 8 K cool]	Temperature difference across the distribution zones (ΔT_{zone}).
MANUAL_TANK_KWH_H	[kWh]	Option to manually fill in a tank size.

Table 22: Global input variables and strategy parameters as defined in the main simulation script for the heating side of the system.

Cooling Side Parameters

The table below defines the parallel parameters for the cooling circuit. Mirroring the heating side, these settings define the rated output of the heating heat pump and the logic used to charge the thermal mass or discharge the hot tank during periods of limited electrical availability.

Variable	Unit	Description
HP_MAX_CAPACITY_C	[75 kW]	Rated capacity of the ASHP (Q_{cap}).
REHEAT_STRATEGY_C	[sequential or proportional]	Strategy for thermal mass charging surplus.
DISCHARGE_STRATEGY_C	[sequential or proportional]	Strategy for modulated heat pump distribution during grid congestion ($Q_{HP,max}(t)$).
ZONE_TES_FIRST_C	[True or False]	Determines if the TES is used immediately to maintain set-point or after drifting to minimum.
ZONES_DELTA_T_C	[10 K heat, 8 K cool]	Temperature difference across the distribution zones (ΔT_{zone}).
MANUAL_TANK_KWH_C	[kWh]	Option to manually fill in a tank size.

Table 23: Global input variables and strategy parameters as defined in the main simulation script for the cooling side of the system..

Global System Parameters

The table below presents the global constants that synchronize the two heat pumps with the electrical infrastructure. Key parameters include the method for splitting available kVA between units and the minimum modulation thresholds required to ensure compressor stability and prevent rapid cycling.

Variable	Unit	Description
UTILIZATION_FACTOR	[1.2]	Utilization factor (η) of the thermal mass storage.
TAU_STABILITY	[0.25 h]	Hydraulic stability constant (τ_{min}).
KVA_SPLIT_MODE	[fixed or proportional]	Method for splitting electrical capacity between the two heat pumps.
HP_MIN_MOD_KVA	[1.5 kVA]	Electrical maintenance floor for compressor stability (5%).
DRIFT_RATE	[0.0001]	Hourly thermal energy degradation rate for the TES (e.g., 0.01%).

Table 24: Global input variables and strategy parameters as defined in the main simulation script used for both heating and cooling sides of the system.

Tank Volume Parameters

The table below defines the variables that are part of the Simulation Engine to calculate the final tank sizes for formula's V_C and V_H . The constants are specific to the sensible heat storage (water-based).

Variable	Unit	Description
rho	[1000 kg/m ³]	Density of water (ρ).
cp	[4.18 kJ/(kg·K)]	Specific Heat Capacity of water (c_p).
delta_t	[10 K heat, 8 K cool]	Temperature difference between top and bottom of the tank.
DEAD_ZONE	[0.1 – 0.2]	The unusable volume fraction of the tank due to mixing.
eta_str	[0.95]	Stratification efficiency (η_{str}) depending on the tank diffusers.
S	[1.1 – 1.25]	Safety Factor.

Table 25: Variables and constants for the final tank size formulas V_C and V_H .

Zonal Parameters

While global settings dictate the overall system capacities and logic, the table below defines the localized constraints and thermal characteristics unique to each climatization zone. These parameters allow the engine to treat the building as a collection of independent climatization environments, each with its own comfort boundaries (T_{min} , T_{max}) and thermal mass storage potential (M_{zone}). By assigning specific emitter differentials and discharge strategies to each zone, the simulation can precisely modulate the distribution of the global heat pump output to meet individual zone demands while respecting localized comfort drift preferences (T_{swing}).

Variable	Unit	Description
T_START	[°C]	Initial zone temperature at the beginning of the simulation.
T_SET	[°C]	Target indoor temperature set-point for zone n .
T_SWING	[°C]	Permissible temperature deviation compared to T_{set} .
T_MIN	[°C]	Minimum allowed temperature boundary ($T_{min} \geq T_{set}$ possible).
T_MAX	[°C]	Maximum allowed temperature boundary ($T_{max} \geq T_{set}$ possible).
ZONE_T_DELTA	[K]	Designed temperature differential across the zonal emitters (value for cooling and value for heating).
M_{zone}	[kWh/K]	Functional thermal mass constant.

Table 26: Zonal input variables and thermal comfort boundaries.

Simulation Flowchart

The following flowchart illustrates the logic and data integration of the complete simulation model, mapping the interaction between the Availability Engine, Simulation Engine, and Multi-zone thermal demand model. It visualizes how various dataset inputs are processed by the Availability Engine to define operational boundaries, which the Simulation Engine script then applies to balance parallel heating and cooling demands across the zones. This sequential overview clarifies the relationship between global system constraints, hierarchical storage strategies, and the resulting thermal comfort maintenance within the building structure.

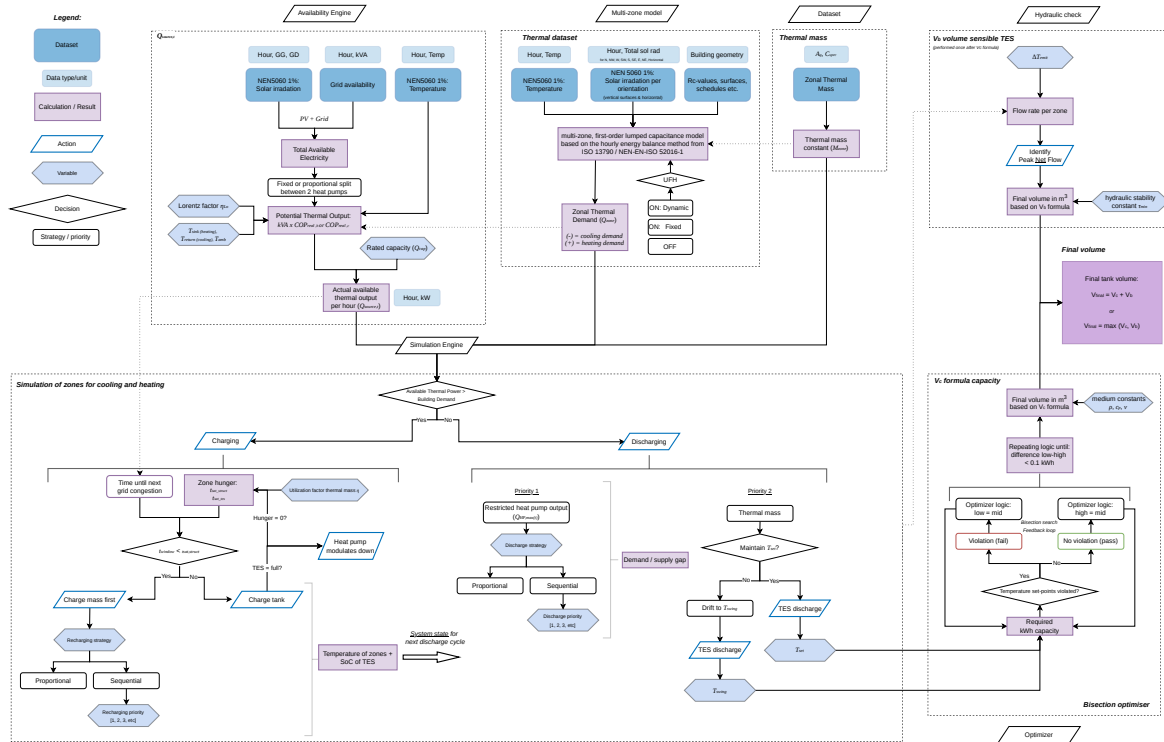


Figure 69: Flowchart

Flowchart of simulation model

4.9 Results: Validation and Optimisation

This section presents simulation outcomes derived from consistent input parameters to ensure a standardized comparative analysis, as detailed in the table below.

Zone 2 (the atrium) is maintained at a set-point of 22°C, which represents the median of the 16–28°C, allowable temperature drift defined in the multi-zone model. This drift range aligns with the broader climate design of the case study. To accurately simulate this behaviour without modifying the core control logic within the Simulation Engine (which already incorporates thermal drift and building mass) the T_{swing} for the atrium is set to 0.

This effectively embeds the thermal dynamics and mass characteristics directly into the thermal demand dataset. To maintain neutrality across the building, all zones utilize a proportional priority strategy, and the system is configured to prioritize the use of its thermal mass before drawing from the TES buffer.

Zone	T_START_LIST [°C]	T_SET [°C]	T_SWING [°C]
Z1	21.0	21	2
Z2	22.0	22	0
Z3	21.0	21	2
Z4	21.0	21	2
Z5	21.0	21	2
Default settings for all zones: ZONE_TES_FIRST_H = False, ZONE_TES_FIRST_C = False			
Default settings for all zones: REHEAT_STRATEGY_H = proportional, REHEAT_STRATEGY_C = proportional			
Default settings for all zones: ZONES_DELTA_T_H = 10.0 °C, ZONES_DELTA_T_C = 8.0 °C			
Default settings for all zones: KVA_SPLIT_MODE = proportional			

Table 27: Zone and Emitter Parameters

4.9.1 Sensitivity Analysis

A sensitivity analysis of heating and cooling heat pump capacities was conducted to characterize the system's performance boundaries. The resulting heat maps visualize these feasible design thresholds, accounting for the interdependency of both capacities under a shared kVA constraint. This analysis identifies the optimal capacity configuration that minimizes E_{maxgap} (the maximum cumulative energy deficit) thereby optimizing thermal energy storage sizing to maintain building comfort levels.

A heat map is a visual representation of data where individual values contained in a matrix are represented as colours. In the context of the sensitivity analysis performed in this section, the x-axis represents the cooling heat pump capacity, the y-axis represents the heating capacity, and the colour intensity of each cell corresponds to the magnitude of E_{maxgap} . This visualization technique allows for the rapid identification of performance patterns, such as identifying the "cliffs" where the system transitions from infeasible to feasible, or locating the optimal capacity combination that minimizes the energy storage requirements.

4.9.2 Scenario A: Baseline Without UFH

The following heat maps display the required storage volumes (V_C) based on the thermal demand dataset from the multi-zone model without any UFH integration. These volumes were calculated by the simulation engine's optimization process, which determines the required tank size by calculating the maximum energy deficit observed for each thermal load profile. The results indicate that the heat pump maximum capacities, in most cases, act as independent variables; an increase in heating system capacity does not correlate with a reduction in the required volume for the cooling system, and vice versa.

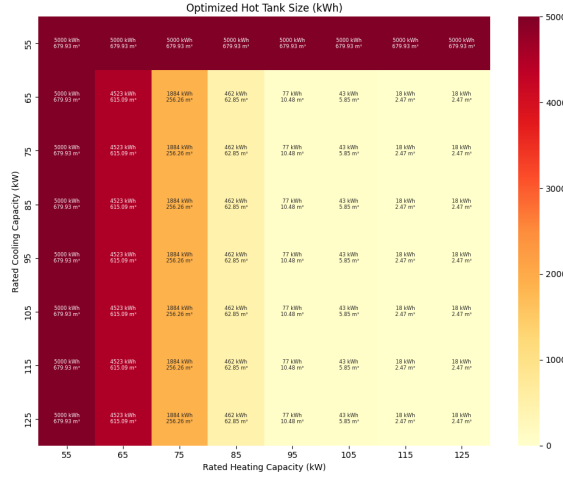


Figure 70: Heat map for hot tank (E_{max_gap}).

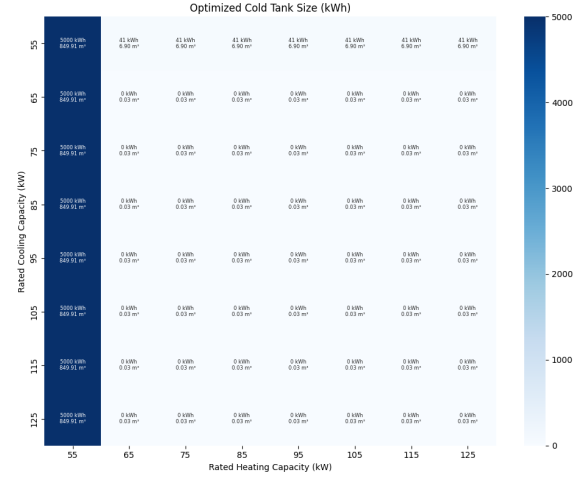


Figure 71: Heat map for cold tank (E_{max_gap}).

Heat Map for Heating.

The heat maps demonstrate that the cooling heat pump exerts minimal influence on the peak energy deficit for the heating system. A significant reduction in the required tank size occurs only when the cooling capacity increases from 55 kW to 65 kW.

Furthermore, once the heating-dedicated heat pump reaches a capacity of 115 kW, the peak energy deficit and the required tank volume remain constant.

Heat Map for Cooling.

The heating heat pump exerts minimal influence on the peak energy deficit for the cooling system. A significant reduction in the required tank size occurs only when the heating capacity increases from 55 kW to 65 kW. At this capacity threshold, the need for a cold thermal storage tank becomes obsolete. Under these conditions, the control strategy and the allowed temperature drift enable the zones to remain within defined comfort bounds without additional supply from a tank.

However, despite the reduction in cooling demand, a cold tank volume remains necessary to satisfy the hydraulic stability requirements (V_H).

4.9.3 Scenario B: UFH as part of TES Strategy

This simulation evaluates UFH systems using two approaches: a fixed schedule optimized through a grid search for the best annual starting time, and a dynamic schedule governed by a 24-hour rolling horizon MPC framework. The cooling capacity is held constant at 65 kW, as the previous results showed that cold tank volumes stabilize at this level. While the UFH strategy affects the total thermal demand, this fixed cooling baseline allows heating capacity to be isolated as the primary variable for storage volume optimization.

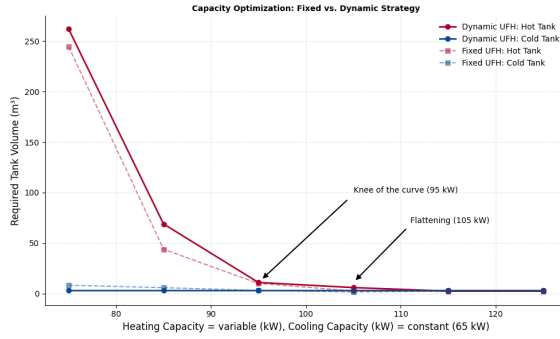


Figure 72: Fixed versus Dynamic UFH schedule.

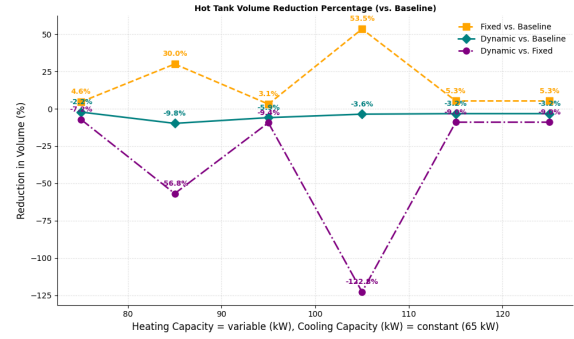


Figure 73: Comparative volume reduction.

Sensitivity Analysis.

The sensitivity analysis reveals a non-linear relationship between heating capacity and required storage volume, with a clear turning point, or "knee," at 85 kW. This point represents the most efficient capacity increase to volume reduction ratio. However, to reach a more practical tank volume, a capacity increase from 95 kW to 105 kW is required.

Comparative Volume Reduction.

The sensitivity analysis shows a non-linear relationship between heating capacity and required storage volume. The fixed schedule strategy consistently outperforms the baseline across all tested capacities, while the dynamic strategy slightly underperforms the baseline throughout the capacity spectrum.

At lower capacities, both strategies require significant storage volumes; however, as heating capacity increases, these requirements decrease until they plateau. Beyond a capacity of 115 kW, all UFH schedules and the baseline configuration stabilize at a minimal, constant tank volume.

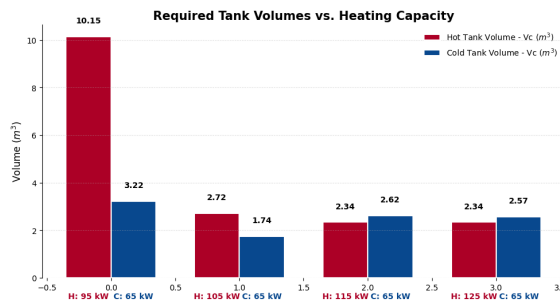


Figure 74: Fixed UFH schedule - Volume comparison after knee of curve: 95 kW.

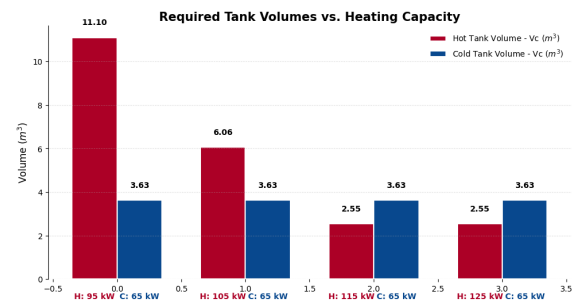


Figure 75: Dynamic UFH schedule - Volume comparison after knee of curve: 95 kW.

Marginal Optimization - Fixed.

The bar chart indicates that beyond a capacity of 95 kW, the marginal benefit of increasing heat pump capacity decreases rapidly. Increasing capacity from 95 kW to 115 kW results in a volume reduction from 10.15 m^3 to 8.01 m^3 . While the 95 kW configuration represents an efficient balance between storage size and heat pump capacity, the 105 kW configuration provides a 26.71% reduction in hot tank volume compared to the 95 kW case.

In all instances, the cold tank volume is determined by the hydraulic stability requirement (V_H), as this value consistently exceeds the calculated cooling capacity requirement (V_C).

Marginal Optimization - Dynamic.

The bar chart shows that beyond 95 kW, the marginal benefit of increasing capacity decreases rapidly, with storage volume dropping from 11.10 m^3 to 9.05 m^3 . As seen in the fixed schedule, increasing the heating capacity to 150 kW results in no further changes to the tank size.

In all cases, the cold tank volume is determined by the hydraulic stability requirement (V_H), which consistently exceeds the cooling demand requirement (V_C).

UFH Strategy Selection

The simulation compares two control approaches: a fixed schedule and a dynamic Model Predictive Control (MPC) strategy. The fixed schedule functions as an open-loop system, identifying an optimal operating window through a grid search to minimize the peak energy deficit ($E_{max,gap}$). In contrast, the dynamic schedule employs a 24-hour rolling horizon MPC to modulate UFH thermal delivery based on real-time variables, including weather and grid kVA availability.

Feature	Fixed UFH Strategy	Dynamic UFH Strategy (MPC)
Control Logic	Static, time-based scheduling.	Adaptive, forecast-driven (MPC).
Responsiveness	None; relies on predefined blocks.	Real-time adjustment to weather/load.
Resource Usage	Low; computationally inexpensive.	High; requires modelling and forecasting.
Energy Efficiency	Moderate; prone to operational waste.	High; optimized via load shifting.
System Behaviour	Predictable, steady-state response.	Highly sensitive to real-time variables.
Optimised volume (for H: 105 kW C: 75 kW)	8.01 & 2.18	9.05 & 2.39.

Table 28: Comparison of Fixed versus Dynamic UFH control strategies.

4.9.4 Largest Energy Deficit Window

This analysis evaluates system performance during the time windows that dictate the largest energy deficit ($E_{max,gap}$) observed throughout the simulated year. The baseline scenario, representing the initial demand analysis with the starting heat pump capacity and no UFH or thermal storage (TES), is compared against the integrated TES+UFH model.

The results quantify the energy measurements required to maintain thermal comfort boundaries, illustrating the points at which the baseline system fails to meet demand. For more detailed results per time-step for these energy deficit windows, see *Appendix A*.

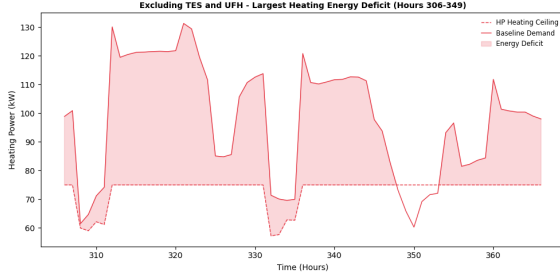


Figure 76: Baseline demand heating against two 75 kW rated heat pumps.

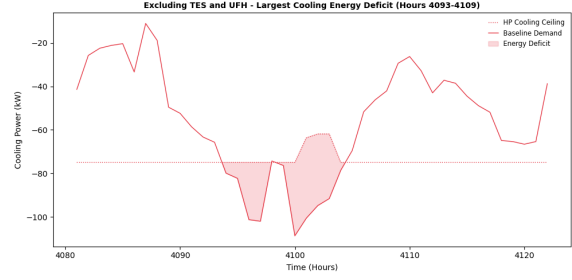


Figure 77: Baseline demand cooling against two 75 kW rated heat pumps.

Heating Baseline Deficit.

This graph captures the thermal energy shortfall in the raw system, revealing how current heat pump capacity frequently fails to meet demand during peak periods.

Without thermal storage, these deficits manifest as direct comfort losses, as a result of inadequate rated heating capacity and electricity supply from the grid. Both limiting factors can be seen in the graph for this time-window.

Cooling Baseline Deficit.

This graph maps the unmitigated cooling demand shortfall. It shows that when grid limits and equipment sizing cap the heat pump's output, the system cannot buffer against high demand surges. This leads to persistent performance gaps, caused entirely by operating at the heat pump's maximum rated capacity without thermal storage for this time-window.

Furthermore, simply increasing the heat pump's capacity is often insufficient; it may merely reveal underlying grid bottlenecks that prevent that extra power from being used.

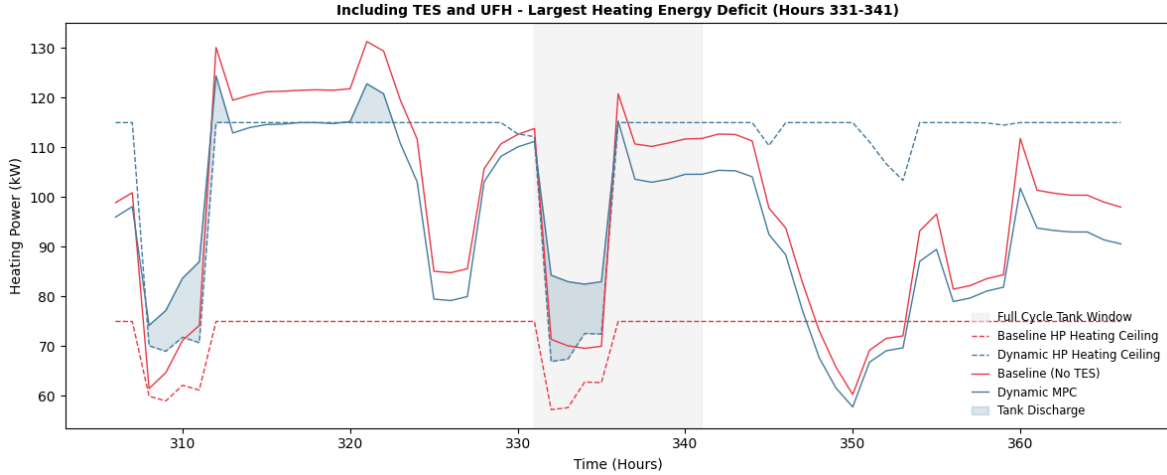


Figure 78: Baseline compared to TES integrated system with HP rated capacities of Heating: 115 kW & Cooling: 65 kW.

Simulation Model Results

Dictating Heating Energy Deficit Window

The graph illustrates the largest $E_{max,gap}$ for the heating system. The grey region highlights the only instance of a complete tank cycle, representing the specific window where the system transitions from a fully charged state to total depletion and back to full recovery, occurring between January 14 and January 15. The blue area denotes the energy supplied by the tank during the discharge phase. For this scenario, the V_H (hydraulic check) volume results in $0.47 m^3$ for heating.

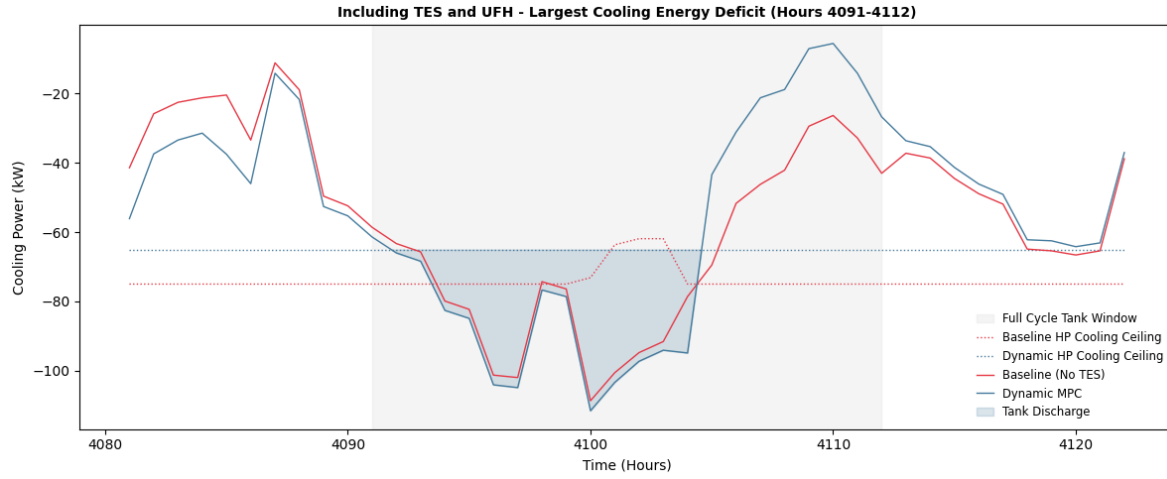


Figure 79: Baseline compared to TES integrated system with HP rated capacities of Heating: 115 kW & Cooling: 65 kW.

Simulation Model Results

Dictating Cooling Energy Deficit Window

The graph shows the largest $E_{max,gap}$ for the cooling system. The grey region highlights the only instance of a complete tank cycle, representing the singular window where the system transitions from fully charged to total depletion and back to full recovery. This cycle occurs between June 20 and June 21. The blue area denotes the energy supplied by the tank during the discharge phase. For this scenario, the V_H (hydraulic check) volume results in 2.73 m^3 for heating.

5 Discussion and Conclusions

5.1 Interpretation of the Results

This section of the discussion will interpret the results from the previous chapter.

5.1.1 System Decoupling and Capacity Constraints in the Baseline Configuration

The observed independence between heating and cooling capacity requirements suggests that the systems are thermally decoupled under the current baseline. This lack of interaction arises because peak heating and cooling demands occur at different times, meaning the simulation treats the two thermal storage systems as distinct, non-interacting parameters. Consequently, because tank sizing is dictated by the specific window of peak energy deficit for each system, the cooling and heating systems function as parallel, independent variables. Any attempt to optimize the volume of one system yields negligible benefits for the other, confirming that the baseline configuration lacks the cross-system synergy achievable through more integrated control strategies.

Heat Map Heating

The sensitivity analysis for the heating system, characterized by a transition at 65 kW and a saturation point at 115 kW, stems from the distribution of available kVA between the heat pumps. At a cooling capacity of 55 kW, simultaneous zone cooling demands prioritize the cooling-dedicated heat pump, which restricts the kVA available for the heating system to manage its thermal deficit. The plateau observed after 115 kW indicates a structural limit; beyond this capacity, the limiting factor for storage optimization is not heat pump performance, but the total available kVA during the period of the largest cumulative energy deficit.

Heat Map Cooling

The interaction between heating capacity and cooling requirements presents a reciprocal relationship to the heating analysis. The change at 65 kW demonstrates that the cooling heat pump can independently handle peak cooling demands once it reaches a sufficient power threshold. Furthermore, even when the thermal deficit is resolved, a specific cold tank volume is still required to satisfy the hydraulic stability check. This confirms that the final tank size is not determined by thermal needs alone, as it must also account for the hydraulic requirements of the system.

5.1.2 Integrated UFH Strategy

In this scenario, heating capacity is the dominant design factor. Increasing capacity significantly reduces the peak energy deficit ($E_{max,gap}$) during high-demand periods, allowing the system to bridge supply-demand mismatches more efficiently. By holding cooling capacity constant, the influence of the fixed and dynamic schedules on heating storage requirements is isolated, revealing how each strategy impacts overall performance.

Sensitivity and Capacity Thresholds

The sharp reduction in storage requirements occurs because higher heating capacities decrease the peak energy deficit. As heating capacity rises, the time window of the supply-demand mismatch shrinks, allowing the heat pump to recover and recharge the thermal energy storage tank more rapidly. The 85 kW knee point identifies the threshold of diminishing returns for capacity investment, while the further reduction observed at 105 kW demonstrates how additional capacity can bring the storage system within realistic sizing constraints.

Saturation and Scheduling Performance

The plateau observed beyond 115 kW marks a saturation point where the system's heating capacity becomes the primary driver for neutralizing thermal deficits, rather than the scheduling strategy. At these higher capacity levels, the physical ability of the heat pump to meet demand overwhelms the

potential gains from scheduling, rendering further storage optimization negligible.

The dynamic strategy underperforms relative to the fixed schedule in this regard. This is due to internal constraints within the predictive model, which limit the dynamic framework's ability to exploit the building's thermal mass as effectively as the structured, pre-defined fixed schedule.

Marginal Optimization

The 95 kW configuration serves as an optimal design point when balancing capital costs against storage footprint. However, if the primary objective is to minimize the physical footprint, the 105 kW configuration is the preferred choice, as it achieves the lowest practical storage requirement before reaching the point of diminishing returns. In all cases, the reliance on V_H for cold tank sizing demonstrates that the final design is constrained by hydraulic system stability rather than purely by the thermal cooling deficit.

For the dynamic UFH schedule, the stagnation in volume reduction at 150 kW suggests a similar structural limit. Ultimately, the available kVA during the period of maximum thermal deficit becomes the limiting factor for storage optimization rather than the maximum potential heat pump capacity. This confirms that even under a dynamic MPC framework, storage requirements are fundamentally constrained by the interaction between hydraulic stability and peak power availability.

5.1.3 UFH Strategy Selection: Predictability versus Adaptability

The comparison between control strategies highlights a fundamental trade-off between predictability and adaptability. The fixed strategy prioritizes static stability and minimizes $E_{max,gap}$ by optimizing for a worst-case scenario. This results in smaller required tank volumes because the system follows a rigid, repeatable profile.

In contrast, the dynamic strategy prioritizes operational agility and daily performance. While this increases the storage volume requirement compared to the fixed approach, it allows the system to respond to real-time fluctuations rather than relying on a singular statistical worst-case. The performance difference suggests that the dynamic MPC is tuned to optimize for energy efficiency and operational flexibility, whereas the fixed schedule is more effective at minimizing $E_{max,gap}$ and the associated physical storage capacity. The subsequent analysis examines specific time-steps to demonstrate how these strategies differ in operation at a more detailed scale.

5.1.4 Analysis of Peak Energy Deficit Windows

The implementation of active underfloor heating managed by Model Predictive Control, combined with thermal energy storage and increased heat pump capacity, effectively redistributes thermal loads. By dynamically shifting demand, the integrated system resolves energy deficits that the baseline configuration cannot satisfy. These findings confirm that the primary benefit of the integrated approach is its ability to bridge supply-demand gaps that would otherwise cause the system to violate thermal comfort constraints.

Heating and Cooling Deficit Dynamics

The system manages thermal energy flow by balancing temporal windows against structural saturation constraints ($\Delta t_{window} \leq \Delta t_{sat,struct}$).

- **Heating Deficit:** When the dynamic MPC demand curve falls below the heating supply ceiling, supply exceeds demand. The system then initiates either a tank recharge or returns the building zones to the set-point temperature. This mechanism ensures comfort while preventing the tank from reaching a state of total, unrecoverable depletion.
- **Cooling Deficit:** Because cooling demands are represented as negative values, the demand curve appears visually above the cooling supply capacity when a cooling surplus exists. During these intervals, the system similarly recharges the tank or returns zones to the set-point temperature.

This complementary relationship between demand and supply capacity confirms how the integrated system maintains thermal balance, even when cooling and heating requirements fluctuate significantly throughout the year.

5.1.5 Final TES Volumes

The determination of the total tank capacity relies on whether the volumes for thermal storage (V_C) and the hydraulic stability (V_H) are treated as a combined functional requirement or as mutually exclusive safety margins. In a "maximum" sizing approach for the selected scenario of the dynamic UFH strategy (with heating max capacity: 115 kW and cooling max capacity: 65 kW):

$$V_{final,heating} = \max(V_C = 2.55m^3, V_H = 0.47m^3) \quad (48)$$

$$V_{final,cooling} = \max(V_C = 3.63m^3, V_H = 2.73m^3) \quad (49)$$

the larger of the two values is selected under the assumption that the substantial volume required for long-term energy storage naturally encompasses the smaller volume needed for short-term control stability. For this logic to remain physically sound, the system's control sensors must be positioned to ensure that even when the storage capacity is being utilized, a residual buffer zone equivalent to V_H remains available at the bottom of the tank to protect the heat pump during sudden flow transitions.

Conversely, a "sum" approach where:

$$V_{final,heating} = 2.55m^3 + 0.47m^3 = 3.02m^3 \quad (50)$$

$$V_{final,cooling} = 3.63m^3 + 2.73m^3 = 6.36m^3 \quad (51)$$

is often utilized in high-reliability applications to prevent thermocline "washout" during periods of maximum thermal saturation. While V_C defines the capacity required for discharge during grid congestion, a vessel sized exclusively for this energy volume risks reaching a state of total high-temperature saturation at the conclusion of a charging cycle. Should a hydraulic transition occur at this peak (where building demand decreases further while the heat pump maintains a high-output charging mode), the absence of a residual cold-water zone would cause the immediate ingestion of high-temperature return water, resulting in so-called "short cycling" leading to mechanical stress. By adding V_H as a dedicated backup volume, the 15-minute τ_{min} stability period is preserved, ensuring the heat pump can modulate safely even when the active energy storage (V_C) is fully exhausted.

It is important to stress that the final volumes resulting from the simulation model are directly dependent on the input data. Currently, the climate datasets simulate an extreme year that will likely never occur. The actual tank volumes and heat pump capacities required in real-life can be assumed to be much lower. Moreover, these volumes are based on active HVAC without the use of natural ventilation. Even though, the case study specifically required the thermal demand modelling without natural ventilation, in most other cases, the use of natural ventilation before active HVAC drastically reduces thermal demand, and therefore likely also reduces the required TES tank volume.

5.2 Synthesis and Research Conclusions

This research developed a comprehensive design-to-operation basis for the integration of Thermal Energy Storage (TES) systems. By replacing theoretical, static sizing methods with a dynamic, constraint-aware methodology and simulation model, this study provides a thermal buffering solution to mitigate electrical grid congestion.

5.2.1 Research Objectives

The core research objective was to develop a unified framework that optimizes thermal storage through transient energy calculations and precise energy deficit tracking. This was achieved by integrating a multi-zone thermal network demand model with a simulation model that utilises advanced control strategies.

The study demonstrates that TES implementation is not a purely thermal challenge but a multi-dimensional optimization problem. The developed workflow successfully transforms building energy profiles into manageable, grid-aware loads by identifying the non-linear relationship between heating capacity, cooling hydraulic stability, control strategies, and storage volume requirements.

5.2.2 Main Findings

The main findings are summarized below and answer the main research question and its sub-questions.

- **Varying Load Profiles:** Suitable TES technology selection is dependent on a building's load profile, where the Chronological Hourly Load curve gives most insight into its thermal behaviour.
- **TES Integration:** Important infrastructure and system-level requirements for integrating TES into building climate systems is choosing a TES technology, TES medium, and operating temperatures that are compatible with the heat source and emitters.
- **Systemic Buffering:** This study confirms that combining transient thermal network modelling with active control strategies provides a critical thermal buffer, allowing the system to resolve thermal comfort violations that baseline configurations cannot address. This dynamic modelling for a continuous energy balance provides a more robust and efficient TES volume compared to simple static calculations.
- **Constraint-Aware Design:** Storage footprint is governed not only by thermal deficits but by structural hydraulic stability and peak power availability. The case study illustrates that designing for thermal capacity alone is insufficient, as systems often reach saturation points where further hardware investment yields negligible efficiency gains.
- **Framework Applicability:** The framework and its elements has proven to be able to provide a solid basis for TES selection, integration, and operation. However, as the case study has shown, TES implementation is very case specific, where every TES technology, medium, and heat source are major influential factors on a systemic level.

5.2.3 Flexibility and Adaptability

The entire simulation model architecture allows for personalized and transferable inputs, ensuring the framework remains adaptable rather than rigid. Users can define specific building characteristics and control strategies as variables within the simulation. While the architecture is primarily energy-based, it incorporates some essential hydraulic constraints, providing a versatile tool that can be tailored to various architectural configurations and operational requirements.

6 Limitations and Recommendations

6.1 Limitations

This research acknowledges several constraints that affect the scalability and precision of the findings. Since this thesis is comprised of two parts: the general TES framework and the case study, the limitations for each part will be addressed.

6.1.1 General TES Framework

The broader applicability of this research is constrained by a primary focus on energy management. This thesis offers a generalized understanding of Thermal Energy Storage utility, yet it does not account for the extensive variability in specific system designs. The case study does include a transient thermal analysis but is mostly based on sensible heat storage and not other forms of TES.

As each system presents unique inherent challenges, the general TES framework approaches energy treatment from a more macro-management perspective rather than exploring the internal fluid dynamics or local thermodynamic processes. Therefore, actual integration, design, and control strategies will vary significantly depending on the defined system boundaries.

Lastly, the developed framework is inherently biased toward sensible storage, particularly buffer tanks. Even though the general TES framework is kept as broad as possible, the implementation logic is partly derived from the operational characteristics of sensible TES.

6.1.2 Case Study

Single-node Energy Bucket

Concerning the storage medium, the buffer tank is modelled as a single, perfectly mixed node. By failing to track temperature stratification layers within the volume, the model loses the ability to account for the actual state of charge gradients. Therefore the real exergy inside the tank is not precisely known. Not as accurate, but a way to account for this lack of information, a total efficiency factor (ϵ), comprised of a stratification efficiency factor and a dead zone volume, is applied.

Atrium Air Temperature Gradient

Regarding the spatial modelling of the building, the atrium (zone 2) is presented as a single zone with a uniform temperature. The development of thermal stratification temperature layers is neglected. In reality, large vertical spaces typically exhibit significant temperature layering due to buoyancy effects.

Originally, the UFH system was designed to only heat or cool the lower 3 meters for occupants, and leave the upper air temperatures free-floating within the set temperature boundaries. However, the simulation model explores the UFH system as an active TES system pre-charging the atrium as a buffer for the cascaded air strategy as well as internal heat exchange between zones. Moreover, modelling thermal stratification within the atrium would necessitate live-tracking of temperature gradients at each time-step of the simulation. Because the zones receiving cascaded air are located at varying elevation (floors), their supply air temperature is fundamentally dependent on the atrium's local air temperature at that specific height.

Emitter Dynamics and Thermal Inertia

A further limitation of the model lies in the assumed thermal coupling between the emitters and the room air. The simulation calculates temperature drift based on the global thermal mass of the building's construction. However, it implicitly assumes that air temperature follows the same cooling curve of this thermal mass.

In reality, convective air-based systems (AHUs, VAV units, FCUs) have negligible thermal inertia. This means that when these systems are deactivated, the indoor air temperature often experiences a rapid decline due to infiltration and convection, even while the structural mass remains warm. By

failing to differentiate between the rapid thermal decay of air-supplied zones and the sustained radiant output of structural mass, the model may overestimate the effective temperature drift duration of the indoor environment. This would lead to an overly optimistic assessment of energy savings achievable through the allowed temperature swing in the control strategy.

Heat Pump Configuration

Finally, this model assumes a dedicated heat pump for both the hot and cold storage tanks, with each unit operating exclusively within its assigned circuit. However, in reality, many systems utilize heat pumps in a parallel configuration, allowing for greater operational flexibility. In such configurations, heat pumps are not strictly bound to a single tank, but instead they can be dynamically reassigned to either heating or cooling based on real-time demand.

By treating the capacity as a fixed, isolated constraint, the model may underestimate the system's true potential. In reality, both units could theoretically switch heating or cooling mode to address a surge in demand in the opposing circuit. This would effectively sacrifice the performance of their "dedicated" tank to mitigate a more critical deficit elsewhere. Failing to account for this parallel flexibility, where the heat pumps can work together to prioritize the highest thermal demand, results in a conservative estimation of the system's maximum output. This may limit the model's ability to accurately represent how real-world systems respond to grid congestion or significant shifts in peak demand.

Moreover, if both heat pumps enter the same mode, supplying the same tank with energy, instead of one tank operating at max capacity and the other heat pump supplying only the extra additional required energy, they can spread the thermal load equally. This would lead to both heat pumps running at a lower capacity which is more efficient and less mechanical stress on the systems.

6.2 Recommendations

Future research would mainly aim to advance the robustness and applicability of the proposed methodology by directly addressing the limitations identified in both the general TES framework and the case study. The following recommendations are structured to bridge the gap between global energy management and high-fidelity physical modelling. This would ensure that future iterations improve upon current simplifications regarding system dynamics, thermal coupling, and operational control. By targeting these current constraints, the following recommendations provide a path toward refining the accuracy and real-world application possibilities of the thermal energy storage implementation framework.

6.2.1 Live-link Between Simulations

An improvement for accuracy in the simulation models would be transitioning from the current sequential, CSV-based data exchange to a high-fidelity, bidirectional coupling between the building performance model (multi-zone model) and the thermal storage controller (TES Simulation Engine). In the current workflow, the TES model operates on pre-calculated, fixed load profiles, preventing the system from accounting for the transient interactions between building physics and control actions. By establishing a live, real-time link, the simulation can accurately capture the net thermal demand.

This live-link would be able to dynamically update heat losses as a result of the allowed temperature drifts inside the Simulation Engine. Moreover, climate strategies like: natural ventilation, active sun shading, and free-floating thermal boundaries would be possible inside the multi-zone model. This is not possible in the current architecture because the Simulation Engine requires a fixed reference set-point temperature for all time-steps, in order to prevent the double accounting of thermal mass usage. The case study specifically bases its HVAC sizing without these climate strategies, however, most other buildings would utilise them to reduce thermal demand.

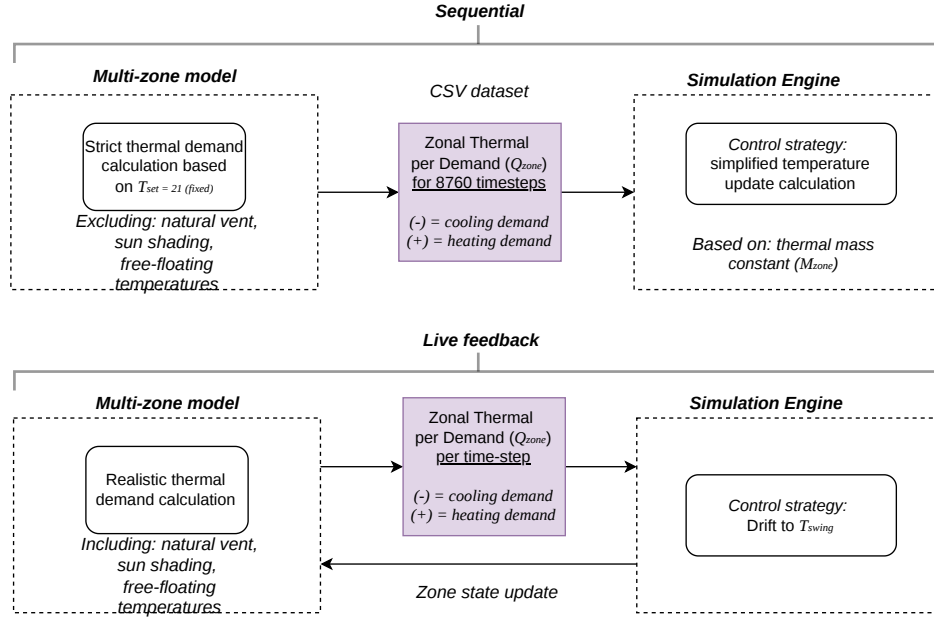


Figure 80: Flowchart: data exchange

Schematic illustration of offline versus online model.

This integration ensures the Simulation Engine possesses precise, step-by-step awareness of both the interior temperature and the active thermal load at the moment of HVAC engagement, thereby correcting for the inaccuracies inherent in static, decoupled estimations. The reason this was not done in the first place is because of time constraints and computational power, since this live-link would perform more calculations per time-step.

6.2.2 System Energy Conversion and Operational Constraints

The current simulation uses a simple formula for heat transfer for its emitters, $Q_{delivered,i} = UA \cdot \Delta T_i$, where the temperature difference is just the gap between the incoming air and the target room temperature. It also uses a fixed UA value of 0.5 kW/K for every zone. This approach is not fully accurate because it ignores the fact that different emitter units (like fan coils, VAV units, and AHUs) have their own unique specifications and performance limits. Furthermore, heat transfer is more realistically calculated using the Log Mean Temperature Difference (ΔT_{lm}) rather than a basic temperature difference.

To make the research more realistic, future models should replace these general assumptions with more exact system specs and calculations. By using the ΔT_{lm} method and applying specific UA values for different pieces of equipment, the model can better reflect how these systems actually work. This allows for a much more accurate picture of how these emitters interact with changing air temperatures, giving a clearer understanding of how the equipment performs in real-world conditions. More accurate modelling will also reflect a more accurate (realistic) demand per time-step, since its a direct result of these systems.

6.2.3 Heat Pump COP

By transitioning from a theoretical Lorentz-based COP to performance-based COP curves, real-world heat pump operation and efficiency is achieved. The current approach relies on an idealized thermodynamic limit (although capped), which inherently overestimates efficiency by omitting the non-linear operational losses and part-load penalties experienced by real hardware.

Instead of relying on theoretical formulas to calculate heat pump efficiency, future models should use real-world performance data from manufacturers. Heat pumps don't run at perfect theoretical limits, since their efficiency changes depending on the workload and the weather. By using actual performance

curves, the model can account for how the equipment really behaves, which gives a much more accurate picture of energy consumption and system performance.

6.2.4 Heat Pump Dual Mode

To move beyond the current assumption of isolated heat pump operation, future research should implement a parallel configuration where heat pumps are dynamically reassigned between hot and cold circuits based on real-time demand. This implementation can effectively mimic a dual-mode heat pump setup by allowing units to switch modes or collaborate to satisfy a high-priority thermal deficit. Specifically, when demand in one circuit becomes critical, the control logic should permit a heat pump to pivot from its dedicated tank to assist the other, effectively doubling the available thermal capacity. This increase in available thermal capacity will ultimately result in a smaller required TES tank, because the energy deficit will be smaller when the heat pump thermal supply is increased. This solution prevents the need for a higher rated capacity heat pump.

To maintain model simplicity without requiring the complexity of modelling internal thermal stratification, this flexibility can be governed by a "drift penalty" rule. When a heat pump is reassigned to assist the opposing circuit, the tank left behind experiences a pre-defined energy reduction based on the duration of no supply/maintenance. This penalty represents the thermal degradation and temperature drift that occurs during the period of non-supply. This approach allows the framework to capture the operational benefits of load-sharing, such as increased total system output and improved efficiency from reduced part-load stress, without the need for high-fidelity fluid dynamic modelling.

6.2.5 Advanced Optimization

To build upon this research, future work could focus on refining control logic and expanding the simulation environment. Investigating advanced optimization methods, such as Genetic Algorithms, could identify the smallest storage volumes that standard linear programming might overlook, potentially revealing opportunities to reduce tank sizes without violating occupant thermal comfort.

Furthermore, testing alternative control architectures like Reinforcement Learning alongside higher-fidelity building physics would allow for a more rigorous assessment of system resilience. This would help determine whether a smaller physical storage footprint can remain reliable during peak demand periods without compromising performance.

Declarations

Google Gemini (Google, Mountain View, CA; version accessed May 28, 2026) was utilised as an assistive tool throughout the research and development process. Specifically, Gemini was employed for:

- **Technical Implementation:** Assisting in the development and debugging of Python code.
- **Visual Content Generation:** Generating conceptual diagrams and illustrations for [mention specific figures].
- **Editorial Refinement:** Enhancing text clarity, grammar checks across the paper, and LaTeX conversion code for tables and text.

All AI-generated outputs, including code segments and images, were independently reviewed, tested, and verified to ensure scientific accuracy, technical integrity, and adherence to ethical standards.

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A Appendix - Technical and Economic Specifications

The International Energy Agency organization provides an estimation regarding energy densities and installed cost specifications. Listed below are those specifications for four thermal energy storage types.

Table 29: SHS - Water

Specific energy storage density	kWh/m ³	kWh/t
	70–150	50–100
Specific power density	kW/m ³	kW/t
	20–40	15–25
Feasible storage size	MWh _{th}	MW _{th}
	1–1,000	n.a.
Storage efficiency	98 %	
Storage duration	Hours–days	
Service life (max)	> 10,000 cyc	> 20 yrs
Loss per time	2–4% of capacity / 24h	

Table 30: SHS -Solids

Specific energy storage density	kWh/m ³	kWh/t
	60–100	60–100
Specific power density	kW/m ³	kW/t
	30–500	30–500
Feasible storage size	MWh _{out}	MW _{out}
	0.03–1,000	0.015–1
Storage efficiency	50–90 %	
Storage duration	Hours–months	
Service life (max)	20–4,000 cyc	n.a.
Loss per time	0.5 to 2.5 per day	

Table 31: LHS - Low-temperature (PCM)

Specific energy storage density	kWh/m ³	kWh/t
	80–110	40–110
Specific power density	kW/m ³	kW/t
	15–250	10–175
Feasible storage size	MWh _{out}	MW _{out}
	0.1–2.5	0.01–0.22
Storage efficiency	60–98 %	
Storage duration	Minutes–weeks	
Response time	Minutes	
Service life (max)	3,500–10,000	n.a.
Loss per time	Dep. on conditions	

Table 32: THS - Sorption

Specific energy storage density	kWh/m ³	kWh/t
	120–250	85–175
Specific power density	kW/m ³	kW/t
	35–85	25–75
Feasible storage size	kWh _{out}	kW _{out}
	2,000–4,000	200/1,000
Storage efficiency	–	
Storage duration	Hours–months (mostly days)	
Response time	Minutes–hours	
Service life (max)	3,500 (proven)	–
Loss per time	Max. 15 %	

Fact sheets data. Adapted from International Energy Agency, (z.d).

Notes on Technical Specifications per table:

- *Table 29: The technical specifications depend strongly on the actual application's boundary conditions. Also, due to the very wide volume range of sensitive storage tanks (several liters to 10,000 m³), figures vary widely. The first figure in each given range corresponds to a typical domestic water storage with a volume of 500 l and a discharge pump rated at 500 l/hour. The second figures correspond to a seasonal large-scale storage with a water volume of 10,000 m³ and a discharge pumping capacity of 5 m³/h. 1 cycle per 2 days (domestic) or 1 cycle per year (seasonal) is assumed. Both storage are assumed to be pressure less, therefore their maximum storage temperature is 100 °C, the usable temperature difference about 60–100 K. Losses per time depend on insulation thickness, thermal conductivity, and surface-to-volume ratio. Typically, a domestic storage loses about 2 K/day, a seasonal one about 10 K/month.*

- **Economic specifications:**
 - Investment cost per kW: 1-15 €
 - Investment cost per kWh: 0.4 - 10 €
- *Table 30: -*
 - **Economic specifications:**
 - Investment cost per kW: Depends on application
 - Investment cost per kWh: 20-70 €/kWhth
 - Operating and maintenance cost (based on investment/kW and kWh): About 1% of overall investment per year
- *Table 31: The specific performance of latent heat storage may be significantly increased through appropriate measures. Current research indicates that 250-450 kW/m³ (or 160-250 kW/t) may be achieved. Such high-performance storage units would tend to be used for minute to day storage.*
 - **Economic specifications:**
 - Investment cost per kW: 100-150 € per 6 h of storage
 - Investment cost per kWh: 15-40 €
 - Operating and maintenance cost (based on investment/kWhth): 1% of overall investment per year
- *Table 32: The efficiency of sorption storage can exceed 100%, as such systems may thermodynamically be considered as heat pumps. In this sense, they store the ability to raise heat from an unusable temperature level (whose energy is not included in the efficiency balance) to a usable one. The loss rate ranges around 15%, which corresponds to the sensible share of the stored heat. The speed at which it is lost depends on the quality of the insulation. Thereafter, the system stops losing heat until the reaction partners are brought back together.*
 - **Economic specifications:**
 - Investment cost per kW: 500 €
 - Investment cost per kWh: 30-130 €
 - Cost of energy provided in concrete applications: A mobile sorption storage unit containing zeolite was developed and built to recover exhaust heat from a waste incineration plant. The container can store up to 4 MWh of energy. The cost of the heat provided is about 75 €/MWh. This cost estimate is based on an assumed 200 cycles per year.

B Appendix - Simulation Results Overview

The following tables present the transient performance data derived from the simulation framework. Each table summarizes key metrics for the peak energy deficit ($E_{max,gap}$), the duration of the identified thermal deficit, and the total required storage capacity. These results display the high-resolution output of the simulation per climatization zone, demonstrating the control strategies.

The presented data serves to validate the system's ability to maintain thermal comfort while adhering to hydraulic and power availability constraints across varying demand profiles. The tables are the results of the simulation ran for the dynamic schedule TES integrated simulation with rated capacities of 115 kW for heating and 65 kW for cooling. Time-steps where supply is lower than demand is highlighted in blue. The red colour highlights the time-step where the peak net flow from the tank is highest.

B.1 Heating Results V_C

Sim_Timestep	Total_Demand_kW	Total_Demand_C_kW	Max_Supply_kW	HP_Out_kW	Tank_util%	Deficit_kW	Window_h	Tot_TES	Demand_21_kW	Temp_21	Tot_21_h	Flow_21_m3/h	Demand_22_kW	Temp_22	Tot_22_h	Flow_22_m3/h	Demand_23_kW	Temp_23	Tot_23_h	Flow_23_m3/h	Demand_24_kW	Temp_24	Tot_24_h	Flow_24_m3/h	Demand_25_kW	Temp_25	Tot_25_h	Flow_25_m3/h	Strategy	Net_Power_Deficit_kW	Net_Flow_m3/h		
101	112.20	0	112.24	122.87	0	0	0	0.00	10.90	21.0	0	0.70	10.90	22.0	0	1.10	10.90	23.0	0	1.40	10.90	24.0	0	1.80	10.90	25.0	0	1.90	10.90	0	1.90	0.00	
102	84.20	0	84.84	84.84	122.87	0	0	0	11.50	20.96	0	0.70	10.90	22.0	0	2.00	11.50	20.96	0	0.30	21.80	20.96	0	1.40	10.90	20.96	0	1.40	10.90	12.70	1.50	0.00	
103	100.00	0	112.74	122.74	122.77	0	0	0	0.00	20.90	22.0	0	2.00	11.50	20.96	0	2.00	21.80	20.96	0	0.30	21.80	20.96	0	1.40	10.90	20.96	0	1.40	10.90	12.70	1.50	0.00
104	82.00	0	72.16	72.16	0.79	0	0	0	11.30	20.90	0	0.66	10.70	22.0	0	2.47	11.30	20.90	0	0.19	21.50	20.90	0	1.43	10.90	20.96	0	1.40	10.90	9.40	0.00	0.00	
105	140.00	0	72.45	72.45	0.12	0	0	0	11.90	20.87	0	0.66	10.70	22.0	0	2.60	11.90	20.87	0	0.34	21.90	20.87	0	1.42	10.90	20.96	0	1.40	10.90	10.50	0.00	0.00	
106	115.00	0	115	115	0.03	0	0	0	10.50	20.87	0	1.00	10.50	22.0	0	1.00	10.50	20.87	0	2.00	11.50	20.87	0	1.84	10.90	20.95	0	1.84	10.90	8.50	0.00	0.00	
107	103.00	0	115	115	0.03	0	0.09	1.49	24.70	20.81	0.08	2.33	18	22	0	1.05	24	20.87	0.08	2.16	21.20	20.80	0.08	2.22	10.70	20.86	0.44	1.64	10.90	0	0	0.00	
108	100.00	0	115	115	0.03	0	0.09	1.96	14.40	20.76	2.18	1.36	17.00	22	0	1.10	17.00	20.76	1.36	2.10	21.10	20.70	2.18	2.22	10.80	20.84	2.16	1.65	10.90	0	0	0.00	
109	103.00	0	115	115	0.03	0	0.07	1.84	14.70	21.00	1.12	2.30	18	22	0	1.05	24	21.00	1.12	2.16	21.20	21.00	1.12	2.22	10.70	21.00	1.12	1.64	10.90	0	0	0.00	
110	104.00	0	115	115	0.04	0	0.06	1.80	14.90	21.10	1.10	2.10	18.00	22	0	1.10	24.10	21.10	1.10	2.40	21.40	21.10	1.10	1.80	10.80	21.10	1.10	1.17	10.90	0	0	0.00	
111	104.00	0	115	115	0.07	0	0.05	0.87	14.90	21	0	2.14	18.00	22	0	1.30	24.10	21	0	2.08	21.40	21	0	1.84	10.80	21	0	1.36	10.90	0	0	0.00	

Figure 81: Full tank cycle for heating based on V_C

Results from the Simulation Engine.

B.2 Heating Results V_H

Sim_Timestep	Total_Demand_kW	Max_Demand_C_kW	Max_Supply_kW	HP_Out_kW	Tank_util%	Deficit_kW	Window_h	Tot_TES	Demand_21_kW	Temp_21	Tot_21_h	Flow_21_m3/h	Demand_22_kW	Temp_22	Tot_22_h	Flow_22_m3/h	Demand_23_kW	Temp_23	Tot_23_h	Flow_23_m3/h	Demand_24_kW	Temp_24	Tot_24_h	Flow_24_m3/h	Demand_25_kW	Temp_25	Tot_25_h	Flow_25_m3/h	Strategy	Net_Power_Deficit_kW	Net_Flow_m3/h	
101	112.20	0	112.74	122.87	0	0	0	0.00	10.90	21.0	0	0.70	10.90	22.0	0	1.10	10.90	23.0	0	1.40	10.90	24.0	0	1.80	10.90	25.0	0	1.90	10.90	0	1.90	0.00
102	84.20	0	84.84	84.84	122.87	0	0	0	11.50	20.96	0	0.70	10.90	22.0	0	2.00	11.50	20.96	0	0.30	21.80	20.96	0	1.40	10.90	20.96	0	1.40	10.90	12.70	1.50	
103	100.00	0	112.74	122.74	122.77	0	0	0	0.00	20.90	22.0	0	2.00	11.50	20.96	0	2.00	21.80	20.96	0	0.30	21.80	20.96	0	1.40	10.90	20.96	0	1.40	10.90	12.70	1.50
104	82.00	0	72.16	72.16	0.79	0	0	0	11.30	20.90	0	0.66	10.70	22.0	0	2.47	11.30	20.90	0	0.19	21.50	20.90	0	1.43	10.90	20.96	0	1.40	10.90	9.40	0.00	

Figure 82: Hydraulic check volume based on peak net flow V_H

Results from the Simulation Engine.

B.3 Cooling Results V_C

Sim_Timestep	Total_Demand_kW	Total_Demand_C_kW	Max_Supply_kW	HP_Out_kW	Tank_util%	Deficit_kW	Window_h	Tot_TES	Demand_21_kW	Temp_21	Tot_21_h	Flow_21_m3/h	Demand_22_kW	Temp_22	Tot_22_h	Flow_22_m3/h	Demand_23_kW	Temp_23	Tot_23_h	Flow_23_m3/h	Demand_24_kW	Temp_24	Tot_24_h	Flow_24_m3/h	Demand_25_kW	Temp_25	Tot_25_h	Flow_25_m3/h	Strategy	Net_Power_Deficit_kW	Net_Flow_m3/h
4002	0	65	65	65	21.16	0	0	0	13.07	21.06	0	1.40	0	22	0	0	13.00	21.00	0	1.10	10.50	21.00	0	1.47	17	21.06	0	1.40	10.90	1	0.11
4003	0	10.40	65	65	21.16	0	0	0	13.00	21.03	0	1.40	0	22	0	0	13.00	21.03	0	1.43	10.50	21.03	0	1.40	10.40	21.03	0	1.47	10.90	1	0.00
4004	0	10.40	65	65	21.16	0	0	0	14.70	21.07	0	1.25	0	22	0	0	14.20	21.08	0	1.05	10.30	21.08	0	1.10	11.90	21.08	0	1.40	10.90	17.60	1.00
4005	0	10.40	65	65	21.16	0	0	0	15	21.11	0	1.25	0	22	0	0	14.60	21.14	0	1.05	11.90	21.14	0	1.10	11.90	21.14	0	1.40	10.90	18.90	1.14
4006	0	100.10	65	65	21.16	0	0	0	10.50	21.10	0	1.17	0	22	0	0	10.40	21.10	0	1.11	10.90	21.10	0	1.40	10.40	21.10	0	1.40	10.90	48.10	0.10
4007	0	100.10	65	65	21.16	0	0	0	33	21.17	0	0.20	0	22	0	0	30.20	21.17	0	1.71	10.50	21.16	0	1.87	10.40	21.17	0	1.17	10.90	18.90	0.10
4008	0	10.70	65	65	21.16	0	0	0	10.50	21.05	0	1.00	0	22	0	0	10.50	21.05	0	1.01	11.90	21.05	0	1.10	11.90	21.05	0	1.40	10.90	17.50	1.00
4009	0	10.60	65	65	21.16	0	0	0	10.60	21.16	0	0.96	0	22	0	0	10.30	21.17	0	1.14	12.50	21.16	0	1.11	6.80	21.16	0	0.67	10.90	18.60	0.60
4010	0	111.00	65	65	21.16	0	0	0	0.70	22.18	0	0.40	0	22	0	0	44.40	22.09	0	2.00	4.10	22.05	0	0.90	10.20	22.05	0	0.60	10.90	48.60	0.60
4011	0	110.40	65	65	21.16	0	0	0	10.50	22.14	0	0	0	22	0	0	41.20	22.07	0	2.06	4.10	22.17	0	0.10	1.90	22.14	0	0.12	10.90	18.40	0.12
4012	0	107.34	65	65	21.16	0	0	0	53	22.05	0	0.05	0	22	0	0	40.00	22.03	0	2.40	2.90	22.06	0	0.21	0.80	22.14	0	0.06	10.90	12.30	1.08
4013	0	106.24	65	65	21.03	0	0	0	10.50	22	0	0.40	0	22	0	0	39.40	22.11	0	2.40	2.90	22.09	0	0.19	0.80	22.14	0	0.06	10.90	12.10	1.12
4014	0	106.91	65	65	21.03	0	0	0	45.90	22	0	4.08	0	22	0	0	22.40	22.27	0	1.87	1.80	21.55	0	1.00	12.40	21.51	0	0.61	10.90	12.60	1.22
4015	0	10.40	65	65	21.02	0	18	0.40	14.50	21.06	4.10	0.90	0	22	0	0	14.20	21.03	4.10	2.40	6.40	21.43	1.60	1.27	0	21.42	1.60	0.37	10.90	0	0
4016	0.40	31.50	65	65	21.02	0	18	0.43	12.70	22.03	3.78	0.70	0	22	0	0	14.20	22.03	0.60	2.43	6.40	21.43	1.60	1.27	0	21.42	1.60	0.37	10.90	0	0
4017	1	22.20	65	65	21.02	0	17	0.36	11.30	22.05	2.83	0.90	0	22	0	0	10.80	22.01	2.40	2.83	0	21.30	1.11	0.74	0	21.34	0.70	0.47	10.90	0	0
4018	1.10	10.80	65	65	21.02	0	16	0.47	10.10	21.05	2.84	1.00	0	22	0	0	9.80	21.00	1.00	2.80	0	21.10	0.87	0.70	0	21.17	0.51	0.40	10.90	0	0
4019	1.00	8.80	65	65	21.02	0	15	0.39	8.80	21.48	1.18	1.23	0	22	0	0	9	21.43	1.22	2.18	0	21.10	0.84	0.98	0	21.17	0.34	0.61	10.90	0	0
4020	2.20	7.70	65	65	21.02	0	14	0.17	7.70	21.10	0.81	1.00	0	22	0	0	9	21.10	0.77	2.11	0	21.00	0.74	0.80	0	21.08	0.11	0.63	10.90	0	0
4021	0.50	14.60	65	65	21.04	0	13	0.42	7.50	21	0.40	2.60	0	22	0	0	7.10	21	0.30	2.10	0	21	0.37	0.70	0	21	0.11	0.49	10.90	0	0
4022	0	16.70	65	65	21.06	0	12	0.45	6.40	21	0	0.60	0	22	0	0	6	21	0	0.88	5.40	21	0	0.08	4.80	21	0	0.10	10.90	0	0

Figure 83: Full tank cycle for cooling based on V_C

Results from the Simulation Engine.

B.4 Cooling Results V_H

Sim_Timestep	Total_Demand_kW	HP_Total_Demand_kW	Max_Supply_kW	HP_Out_kW	Tank_util%	Deficit_kW	Window_h	Tot_TES	Demand_21_kW	Temp_21	Tot_21_h	Flow_21_m3/h	Demand_22_kW	Temp_22	Tot_22_h	Flow_22_m3/h	Demand_23_kW	Temp_23	Tot_23_h	Flow_23_m3/h	Demand_24_kW	Temp_24	Tot_24_h	Flow_24_m3/h	Demand_25_kW	Temp_25	Tot_25_h	Flow_25_m3/h	Strategy	Net_Power_Deficit_kW	Net_Flow_m3/h
4170	0	10.60	65	65	21.16	0	0	0	11.40	21.16	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4171	0	10.60	65	65	21.16	0	0	0	10.50	21.10	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4172	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4173	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4174	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4175	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4176	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4177	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4178	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4179	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4180	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4181	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4182	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4183	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4184	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4185	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4186	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4187	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4188	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4189	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4190	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4191	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4192	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4193	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4194	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4195	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4196	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4197	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4198	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4199	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10
4200	0	11.60	65	65	21.16	0	0	0	10.50	22.67	0	1.10	0	22	0	0	10	21.20	0	2.10	0.70	21.06	0	0.27	1.90	21.05	0	0.11	10.90	11.60	1.10

B.5 Annual Demand Overview

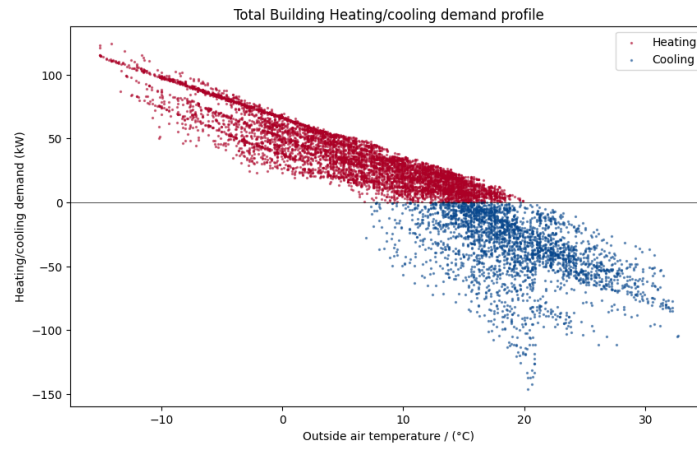


Figure 85: Yearly demands plotted against outside temperature
Results from the Simulation Engine.

B.6 Annual Temperatures per Zone

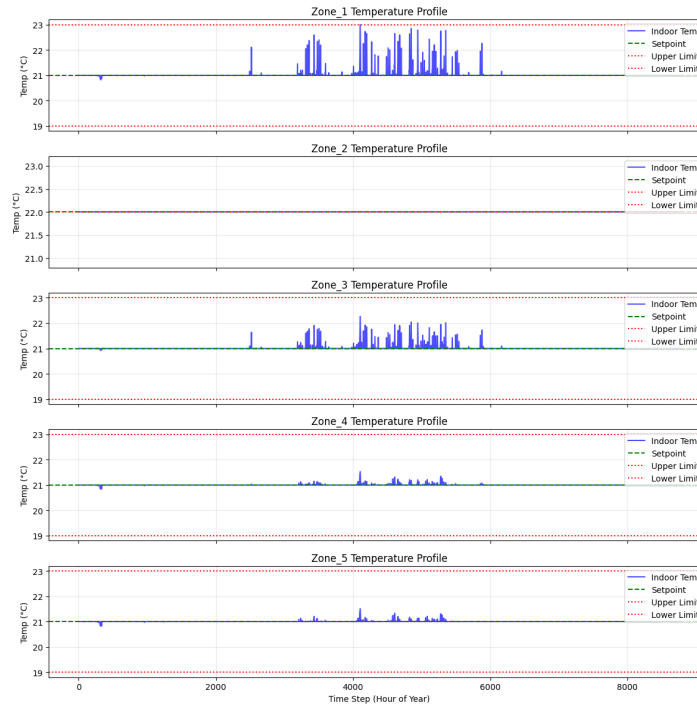


Figure 86: Fluctuating zone temperatures plotted against the time-steps (8760 hours)
Results from the Simulation Engine.

C Appendix - Transient First-order Lumped Capacitance Model

The multi-zone model in this thesis is developed by building upon the foundational principles of the simplified, one-zone thermal model detailed in the provided documentation. The core methodology utilizes a one-node approach, where the combined thermal storage capacity of the building—including air volume, furniture, and internal components—is represented by a single node to estimate the indoor temperature.

By transitioning from this baseline one-zone framework to a multi-zone configuration, the model facilitates a more in-depth analysis of thermal interactions between zones while maintaining the rigorous thermodynamic balance of energy flows, such as transmission, ventilation, infiltration, and internal heat gains. This approach allows for a structured, physics-based assessment of building performance, ensuring that design choices are evaluated against realistic transient conditions.

C.1 Theoretical Background

The following methodology is property of the TU Delft and is created by one of the supervisors of this thesis: Willem van der Spoel, head of department of building physical at the Faculty of Architecture and the Built Environment.

Determining the heating and cooling requirements for a building involves an inventory of all sensible heat flows. While latent heat can be significant, this model focuses exclusively on sensible heat. The system is defined as a building or room bounded by the external surfaces of the walls, roof, and ground floor. The energy balance considers six primary heat flows: transmission, ventilation, infiltration, solar gains, internal gains, and thermal accumulation.

C.1.1 Heat Balance Components

- **Transmission:** Heat transfer through external envelopes due to temperature gradients.

$$Q_{tr,e}(t) = U_e A (T_e(t) - T_i(t)) \quad (52)$$

For the ground floor, heat flow is estimated using a constant ground temperature (T_{gr}):

$$Q_{tr,gr}(t) = U_{gr} A (T_{gr}(t) - T_i(t)) \quad (53)$$

- **Ventilation and Infiltration:** Sensible heat exchange from intentional air supply and unintentional leakage.

$$Q_{vent}(t) = (1 - \eta) \dot{m}_{vent} c_a (T_e(t) - T_i(t)) \quad (54)$$

$$Q_{inf}(t) = \dot{m}_{inf} c_a (T_e(t) - T_i(t)) \quad (55)$$

- **Solar Gains:** Radiation enters through glazing and is absorbed by internal mass.

$$Q_{i,sol,gl}(t) = g_{gl}g_{sh}A_{gl}q_{sol,e}(t) \quad (56)$$

For opaque surfaces, solar absorption increases the surface temperature, resulting in transmitted heat:

$$Q_{i,sol,op}(t) = U_c A \frac{a_{sol} q_{sol}(t)}{\alpha_e} \quad (57)$$

- **Internal Gains:** Heat generated by occupants (approx. 65 W/pp), appliances, and lighting.

C.1.2 Thermal Storage and Balance

A one-node model represents the thermal mass (M) of the room, assuming all internal capacity is concentrated at a single operative temperature (T_i). The balance equation is defined as:

$$M \frac{dT_i(t)}{dt} + Q_e(t) + Q_i(t) + Q_{h/c}(t) = 0 \quad (58)$$

Where M is the sum of component masses and specific heat capacities:

$$M = \sum m_n c_n \quad (59)$$

To simplify, heat flows dependent on external temperatures are bundled into a single term (H_e):

$$H_e = \sum U_e A + (1 - \eta) \dot{m}_{vent} c_a + \dot{m}_{inf} c_a \quad (60)$$

This one-node simplification allows for transient temperature calculations by assuming environmental conditions remain constant over a discrete time-step Δt , enabling the derivation of indoor temperature development over time.

C.1.3 Transient Temperature Calculation

The heat balance is solved as a differential equation to determine the indoor temperature development over time. By assuming that external conditions (T_e and T_{gr}) remain constant over a discrete time-step Δt , the governing equation becomes:

$$M \frac{dT_i(t')}{dt'} + (H_e + H_{gr}) T_i(t') = Q_{total}(t) \quad (61)$$

Where $Q_{total}(t)$ aggregates internal gains (Q_i) and heating/cooling power ($Q_{h/c}$). The exact solution for the indoor temperature at the end of the time-step ($t + \Delta t$) is:

$$T_i(t + \Delta t) = T_{i,eq} + (T_i(t) - T_{i,eq}) \cdot \exp\left(-\frac{H_e + H_{gr}}{M} \Delta t\right) \quad (62)$$

In this expression, $T_{i,eq}$ represents the steady-state equilibrium temperature that the zone would reach as $t \rightarrow \infty$:

$$T_{i,eq} = \frac{Q_i + Q_{h/c} + H_e T_e + H_{gr} T_{gr}}{H_e + H_{gr}} \quad (63)$$

C.1.4 Thermostat Control Logic

The simulation incorporates a control loop to maintain indoor temperatures between defined set-points ($T_{set,h}$ for heating and $T_{set,c}$ for cooling). Within each time-step, the model assesses three operational states to determine the required power ($Q_{h/c}$):

1. **Controlled response:** When the target temperature is reached within Δt , the system modulates output to maintain T_{set} , and power is derived by solving for $Q_{h/c}$ in the balance equation.
2. **Capacity constrained:** When the capacity is insufficient to reach T_{set} within Δt , the unit operates at maximum output ($Q_{h/c,max}$), and the resulting temperature is calculated using the transient solution.
3. **Free-floating:** When the indoor temperature remains within the deadband ($T_{set,h} < T_i < T_{set,c}$), no active conditioning is required.

In the Excel tool (of the one-zone model), the following workflow is used at each time-step:

1. Pre-calculate inside temperature $T(t + \Delta t)$ for four situations:
 - a. No heating and no cooling with $H_{e,heat}$, denoted as $T(t + \Delta t)_{free,heat}$ (free floating)
 - b. No heating and no cooling with $H_{e,cool}$, denoted as $T(t + \Delta t)_{free,cool}$ (free floating)
 - c. Maximum heating capacity with $H_{e,heat}$, denoted as $T(t + \Delta t)_{heat}$
 - d. Maximum cooling capacity with $H_{e,cool}$, denoted as $T(t + \Delta t)_{cool}$
2. The actual inside temperature $T(t + \Delta t)$ is chosen according to the following flow of logic:

```

If  $T(t + \Delta t)_{heat} < T_{set,h}$  then  $T(t + \Delta t) = T(t + \Delta t)_{heat}$ ,  $Q_h = Q_{h,max}$  else
If  $T(t + \Delta t)_{heat} > T_{set,h}$  and  $T(t + \Delta t)_{free,heat} < T_{set,h}$  then  $T(t + \Delta t) = T_{set,h}$  (calculate  $Q_h$ ) else
If  $T(t + \Delta t)_{free,heat} > T_{set,h}$  and  $T(t + \Delta t)_{free,heat} < T_{set,v}$  then  $T(t + \Delta t) = T(t + \Delta t)_{free,heat}$ ,  $Q_h = Q_c = 0$  else
If  $T(t + \Delta t)_{free,heat} > T_{set,v}$  and  $T(t + \Delta t)_{free,cool} < T_{set,v}$  then  $T(t + \Delta t) = T_{set,v}$ ,  $Q_h = Q_c = 0$  else
If  $T(t + \Delta t)_{free,cool} > T_{set,v}$  and  $T(t + \Delta t)_{free,cool} < T_{set,c}$  then  $T(t + \Delta t) = T(t + \Delta t)_{free,cool}$ ,  $Q_h = Q_c = 0$  else
If  $T(t + \Delta t)_{cool} < T_{set,c}$  and  $T(t + \Delta t)_{free,cool} > T_{set,c}$  then  $T(t + \Delta t) = T_{set,c}$  (calculate  $Q_c$ ) else
If  $T(t + \Delta t)_{cool} > T_{set,c}$  then  $T(t + \Delta t) = T(t + \Delta t)_{cool}$ ,  $Q_c = Q_{c,max}$ 

```

The model performs a predictive check for each hour, evaluating four scenarios-free-floating heating, free-floating cooling, maximum heating, and maximum cooling—to select the appropriate state and ensure set-point compliance. This logic accounts for ventilative cooling via the window opening set-point ($T_{set,v}$), dynamically adjusting H_e based on the operational mode.

D Appendix - Multi-zone Model

This section will cover the complete Python code for the multi-zone thermal network model that was used in this thesis. This section will cover the complete Python code for the multi-zone thermal network model that was used in this thesis. This version does not include the Grid Search or MPC methodology, which are executed by an external master engine script and are considered outside the scope of this core model documentation. The code is divided into sections to get a clear overview.

The ZoneModel class serves as the fundamental computational unit of the simulation, encapsulating the thermodynamic state and energy dynamics of an individual zone. The Orchestrator acts as the high-level manager, instantiating this class to create a scalable array of independent zone models. By maintaining a collection of these objects, the Orchestrator effectively decouples local zone physics from global system constraints.

D.1 Zone Model Class

During each simulation time step, the Orchestrator sequences the execution of these models, passing aggregate boundary conditions (such as external temperature, solar gains, and shared HVAC supply) to each ZoneModel instance. It then collects the resulting thermal loads and indoor temperatures from every zone, computing the necessary system-level heating or cooling demand. This architecture allows the Orchestrator to solve the global energy balance while delegating the complex, zone-specific transient heat transfer calculations to the individual ZoneModel class.

D.1.1 Zone Model Initialisation

The ZoneModel class serves as the localized engine for thermal simulation, encapsulating all physical and operational parameters required to compute the transient response of a single space. By utilizing a dictionary-based kwargs unpacking strategy, the orchestrator passes a comprehensive suite of inputs including geometry, thermal properties, internal gain profiles, and HVAC system constraints into each instance. During initialization, the model calculates derived constants such as total thermal capacity and initializes internal surface structures, ensuring that each zone maintains a consistent state while remaining flexible enough to represent diverse architectural configurations.

```
# =====
# 1. ZONEMODEL CLASS INITIALIZATION
# =====

class ZoneModel:
    def __init__(self, zone_name, **kwargs):
        self.zone_name = zone_name

        # --- Unpack all inputs from the orchestrator ---
        # Dataframe storage and occupancy/ventilation schedules
        self.hourly_df = kwargs.get('hourly_df')
        self.occ_profile = kwargs.get('occ_profile')
        self.equip_profile = kwargs.get('equip_profile')
        self.vent_profile = kwargs.get('vent_profile')
        self.system_profile = kwargs.get('system_profile')

        # Geometry parameters for heat transfer surface calculations
        self.floor_area = kwargs.get('floor_area')
        self.room_volume = kwargs.get('room_volume')
        self.area_roof = kwargs.get('area_roof')
        self.area_ground = kwargs.get('area_ground')
        self.total_facade_areas = kwargs.get('total_facade_areas')

        # Thermal Properties and System Constants
        self.rc_facade = kwargs.get('rc_facade')
        self.rc_roof = kwargs.get('rc_roof')
        self.rc_ground_floor = kwargs.get('rc_ground_floor')
        self.u_value_windows = kwargs.get('u_value_windows')

        # Internal Gains and HVAC System limits
        self.thermal_mass_factor = kwargs.get('thermal_mass_factor', 165000)
        self.thermal_capacity = self.thermal_mass_factor * self.floor_area
        self.dt = 3600

        # --- Floor heating and cooling activation logic ---
        self.u_floor_heating = kwargs.get('u_floor_heating', 11.0)
```

```

self.floor_heating_area = kwargs.get('floor_heating_area', 0.0)
self.t_floor_water_heating = kwargs.get('t_floor_water_heating', 35.0)
self.t_floor_water_cooling = kwargs.get('t_floor_water_cooling', 18.0)
self.floor_heating_activated = kwargs.get('floor_heating_activated', False)

# Pre-calculate surface areas for the thermal loop
self.solar_orientations = ['N', 'NE', 'E', 'SE', 'S', 'SW', 'W', 'NW']
self._initialize_surfaces()

```

D.1.2 Geometric Initialisation and Data Tracking

The `_initialize_surfaces` method executes the geometric pre-processing required to map thermal loads to specific building orientations. It partitions facade areas into glass and opaque components, calculates cumulative surface areas, and derives base ventilation and fan power requirements. Furthermore, it initializes the structured containers needed for high-resolution hourly data tracking, setting up the lists that the simulation will populate at every time step to record detailed energy balances, indoor temperatures, and operational schedules.

```

# =====
# 2. GEOMETRIC PRE-PROCESSING AND DATA INITIALIZATION
# =====

def _initialize_surfaces(self):
    # Reset tracking variables
    self.area_windows = 0
    self.area_walls = 0
    self.glass_areas = {}
    self.opaque_wall_areas = {}

    # Calculate glass and wall areas per orientation
    for orient in self.solar_orientations:
        facade = self.total_facade_areas.get(orient, 0.0)
        win_perc = self.window_percentages.get(orient, 0.0)
        glaz_perc = self.glazing_percentages.get(orient, 1.0)

        window_area = facade * win_perc
        self.glass_areas[orient] = window_area * glaz_perc
        self.opaque_wall_areas[orient] = facade - window_area

        self.area_windows += window_area
        self.area_walls += self.opaque_wall_areas[orient]

    # --- Auxiliary system and load calculations ---
    self.max_people = self.floor_area * self.max_people_per_m2
    self.flow_rate_vent = self.max_people * self.vent_flow_per_person
    self.total_flow_rate_vent = self.vent_flow_per_person * self.max_people_per_m2 * self.floor_area
    self.fans_power = (self.total_flow_rate_vent * self.system_pressure_drop) / (3600 *
    self.efficiency_fan_and_motor)

    # --- Initialize result tracking containers ---
    self.annual_heating_results = []
    self.annual_cooling_results = []
    self.annual_temp_results = []

    # Dictionary for detailed hourly Excel export logging
    self.detailed_results = {
        "Hour": [], "T_ext": [],
        "Trans window": [], "Trans wall": [], "Trans roof": [], "Transmission tot (W/K)": [],
        "Infiltration (W/K)": [], "Ventilation heat mode (W/K)": [], "Ventilation cool mode (W/K)": [],
        "Heating mode tot coupling (W/K)": [], "Cooling mode tot coupling (W/K)": [],
        "Ground coupling (W/K)": [],
        "Solar glazing (Wh)": [], "Solar opaque (Wh)": [],
        "People (Wh)": [], "Lighting (Wh)": [], "Appliances (Wh)": [], "Fans (Wh)": [],
        "Internal heat gains (Wh)": [],
        "T_i Max heating": [], "T_i free floating with H_heat": [], "T_i Max cooling": [],
        "T_i free floating with H_cool": [],
        "T_i indoor (oC)": [], "Q_heat (kWh)": [], "Q_cool (kWh)": [],
        "Sch_Occupancy": [], "Sch_Equipment": [], "Sch_SystemActive": [], "Sch_Ventilation": []
    }

    # Add orientation-specific solar gain tracking columns
    for orient in self.solar_orientations:
        self.detailed_results[f"G_{orient} (Wh)"] = []
    for orient in self.solar_orientations:
        self.detailed_results[f"O_{orient} (Wh)"] = []

```

D.1.3 U-value Calculation

To maintain consistency with standard building energy performance protocols (NTA 8800), the model includes a dedicated utility for converting thermal resistance (R_c) values into effective heat transfer coefficients (U -values). This function incorporates a simplified yet dynamic approach to thermal bridging by calculating the penalty factor (ΔU) based on the underlying material performance. By adjusting the penalty according to the degree of insulation, the model ensures that conductive heat losses reflect realistic building envelope conditions.

```
# =====
# 3. THERMAL PROPERTY UTILITIES
# =====

def calculate_nta8800_u_value(self, rc_value):
    """
    Calculates the effective U-value based on a simplified NTA 8800
    approach, incorporating a dynamic thermal bridge penalty.
    """
    if rc_value <= 0:
        return 0

    # Calculate undisturbed U-value (inverse of total resistance)
    u_undisturbed = 1 / (rc_value + 0.17)

    # Dynamic penalty calculation: delta_u decreases as insulation
    # quality improves (lower u_undisturbed)
    delta_u = max(0, 0.1 - 0.25 * (u_undisturbed - 0.4))

    return u_undisturbed + delta_u
```

D.1.4 Transient Heat Transfer Physics

This method serves as the core computational engine for the ZoneModel, solving the transient energy balance equation for a single hour of simulation. It dynamically integrates time-varying factors, including solar irradiation based on orientation, internal occupancy and equipment heat gains, and the conductive and convective heat losses across the building envelope. By accounting for the thermal mass of the zone and applying exponential decay formulas for temperature evolution, it accurately scouts the free-floating indoor temperature and determines the auxiliary heating or cooling power required to maintain set-point comfort levels.

```
def calculate_hour_step(self, t, external_q_flow=0, t_source=None, is_winter=True):
    """Processes one single hour of physics."""
    # 1. Update heating/cooling setpoints from profiles
    idx_168 = t % 168
    if self.h_setpoint_profile is not None:
        self.heating_setpoint = self.h_setpoint_profile[idx_168]
    if self.c_setpoint_profile is not None:
        self.cooling_setpoint = self.c_setpoint_profile[idx_168]

    # 2. Update ventilation trigger
    if self.zone_name == "Zone 2":
        self.vent_cooling_setpoint = 27.0
    else:
        self.vent_cooling_setpoint = max(self.vent_comfort_limit, self.cooling_setpoint - 0.1)

    # --- PRE-LOOP CALCULATIONS (now inside step) ---
    u_value_walls = self.calculate_nta8800_u_value(self.rc_facade)
    u_value_roof = self.calculate_nta8800_u_value(self.rc_roof)
    u_value_ground = self.calculate_nta8800_u_value(self.rc_ground_floor)

    trans_e_windows = self.area_windows * self.u_value_windows
    trans_e_walls = self.area_walls * u_value_walls
    trans_e_roof = self.area_roof * u_value_roof
    H_e_transmission = trans_e_walls + trans_e_roof + trans_e_windows

    # --- DATA FETCHING ---
    row = self.hourly_df.iloc[t]
    idx_168 = t % 168
    current_occ_val = self.occ_profile[idx_168]
    current_light_val = self.equip_profile[idx_168]
    current_vent_val = self.vent_profile[idx_168]
    current_sys = self.system_profile[idx_168]
    current_temp = self.current_temp
```

```

t_ext = row['T']
if t_source is None:
    t_source = t_ext

# --- SOLAR GAINS ---
glazing_gains_breakdown = {}
opaque_gains_breakdown = {}

for orient in self.solar_orientations:
    if current_temp >= self.vent_cooling_setpoint and row[orient] > 0:
        active_shading = self.solar_heat_coefficient_shading
    else:
        active_shading = 1.0

    glazing_val = (row[orient] * self.glass_areas[orient] * self.solar_heat_coefficient_glazing *
        active_shading)
    glazing_gains_breakdown[orient] = glazing_val

    opaque_val = (row[orient] * self.opaque_wall_areas[orient] * self.solar_absorption_coefficient *
        (u_value_walls / self.alfao))
    opaque_gains_breakdown[orient] = opaque_val

sun_glazing = sum(glazing_gains_breakdown.values())
sun_opaque_walls = sum(opaque_gains_breakdown.values())
sun_opaque_roof = row['Horizontal'] * self.solar_absorption_coefficient *
    (u_value_roof / self.alfao) * self.area_roof

# --- INTERNAL GAINS ---
people_heat = self.max_people * current_occ_val * self.heat_per_person
lighting_heat = self.lighting_w_m2 * self.floor_area * current_light_val
equipment_heat = self.appliances_w_m2 * self.floor_area * current_light_val
fans_heat = 0.5 * self.fans_power * current_vent_val
total_internal_gains = people_heat + equipment_heat + lighting_heat + (fans_heat * 0.5)

# --- Floor Heating Physics ---
q_floor_gain = 0.0
if self.floor_heating_activated:
    u_eff = self.u_floor_heating if is_winter else 7.0
    t_water = self.t_floor_water_heating if is_winter else self.t_floor_water_cooling

    if is_winter and self.current_temp > self.t_floor_limit_heating:
        q_floor_gain = 0.0
    elif not is_winter and self.current_temp < self.t_floor_limit_cooling:
        q_floor_gain = 0.0
    else:
        q_floor_gain = u_eff * self.floor_heating_area * (t_water - self.current_temp)

# --- the Cascaded Strategy (Atrium) ---
q_atrium_effect = 0.0
self.coil_UA = 0.5
if self.zone_name != "Zone 2" and t_source is not None:
    delta_t_atrium = t_source - 21.0
    q_atrium_effect = self.coil_UA * delta_t_atrium

# --- TOTAL FREE GAINS ---
total_free_gains = sun_glazing + sun_opaque_walls + sun_opaque_roof + total_internal_gains
+ external_q_flow + q_floor_gain + q_atrium_effect

# --- GROUND AND INFILTRATION ---
flow_rate_inf = self.room_volume * self.infiltration_ach
h_inf = (flow_rate_inf * self.air_density * self.air_heat_capacity) / 3600
h_ground = self.area_ground * u_value_ground

# --- VENTILATION ---
current_flow_m3h = self.flow_rate_vent * current_occ_val * current_vent_val
h_vent_heat = (1 - self.eta) * (current_flow_m3h *
    self.air_density * self.air_heat_capacity) / 3600
h_vent_cool = (current_flow_m3h + (self.natural_vent_rate * self.room_volume))
    * self.air_density * self.air_heat_capacity / 3600

# --- TOTAL HEAT TRANSFER ---
H_total_heat = H_e_transmission + h_vent_heat + h_inf
H_total_cool = H_e_transmission + h_vent_cool + h_inf

Total_exterior_heat = ((H_e_transmission + h_inf) * t_ext) +
    (h_ground * self.t_ground) + (h_vent_heat * t_source)

Total_exterior_cool = ((H_e_transmission + h_inf) * t_ext) +
    (h_ground * self.t_ground) + (h_vent_cool * t_source)

H_total_with_ground_heat = H_total_heat + h_ground
H_total_with_ground_cool = H_total_cool + h_ground

# --- DYNAMIC VENTILATION LOGIC ---

```

```

den_test = 1 + (self.dt / self.thermal_capacity) * H_total_with_ground_heat
t_check = (current_temp + (self.dt / self.thermal_capacity) *
(total_free_gains + Total_exterior_heat)) / den_test

t_eq_heat = (total_free_gains + Total_exterior_heat) / H_total_with_ground_heat
t_eq_cool = (total_free_gains + Total_exterior_cool) / H_total_with_ground_cool

if t_check > self.vent_cooling_setpoint and t_ext < current_temp:
    H_active = H_total_with_ground_cool
    self.current_ach = (current_flow_m3h / self.room_volume) + self.natural_vent_rate
else:
    H_active = H_total_with_ground_heat
    self.current_ach = (current_flow_m3h / self.room_volume)

# --- EXPONENTIALS ---
eps = 1e-9
exp_factor_heat_raw = 1 - np.exp(-(H_total_with_ground_heat) / self.thermal_capacity * self.dt)
exp_factor_cool_raw = 1 - np.exp(-(H_total_with_ground_cool) / self.thermal_capacity * self.dt)

exp_factor_heat = max(exp_factor_heat_raw, eps)
exp_factor_cool = max(exp_factor_cool_raw, eps)

# --- NUMERICAL STABILITY CHECK & SCOUTING TEMPERATURES ---
h_limit = 0.01

if H_total_with_ground_heat > h_limit:
    t_room_free_heating = current_temp + (t_eq_heat - current_temp) * exp_factor_heat
    t_room_max_heating = t_room_free_heating +
    (self.heating_power_max / H_total_with_ground_heat) * exp_factor_heat
else:
    t_room_free_heating = current_temp + ((total_free_gains + Total_exterior_heat) / self.thermal_capacity) *
    t_room_max_heating = t_room_free_heating +
    (self.heating_power_max / self.thermal_capacity) * self.dt

if H_total_with_ground_cool > h_limit:
    t_room_free_cooling = current_temp + (t_eq_cool - current_temp) * exp_factor_cool
    t_room_max_cooling = t_room_free_cooling + (
    self.cooling_power_max / H_total_with_ground_cool) * exp_factor_cool
else:
    t_room_free_cooling = current_temp + ((total_free_gains + Total_exterior_cool) / self.thermal_capacity) *
    t_room_max_cooling = t_room_free_cooling +
    (self.cooling_power_max / self.thermal_capacity) * self.dt

# --- CONTROL LOGIC GATE ---
q_heat_kwh = 0.0
q_cool_kwh = 0.0
p_needed = 0.0
system_active = current_sys

if system_active > 0:
    if t_room_max_heating < self.heating_setpoint:
        current_temp = t_room_max_heating
        q_heat_kwh = self.heating_power_max / 1000.0
    elif t_room_max_heating >= self.heating_setpoint and t_room_free_heating < self.heating_setpoint:
        current_temp = self.heating_setpoint
        p_needed = H_total_with_ground_heat * (self.heating_setpoint - t_room_free_heating)
        / exp_factor_heat
        q_heat_kwh = p_needed / 1000.0
    elif t_room_free_heating >= self.heating_setpoint and t_room_free_heating <=
    self.vent_cooling_setpoint:
        current_temp = t_room_free_heating
    elif t_room_free_heating > self.vent_cooling_setpoint and t_room_free_cooling <
    self.vent_cooling_setpoint:
        current_temp = self.vent_cooling_setpoint
    elif t_room_free_cooling >= self.vent_cooling_setpoint and t_room_free_cooling <=
    self.cooling_setpoint:
        current_temp = t_room_free_cooling
    elif t_room_max_cooling <= self.cooling_setpoint and t_room_free_cooling > self.cooling_setpoint:
        current_temp = self.cooling_setpoint
        if t_ext < self.cooling_setpoint:
            p_needed = H_total_with_ground_cool * (self.cooling_setpoint - t_room_free_cooling)
            / exp_factor_cool
        else:
            p_needed = H_total_with_ground_heat * (self.cooling_setpoint - t_room_free_heating)
            / exp_factor_heat
        q_cool_kwh = p_needed / 1000.0
    elif t_room_max_cooling > self.cooling_setpoint:
        current_temp = t_room_max_cooling
        q_cool_kwh = self.cooling_power_max / 1000.0
    else:
        current_temp = t_room_free_heating

# --- Consolidated Billing & Storage ---
floor_heat_kwh = max(q_floor_gain, 0) / 1000.0

```

```

floor_cool_kwh = min(q_floor_gain, 0) / 1000.0

q_heat_total = q_heat_kwh + floor_heat_kwh
q_cool_total = q_cool_kwh + floor_cool_kwh

self.current_temp = current_temp
self.annual_heating_results.append(q_heat_total)
self.annual_cooling_results.append(q_cool_total)
self.annual_temp_results.append(current_temp)

# --- Detailed Dictionary Export ---
d = self.detailed_results
d["Hour"].append(t + 1)
d["T_ext"].append(t_ext)
d["Trans window"].append(trans_e_windows)
d["Trans wall"].append(trans_e_walls)
d["Trans roof"].append(trans_e_roof)
d["Transmission tot (W/K)"].append(H_e_transmission)
d["Infiltration (W/K)"].append(h_inf)
d["Ventilation heat mode (W/K)"].append(h_vent_heat)
d["Ventilation cool mode (W/K)"].append(h_vent_cool)
d["Heating mode tot coupling (W/K)"].append(H_total_with_ground_heat)
d["Cooling mode tot coupling (W/K)"].append(H_total_with_ground_cool)
d["Ground coupling (W/K)"].append(h_ground)
d["Solar glazing (Wh)"].append(sun_glazing)
d["Solar opaque (Wh)"].append(sun_opaque_walls + sun_opaque_roof)
d["People (Wh)"].append(people_heat)
d["Lighting (Wh)"].append(lighting_heat)
d["Appliances (Wh)"].append(equipment_heat)
d["Fans (Wh)"].append(fans_heat)
d["Internal heat gains (Wh)"].append(total_internal_gains)
d["T_i Max heating"].append(t_room_max_heating)
d["T_i free floating with H_heat"].append(t_room_free_heating)
d["T_i Max cooling"].append(t_room_max_cooling)
d["T_i free floating with H_cool"].append(t_room_free_cooling)
d["T_i indoor (oC)"].append(current_temp)
d["Q_heat (kWh)"].append(q_heat_total)
d["Q_cool (kWh)"].append(q_cool_total)
d["Sch_Occupancy"].append(current_occ_val)
d["Sch_Equipment"].append(current_light_val)
d["Sch_SystemActive"].append(current_sys)
d["Sch_Ventilation"].append(current_vent_val)

for orient in self.solar_orientations:
    d[f"G_{orient}_(Wh)"].append(glazing_gains_breakdown.get(orient, 0))
    d[f"O_{orient}_(Wh)"].append(opaque_gains_breakdown.get(orient, 0))

return current_temp

```

D.1.5 Execution and Data Export

The `run_simulation` method serves as the primary engine for iterating through the building's hourly thermal profile, processing the physics and control logic for every time step while aggregating energy performance results. Once the simulation concludes, the `get_hourly_dataframe` method provides a structured interface to extract the complete chronological dataset, enabling detailed analysis of indoor temperature fluctuations, energy demands, and system performance metrics in a format suitable for reporting or further external processing.

```

def run_simulation(self):
    """Can still be used for standalone tests of one zone."""
    # Reset results
    self.annual_heating_results = []
    self.annual_cooling_results = []
    self.annual_temp_results = []

    for t in range(len(self.hourly_df)):
        self.calculate_hour_step(t, external_q_flow=0)

    # --- OUTPUT SECTION ---
    print(f"\n--- Results for {self.zone_name} ---")
    print(f"Simulation Complete.")
    print(f"Room Volume: {self.room_volume:.2f} m3")
    print(f"Peak Heating: {max(self.annual_heating_results):.2f} kW | Peak Cooling: {min(self.annual_cooling_results):.2f} kW")
    print(f"Total Annual Heat Demand: {sum(self.annual_heating_results):.2f} kWh")
    print(f"Total Annual Cool Demand: {sum(self.annual_cooling_results):.2f} kWh")

    return sum(self.annual_heating_results), sum(self.annual_cooling_results)

```

```

def get_hourly_dataframe(self):
    """Returns the full thermal history as a DataFrame."""
    return pd.DataFrame(self.detailed_results)

```

D.2 Orchestrator Module

The orchestrator serves as the central control hub for the multi-zone building simulation. Its primary role is to initialize global building constants, define the geometric and operational characteristics for each individual thermal zone, and manage the connectivity between these zones through defined physical adjacencies. By aggregating individual zone models and overseeing the simulation execution, the orchestrator ensures cohesive data handling, performs system-wide energy demand calculations, and manages final data export and performance profiling for the entire building.

D.2.1 Global Configuration (case study orientated)

This section establishes the foundational environment for the simulation by defining the global building constants and operational set-points. By centralizing these parameters in a `base_inputs` dictionary, the orchestrator ensures consistency across all zones. These settings cover essential thermal properties, HVAC constraints, and internal gain schedules, which act as the baseline configuration before any zone-specific refinements are applied.

```

# =====
# SECTION 1: DATA LOADING & GLOBAL CONSTANTS
# =====

# --- 1.1 Define Operational Profiles ---
# Create weekly setpoint schedules (24 hours * 7 days = 168 hours)
h_day = [21.0] * 24
c_day = [21.0] * 24

# Standard weekly heating/cooling schedules
heating_profile = (h_day * 7)
cooling_profile = (c_day * 7)

# Specialised Atrium temperature profiles
h_atrium = [16.0] * 24
c_atrium = [28.0] * 24
atrium_h_profile = h_atrium * 7
atrium_c_profile = c_atrium * 7

# --- 1.2 Define Universal Building Constants ---
# These parameters apply to all zones by default.
# Specific zone dictionaries can override these values as needed.
base_inputs = {
    # Geometry & Environmental
    "t_ground": 15.0,

    # Thermal Control Setpoints
    "heating_setpoint_profile": heating_profile,
    "cooling_setpoint_profile": cooling_profile,
    "vent_comfort_limit": 21.0, # Syncs window operation with cooling onset
    "heating_setpoint": 21.0,
    "cooling_setpoint": 21.0,

    # Envelope Thermal Properties
    "rc_roof": 7.84,
    "rc_ground_floor": 4.7,
    "u_value_windows": 1.84,
    "alfai": 7.5,
    "alfao": 15.0,
    "thermal_mass_factor": 450000,

    # Solar Gains & Shading
    "solar_absorption_coefficient": 0.5,
    "solar_heat_coefficient_shading": 0.20,
    "solar_heat_coefficient_glazing": 0.35,

    # Ventilation & Air Dynamics
    "air_density": 1.2,
    "air_heat_capacity": 1003.0,
    "vent_flow_per_person": 36.0,
    "infiltration_ach": 0.2,
    "natural_vent_rate": 0.0,

```

```

# Internal Load Profiles
"heat_per_person": 65.0,
"appliances_w_m2": 6.0,
"lighting_w_m2": 6.0,

# HVAC System Limits & Constants
# Caps prevent mathematical instability when thermal coupling approaches zero
"heating_power_max": 1000000.0,
"cooling_power_max": -1000000.0,
"system_pressure_drop": 200.0,
"efficiency_fan_and_motor": 0.6,
"eta": 0.0, # Heat recovery efficiency

# Underfloor Heating/Cooling Configuration
"u_floor_heating": 11.0,
"floor_heating_area": 200.0,
"t_floor_water_heating": 35.0,
"t_floor_water_cooling": 18.0,
"t_floor_limit_heating": 24.0,
"t_floor_limit_cooling": 18.0,

# System Operational Schedule
"system_profile": [1.0] * 168
}

```

D.3 Zone Adjacency and Thermal Coupling

This section defines the thermal interaction between adjacent building zones by specifying the physical properties of shared internal partitions. By providing the surface area and thermal resistance (R value) for these connections, the orchestrator calculates the heat transfer coefficient (UA value) for each pair. This ensures that the simulation accurately accounts for thermal energy exchange across internal boundaries, which is a critical step for modelling heat movement between climate controlled spaces and adjacent buffer or technical zones.

```

# =====
# SECTION 2: SHARED WALL CONNECTIONS (ADJACENCIES)
# =====

# Define physical properties of shared internal partitions
# Area [m2], R_value [m2K/W]
internal_wall_connections = [
    {"zones": ("Zone 1", "Zone 2"), "area": 505.0, "R": 0.33}, # High coupling: Theatre hall to Atrium
    {"zones": ("Zone 1", "Zone 4"), "area": 122.0, "R": 0.60}, # Lower coupling: Theatre hall to support rooms
    {"zones": ("Zone 1", "Zone 6"), "area": 35.0, "R": 1.00}, # Low coupling: Theatre to technical space
    {"zones": ("Zone 3", "Zone 2"), "area": 355.0, "R": 0.33}, # High coupling: Repetition to Atrium
    {"zones": ("Zone 3", "Zone 4"), "area": 295.0, "R": 0.33},
    {"zones": ("Zone 3", "Zone 5"), "area": 525.0, "R": 0.50}, # Moderate coupling: Repetition to workshop
    {"zones": ("Zone 3", "Zone 6"), "area": 177.0, "R": 1.00},
    {"zones": ("Zone 4", "Zone 2"), "area": 208.0, "R": 0.50},
    {"zones": ("Zone 4", "Zone 5"), "area": 20.0, "R": 0.50},
    {"zones": ("Zone 4", "Zone 6"), "area": 218.0, "R": 1.00},
    {"zones": ("Zone 5", "Zone 6"), "area": 266.0, "R": 1.00},
    {"zones": ("Zone 6", "Zone 2"), "area": 359.0, "R": 1.00},
]

# AUTOMATION: Convert physical inputs into UA values for the simulation
# UA = Area / R-value [W/K]
adjacencies = []
for connection in internal_wall_connections:
    ua_calculated = connection["area"] / connection["R"]
    adjacencies.append({
        "zones": connection["zones"],
        "UA": ua_calculated
    })

```

D.3.1 Zone Specification and Operational Profiling

This section configures the individual thermal zones within the building model. Each zone is defined by unique geometric, envelope, and internal load parameters, leveraging the base_inputs as a template while applying specific overrides. The definition includes detailed occupancy, equipment, and ventilation schedules (covering a full 168-hour weekly cycle) to accurately simulate internal heat gains and environmental dynamics for each distinct space.

```

# =====
# SECTION 3: ZONE DEFINITIONS
# =====

zone_definitions = []

# --- ZONE 1: Theatre Hall ---
z1 = base_inputs.copy()
z1.update({
    "floor_area": 455.0,
    "area_roof": 455.0,
    "area_ground": 455.0,
    "room_volume": 4077.0,

    "rc_facade": 4.86,
    "thermal_mass_factor": 450000,

    "total_facade_areas": {'N': 255.0, 'NE': 0.0, 'E': 0.0, 'SE': 0.0, 'S': 0.0,
    'SW': 0.0, 'W': 0.0, 'NW': 0.0},
    "window_percentages": {'N': 0.00, 'NE': 0.00, 'E': 0.0, 'SE': 0.0, 'S': 0.0,
    'SW': 0.0, 'W': 0.0, 'NW': 0.0},
    "glazing_percentages": {'N': 0.00, 'NE': 0.00, 'E': 0.00, 'SE': 0.00, 'S': 0.00,
    'SW': 0.00, 'W': 0.00, 'NW': 0.00},

    "max_people_per_m2": 0.55, # 250 people
    "appliances_w_m2": 12.0,
    "lighting_w_m2": 15.0,

    "floor_heating_activated": False,
    "vent_flow_per_person": 36.0,
    # Profiles [occ, equip, vent] omitted for brevity; consistent with provided logic
})
zone_definitions.append(("Zone 1", z1))

# --- ZONE 2: Atrium/Foyer ---
z2 = base_inputs.copy()
z2.update({
    "floor_area": 565.0,
    "area_roof": 565.0,
    "area_ground": 565.0,
    "room_volume": 7370.0,

    "rc_roof": 13.66,
    "rc_facade": 4.7,
    "thermal_mass_factor": 450000,

    "total_facade_areas": {'N': 0.0, 'NE': 80.0, 'E': 0.0, 'SE': 205.0, 'S': 0.0,
    'SW': 315.0, 'W': 0.0, 'NW': 230.0},
    "window_percentages": {'N': 0.0, 'NE': 0.0, 'E': 0.00, 'SE': 0.293, 'S': 0.0,
    'SW': 0.143, 'W': 0.0, 'NW': 0.187},
    "glazing_percentages": {'N': 0.00, 'NE': 0.00, 'E': 0.00, 'SE': 0.80, 'S': 0.00,
    'SW': 0.80, 'W': 0.00, 'NW': 0.80},

    "max_people_per_m2": 0.28, # 160 people
    "appliances_w_m2": 10.0,
    "lighting_w_m2": 6.0,

    "heating_setpoint_profile": atrium_h_profile,
    "cooling_setpoint_profile": atrium_c_profile,
    "heating_setpoint": 16.0,
    "cooling_setpoint": 28.0,
    "vent_cooling_setpoint": 27.0,

    "floor_heating_activated": False,
    "floor_profile": [0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
    0.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0]*7,
    "vent_flow_per_person": 36.0,
})
zone_definitions.append(("Zone 2", z2))

# --- ZONE 3: Repetition Cluster ---
z3 = base_inputs.copy()
z3.update({
    "floor_area": 685.0,
    "area_roof": 160.0,
    "area_ground": 525.0,
    "room_volume": 4315.0,

    "rc_facade": 4.86,
    "thermal_mass_factor": 450000,

    "total_facade_areas": {'N': 0.0, 'NE': 93.0, 'E': 0.0, 'SE': 265.0, 'S': 0.0,
    'SW': 0.0, 'W': 0.0, 'NW': 64.0},
    "window_percentages": {'N': 0.0, 'NE': 0.032, 'E': 0.0, 'SE': 0.0, 'S': 0.0,

```

```

        'SW': 0.0, 'W': 0.0, 'NW': 0.0},
        'glazing_percentages': {'N': 0.00, 'NE': 0.80, 'E': 0.00, 'SE': 0.00, 'S': 0.00,
        'SW': 0.00, 'W': 0.00, 'NW': 0.00},

        "max_people_per_m2": 0.26, # 110 people
        "appliances_w_m2": 10.0,
        "lighting_w_m2": 12.0,

        "floor_heating_activated": False,
        "vent_flow_per_person": 25.2,
    })
    zone_definitions.append(("Zone 3", z3))

# --- ZONE 4: Offices & Changing Rooms ---
z4 = base_inputs.copy()
z4.update({
    "floor_area": 730.0,
    "area_roof": 295.0,
    "area_ground": 218.0,
    "room_volume": 2407.0,

    "rc_facade": 4.86,
    "thermal_mass_factor": 450000,

    "total_facade_areas": {'N': 0.0, 'NE': 13.0, 'E': 0.0, 'SE': 80.0, 'S': 0.0,
    'SW': 150.0, 'W': 0.0, 'NW': 95.0},
    "window_percentages": {'N': 0.0, 'NE': 0.0, 'E': 0.0, 'SE': 0.475, 'S': 0.0,
    'SW': 0.00, 'W': 0.00, 'NW': 0.642},
    "glazing_percentages": {'N': 0.00, 'NE': 0.00, 'E': 0.00, 'SE': 0.80, 'S': 0.00,
    'SW': 0.00, 'W': 0.00, 'NW': 0.80},

    "max_people_per_m2": 0.06, # 45 people
    "appliances_w_m2": 7.5,
    "lighting_w_m2": 6.0,

    "floor_heating_activated": False,
    "vent_flow_per_person": 25.2,
})
    zone_definitions.append(("Zone 4", z4))

# --- ZONE 5: Workspace/Workshop ---
z5 = base_inputs.copy()
z5.update({
    "floor_area": 480.0,
    "area_roof": 319.0,
    "area_ground": 160.0,
    "room_volume": 2495.0,

    "rc_facade": 4.86,
    "thermal_mass_factor": 450000,

    "total_facade_areas": {'N': 0.0, 'NE': 176.0, 'E': 0.0, 'SE': 110.0, 'S': 0.0,
    'SW': 0.0, 'W': 0.0, 'NW': 74.0},
    "window_percentages": {'N': 0.0, 'NE': 0.034, 'E': 0.0, 'SE': 0.0, 'S': 0.0,
    'SW': 0.0, 'W': 0.0, 'NW': 0.0},
    "glazing_percentages": {'N': 0.00, 'NE': 0.80, 'E': 0.00, 'SE': 0.00, 'S': 0.00,
    'SW': 0.00, 'W': 0.00, 'NW': 0.00},

    "max_people_per_m2": 0.09, # 44 people
    "appliances_w_m2": 5.0,
    "lighting_w_m2": 6.0,

    "floor_heating_activated": False,
    "vent_flow_per_person": 25.2,
})
    zone_definitions.append(("Zone 5", z5))

# --- ZONE 6: Storage/Stairs (Passive) ---
z6 = base_inputs.copy()
z6.update({
    "floor_area": 420.0,
    "area_roof": 360.0,
    "area_ground": 283.0,
    "room_volume": 3456.0,

    "rc_facade": 4.86,
    "thermal_mass_factor": 450000,

    "total_facade_areas": {'N': 0.0, 'NE': 130.0, 'E': 0.0, 'SE': 133.0, 'S': 0.0,
    'SW': 53.0, 'W': 0.0, 'NW': 75.0},
    "window_percentages": {'N': 0.0, 'NE': 0.0, 'E': 0.0, 'SE': 0.083, 'S': 0.0,
    'SW': 0.0, 'W': 0.0, 'NW': 0.0},
    "glazing_percentages": {'N': 0.00, 'NE': 0.00, 'E': 0.00, 'SE': 0.80, 'S': 0.00,
    'SW': 0.00, 'W': 0.00, 'NW': 0.00},

```

```

    "max_people_per_m2": 0.03, # 12 people
    "appliances_w_m2": 0.0,
    "lighting_w_m2": 0.0,

    "floor_heating_activated": False,
    "vent_flow_per_person": 25.2,
    "system_profile": [0.0]*168 # Passive zone
})
zone_definitions.append(("Zone 6", z6))

```

D.3.2 Main Simulation Loop

The main simulation loop orchestrates the thermal interaction across all zones. It integrates weather data, manages inter-zonal heat exchange via adjacency matrices, and enforces the dynamic operating strategies for the Atrium (Zone 2) and the cascaded air strategy for the remaining zones.

```

# =====
# SECTION 4: MAIN SIMULATION LOOP (CASCADED LOGIC)
# =====

# Upload the weather data including temperatures and solar radiation per orientation
file_path = 'Input Multi Zone Model - NEN5060-B2 1% solar orient - Extreme Year.csv'

try:
    weather_df = pd.read_csv(file_path, sep=',')
    weather_df.columns = weather_df.columns.str.strip()
    if 'temp_ext' in weather_df.columns and 'T' not in weather_df.columns:
        weather_df = weather_df.rename(columns={'temp_ext': 'T'})

    # Initialize all zone objects and store them in a dictionary
    zones = {}
    for name, params in zone_definitions:
        params['hourly_df'] = weather_df
        # The __init__ call handles the internal setup
        zones[name] = ZoneModel(name, **params)

    # MASTER HOURLY LOOP (8760 Hours (length of weather dataset))
    for t in range(len(weather_df)):
        zone_external_flows = {name: 0.0 for name in zones.keys()}

        # Calculate Heat Exchange via Shared Walls
        for adj in adjacencies:
            z_a_name, z_b_name = adj["zones"]
            ua_value = adj["UA"]

            # Grabbing the current state from the class objects
            temp_a = zones[z_a_name].current_temp
            temp_b = zones[z_b_name].current_temp

            # Physics: Flow = U * A * Delta_T
            flow_b_to_a = ua_value * (temp_b - temp_a)

            # Storing the "push/pull" of heat for each zone
            zone_external_flows[z_a_name] += flow_b_to_a
            zone_external_flows[z_b_name] -= flow_b_to_a

        # --- UFH Step 1: Determine Seasonal Mode for floor heating (Forecast Logic) ---
        forecast_end = min(t + 24, len(weather_df))
        upcoming_avg_temp = weather_df.iloc[t:forecast_end]['T'].mean()
        is_winter = True if upcoming_avg_temp < 15.5 else False

        # --- UFH Step 2: Weekly Schedule Check ---
        # Get hour of the week (0-167) to index the floor_profile
        hour_of_week = t % 168

        # --- UFH Step 3: Link Atrium Temperature cascaded air strategy ---
        atrium_air_temp = zones['Zone 2'].current_temp

        # --- Update each zone's physics ---
        for name, zone_obj in zones.items():
            current_source = atrium_air_temp if name != 'Zone 2' else None

            # --- Specific logic for the Atrium (Zone 2) floor schedule ---
            if name == 'Zone 2':
                # Grab the configuration for Zone 2 (it's the second item in your list)
                z2_config = zone_definitions[1][1]

                # Check if heating is generally activated AND if the profile allows it this hour
                # Note: We use .get() just in case 'floor_profile' isn't in every zone

```

```

        schedule_val = z2_config.get('floor_profile', [1.0]*168)[hour_of_week]
        is_installed = z2_config.get('floor_heating_activated', False)

        # Update the object attribute immediately before the physics calculation
        zone_obj.floor_heating_activated = bool(is_installed and schedule_val > 0)

    # Physics calculation
    zone_obj.calculate_hour_step(t, external_q_flow=zone_external_flows[name],
                                is_winter=is_winter, t_source=current_source)

except Exception as e:
    print(f"Error during simulation loop: {e}")

```

D.3.3 Data Export and Performance Report

The following script section manages the post-processing of simulation results. It consolidates hourly thermal demand data for all zones, calculates peak building-wide heating and cooling loads, and generates a comprehensive Excel report containing both global summaries and detailed, zone-specific hourly metrics.

```

# =====
# SECTION 5-8: RESULTS POST-PROCESSING AND EXPORT
# =====

# --- SECTION 5: Save CSV of Hourly Results (Combined Heating + Cooling) ---
hourly_export_data = []
for t in range(len(weather_df)):
    row = {"Hour": t + 1}
    for name, zone_obj in zones.items():
        if name == "Zone 6":
            continue
        # This net_demand now correctly includes the UFH energy
        net_demand = zone_obj.annual_heating_results[t] + zone_obj.annual_cooling_results[t]
        row[f"Demand_{name}"] = round(net_demand, 1)
    hourly_export_data.append(row)

pd.DataFrame(hourly_export_data).to_csv("Input - Results_Yearly_Zone_Demands_Combined no vent.csv",
index=False, sep=',')

# --- SECTION 6: Print statements and summary tables per zone ---
final_results = []
all_hourly_results = {"Hour": range(1, 8761)}

for name, zone_obj in zones.items():
    # Calculate Totals
    annual_h = sum(zone_obj.annual_heating_results)
    annual_c = sum(zone_obj.annual_cooling_results)

    # Collect the hourly demand (Heating + Cooling) for this specific zone
    all_hourly_results[f"Demand_{name}"] = [h + c for h, c in zip(zone_obj.annual_heating_results,
zone_obj.annual_cooling_results)]

    # Calculate Peaks (using max/min from the hourly lists)
    peak_h = max(zone_obj.annual_heating_results) if zone_obj.annual_heating_results else 0.0
    peak_c = min(zone_obj.annual_cooling_results) if zone_obj.annual_cooling_results else 0.0

    # Print detailed results per zone (matching Multi_zone_model style)
    print(f"\n--- Results for {name} ---")
    print("Simulation Complete.")
    print(f"Room Volume: {zone_obj.room_volume:.2f} m3")
    print(f"Peak Heating: {peak_h:.2f} kW | Peak Cooling: {peak_c:.2f} kW")
    print(f"Total Annual Heat Demand: {annual_h:.2f} kWh")
    print(f"Total Annual Cool Demand: {annual_c:.2f} kWh")

    final_results.append({
        "Zone": name,
        "Annual Heating [kWh]": round(annual_h, 2),
        "Annual Cooling [kWh]": round(annual_c, 2)
    })

# 3.5 TRACK PEAK TIMESTEPS
hourly_results_df = pd.DataFrame(all_hourly_results)
demand_columns = [col for col in hourly_results_df.columns if col.startswith('Demand_')]
total_hourly_demand = hourly_results_df[demand_columns].sum(axis=1)

peak_heating_val = total_hourly_demand.max()
peak_heating_hour = total_hourly_demand.idxmax() + 1

peak_cooling_val = total_hourly_demand.min()
peak_cooling_hour = total_hourly_demand.idxmin() + 1

```

```

# --- SECTION 7: Final summary of building-wide performance ---
print("\n" + "="*45)
print("          MULTI-ZONE SIMULATION RESULTS          ")
print("="*45)

# Create the DataFrame
results_df = pd.DataFrame(final_results)
print(results_df)

# Calculate Totals
total_h = results_df["Annual Heating [kWh]"].sum()
total_c = results_df["Annual Cooling [kWh]"].sum()

print("-" * 45)
print(f"TOTAL BUILDING HEATING: {total_h:,.2f} kWh")
print(f"TOTAL BUILDING COOLING: {total_c:,.2f} kWh")
print("="*45)

print("-" * 45)
print(f"BUILDING PEAK HEATING: {peak_heating_val:,.2f} kW at Hour {peak_heating_hour}")
print(f"BUILDING PEAK COOLING: {peak_cooling_val:,.2f} kW at Hour {peak_cooling_hour}")
print("-" * 45)

except Exception as e:
    print(f"An unexpected error occurred: {e}")

# --- SECTION 8: Export hourly results to Excel ---
export_filename = 'Building_Thermal_Performance_Detailed no vent.xlsx'

print(f"\nExporting detailed results to {export_filename}...")
print("Please wait, calculating column widths for all zones...")

with pd.ExcelWriter(export_filename, engine='openpyxl') as writer:
    # 1. Save the Global Summary Table first
    results_df.to_excel(writer, sheet_name='Annual_Summary', index=False)

    # Format Summary Sheet
    summary_ws = writer.sheets['Annual_Summary']
    for column_cells in summary_ws.columns:
        content_length = max(len(str(cell.value)) for cell in column_cells)
        adjusted_width = min(max(content_length, 10), 25)
        summary_ws.column_dimensions[column_cells[0].column_letter].width = adjusted_width

    # 2. Iterate through each zone object and export its 'One Zone' style data
    for name, zone_obj in zones.items():
        # Get the dataframe from the zone instance
        zone_detailed_df = zone_obj.get_hourly_dataframe()

        zone_detailed_df['Q_cool (kWh)'] = zone_obj.annual_cooling_results
        # Save to a new sheet named after the zone
        zone_detailed_df.to_excel(writer, sheet_name=name, index=False)

        # Access the openpyxl worksheet object for this specific zone
        worksheet = writer.sheets[name]

    # --- AUTO-ADJUST COLUMN WIDTHS ---
    for column_cells in worksheet.columns:
        content_length = max(len(str(cell.value)) for cell in column_cells)
        adjusted_width = min(max(content_length, 10), 25)
        worksheet.column_dimensions[column_cells[0].column_letter].width = adjusted_width

print(f"Export Complete. Detailed results saved in: {export_filename}")

```

D.3.4 Dynamic Grid Capacity Calculation

This final module calculates the building's hourly electricity consumption from lighting, appliances, fans, and circulation pumps. By subtracting these parasitic loads from the main grid breaker limit (TOTAL_GRID_LIMIT), it determines the residual electrical capacity available for the heat pump, which is then exported as a CSV file for subsequent Thermal Energy Storage (TES) simulations.

```

# =====
# DYNAMIC GRID GENERATOR - kVA PROFILE (for TES Script)
# =====

# 1. Configuration
TOTAL_GRID_LIMIT = 61.25      # The main breaker limit (kVA)
PUMP_POWER_W_M2 = 0.5        # Estimated W/m2 for circulation pumps

grid_kva_history = []

```

```

# Loop through every hour of the year
for t in range(8760):
    total_building_load_w = 0

    for name, zone_obj in zones.items():
        # Get schedules for this specific hour
        idx_168 = t % 168
        light_sch = zone_obj.equip_profile[idx_168]
        vent_sch = zone_obj.vent_profile[idx_168]
        sys_active = zone_obj.system_profile[idx_168]

        # A. Lighting & Appliances
        z_light = zone_obj.lighting_w_m2 * zone_obj.floor_area * light_sch
        z_equip = zone_obj.appliances_w_m2 * zone_obj.floor_area * light_sch

        # B. Fans (Using RAW power, ignoring the 0.5 heat factor)
        z_fans = zone_obj.fans_power * vent_sch

        # C. Pumps (Active only when system is on)
        z_pumps = (PUMP_POWER_W_M2 * zone_obj.floor_area) if sys_active > 0 else 0

        total_building_load_w += (z_light + z_equip + z_fans + z_pumps)

    # Convert Watts to kVA (assuming Power Factor ~1.0)
    building_kva = total_building_load_w / 1000.0

    # Residual left for the Heat Pump
    available_for_hp = TOTAL_GRID_LIMIT - building_kva
    grid_kva_history.append(max(0, available_for_hp))

# 3. Export to CSV for TES Script
df_grid_final = pd.DataFrame({
    'Hour': range(1, 8761),
    'Grid_kVA': grid_kva_history
})

# Save using the filename your TES script expects
grid_filename = 'Input total kVA - Output dataset generator - Hour, Grid_kVA.csv'
df_grid_final.to_csv(grid_filename, index=False)

print(f"\n--- Dynamic Grid Profile Generated ---")
print(f"Max Available: {df_grid_final['Grid_kVA'].max():.2f} kVA (Night)")
print(f"Min Available: {df_grid_final['Grid_kVA'].min():.2f} kVA (Peak Occupancy)")

```

E Appendix - Availability Engine

This section will cover the complete Python code for the Availability Engine that was used in this thesis. The code is divided into sections to get a clear overview.

E.1 Input Section

This section defines the physical characteristics of the photovoltaic (PV) array and the operational parameters for both the heating and cooling heat pump systems. These constants serve as the foundational boundaries for the thermal potential calculations.

```
# =====
# 1. SETTINGS & PHYSICAL CONSTRAINTS
# =====
PV_SETTINGS = {
    'AREA': 300,
    'TILT_DEG': 7,
    'EFF': 0.20,
    'PR': 0.78,
    'D': 0.005
}

# --- POWER ALLOCATION SETTINGS ---
ALLOCATION_SETTINGS = {
    'MANUAL_HEATING_SHARE': 0.5 # 0.5 = 50% to Heating, 50% to Cooling,
    this settings is overridden if the split mode is determined in the main
    tank scripts (this is a safety net).
}

# --- HEATING HEAT PUMP SETTINGS ---
HP_HEATING_SETTINGS = {
    'ETA_LO': 0.5,
    'T_SINK_C': 45.0,
    'MAX_COP': 5.0 #
}

# --- COOLING HEAT PUMP SETTINGS ---
HP_COOLING_SETTINGS = {
    'ETA_LO': 0.5,
    'T_SOURCE_C': 10.0,
    'MAX_COP': 4.5 #
}
```

E.2 Core Logic for Thermal Potential Calculation

This function orchestrates the transformation of meteorological and electrical grid data into available thermal energy for the heating and cooling systems. It performs four distinct operations: irradiance-based power generation, demand-responsive electrical power allocation, thermodynamic coefficient of performance (COP) derivation, and the application of free-cooling efficiencies.

```
# =====
# 2. CORE LOGIC FUNCTION
# =====
def calculate_thermal_potentials(df_weather, df_grid, split_mode='fixed',
                                h_demand=None, c_demand=None, manual_share=None,
                                hp_max_h=97.0, hp_max_c=75.0):
    """
    Calculates potentials with explicit power division between HPs.
    """
    # --- A. Total PV Yield Calculation ---
    beta = np.radians(PV_SETTINGS['TILT_DEG'])
    df_weather['Direct_H'] = df_weather['GG'] - df_weather['GD']
    df_weather['I_poa'] = (df_weather['Direct_H'] * np.cos(beta)) + (df_weather['GD'] * (1 + np.cos(beta)) / 2)

    # Total Electrical kVA generated by PV
    total_pv_kva = (df_weather['I_poa'] * PV_SETTINGS['AREA'] * PV_SETTINGS['EFF'] * \
                    PV_SETTINGS['PR'] * (1 - PV_SETTINGS['D'])) / 1000

    # Total Electrical kVA from Grid
    total_grid_kva = df_grid['Grid_kVA'].values[:len(df_weather)]

    # Total Electrical kVA combined
    total_available_kva = total_pv_kva + total_grid_kva
```

```

# --- B. POWER DIVISION LOGIC (Floor First) ---
# Reserve 1.5 kVA for both HPs (Total 3.0) to ensure stratification maintenance
active_pool = (total_available_kva - 3.0).clip(lower=0)

if split_mode == 'proportional' and h_demand is not None and c_demand is not None:
    total_d = h_demand + c_demand
    ratio_h = np.where(total_d > 0, h_demand / total_d, 0.5)
else:
    # Use the passed argument if it exists; otherwise, use the internal dictionary
    ratio_h = manual_share if manual_share is not None else ALLOCATION_SETTINGS['MANUAL_HEATING_SHARE']

# Final kVA Assignment: Floor + (Remainder * Ratio)
total_kva_h = 1.5 + (active_pool * ratio_h)
total_kva_c = 1.5 + (active_pool * (1 - ratio_h))

# --- C. COP CALCULATION ---
t_amb_k = df_weather['T'] + 273.15

# Heating COP
t_sink_k = HP_HEATING_SETTINGS['T_SINK_C'] + 273.15
raw_cop_h = HP_HEATING_SETTINGS['ETA_LO'] * (t_sink_k / (t_sink_k - t_amb_k + 0.1))
cop_h = raw_cop_h.clip(lower=1.0, upper=HP_HEATING_SETTINGS['MAX_COP'])

# Cooling COP
t_source_k = HP_COOLING_SETTINGS['T_SOURCE_C'] + 273.15
raw_cop_c = HP_COOLING_SETTINGS['ETA_LO'] * (t_source_k / (t_amb_k - t_source_k + 0.1))
cop_c = raw_cop_c.clip(lower=1.0, upper=HP_COOLING_SETTINGS['MAX_COP'])

# --- REALISTIC 3-STAGE FREE COOLING ---
conditions = [
    df_weather['T'] < (HP_COOLING_SETTINGS['T_SOURCE_C'] - 2.0), # Total Free Cooling
    df_weather['T'] < HP_COOLING_SETTINGS['T_SOURCE_C']           # Partial Free Cooling
]
choices = [15.0, 6.0]

# Apply the choices based on conditions, otherwise keep the calculated cop_c
cop_c = np.select(conditions, choices, default=cop_c)

```

E.3 Dynamic Power Redirection Logic

This final segment of the core logic function implements a two-step "slack-redirection" process. It identifies when a heat pump has reached its physical saturation limit and automatically reallocates any surplus electrical power to the opposite machine, maximizing total system efficiency and utilization of the available electrical pool.

```

# =====
# 3. DYNAMIC REDIRECTION LOGIC (TWO-STEP PASS) ---
# =====

# --- PASS 1: Calculate raw thermal outputs based on the initial baseline split ratio ---
raw_heating_thermal = total_kva_h * cop_h
raw_cooling_thermal = total_kva_c * cop_c

# --- PASS 2: Check saturation thresholds against physical machine sizes ---
# Calculate the kVA needed to reach the physical machine ceiling
kva_needed_h = hp_max_h / cop_h
kva_slack_h = np.maximum(0, total_kva_h - kva_needed_h)
# Only claim electrical slack if the heating pump is actively saturating past the ceiling
kva_slack_h = np.where(raw_heating_thermal > hp_max_h, kva_slack_h, 0.0)

kva_needed_c = hp_max_c / cop_c
kva_slack_c = np.maximum(0, total_kva_c - kva_needed_c)
# Only claim electrical slack if the cooling pump is actively saturating past the ceiling
kva_slack_c = np.where(raw_cooling_thermal > hp_max_c, kva_slack_c, 0.0)

# --- PASS 3: Cross-Redirect the Slack to the opposite machine pool ---
final_kva_h = total_kva_h - kva_slack_h + kva_slack_c
final_kva_c = total_kva_c - kva_slack_c + kva_slack_h

# --- PASS 4: Calculate Final Outputs with Recycled Power ---
df_weather['Potential_Heating_kW'] = np.minimum(final_kva_h * cop_h, hp_max_h)
df_weather['Potential_Cooling_kW'] = np.minimum(final_kva_c * cop_c, hp_max_c)
# Keeping your tracking metrics accurate for the orchestrator loops
df_weather['Elec_kVA_Heating'] = final_kva_h
df_weather['Elec_kVA_Cooling'] = final_kva_c
df_weather['COP_Heating'] = cop_h
df_weather['COP_Cooling'] = cop_c

return df_weather.round(2)

```

F Appendix - TES Simulation Engine

This section will cover the complete Python code for the TES Simulation Engine that was used in this thesis. The code is divided into sections to get a clear overview.

F.1 User input section

This section establishes the primary configuration parameters required for the simulation. It defines the hierarchical file structures, thermal comfort boundaries for each building zone, and the operational hardware capacities for the heating and cooling heat pump systems. Additionally, it configures the Thermal Energy Storage (TES) strategies, including charge/discharge priority and stratification management, as well as the grid power allocation logic that governs system-wide energy distribution.

```
# =====
# 1. USER INPUT SECTION (COMBINED STRATEGIES)
# =====

# File Paths
PATHS = {
    'thermal_data': 'Output - Results_Yearly_Zone_Demands_Combined - DYNAMIC.csv',
    'materials': 'Input - Multi zone simplified thermal mass - case study.txt'
}

# Shared Building Settings
COMFORT = {
    'T_start': [21.0, 22.0, 21.0, 21.0, 21.0], # Initial temperature for each zone ( C ).
    'T_set': [21.0, 22.0, 21.0, 21.0, 21.0], # Setpoint temperature for each zone ( C ).
    'T_swing': [2.0, 0.0, 2.0, 2.0, 2.0] # Allowed temperature swing ( C ).
}

# Heat Pump Hardware Capacities (kW)
HP_CAPACITY = {
    'heating': 95.0, # Max kW for the Heating HP.
    'cooling': 75.0, # Max kW for the Cooling HP.
    'min_mod_kva': 1.5 # 5% Electrical Maintenance Floor.
}

# Thermal Energy Storage (TES) Strategy Settings
TES_STRATEGY = {
    'heating': {
        'reheat_strat': "proportional", # For Thermal Mass Charging (Surplus)
        'reheat_prio': [1, 2, 3, 4, 5], # Priority order specifically for Charging.
        'dis_strat': "proportional", # For Modulated HP Distribution (Congestion)
        'dis_prio': [1, 2, 3, 4, 5], # Priority order specifically for Discharging.
        'tes_first': [False] * 5, # True = Use TES to keep T_SET. False = Drift to T_MIN.
        'delta_t': 10.0, # Temperature difference for Heating.
        'manual_kwh': None # Set size in kWh to bypass optimization, or None.
    },
    'cooling': {
        'reheat_strat': "proportional", # For Thermal Mass Charging (Surplus)
        'reheat_prio': [1, 2, 3, 4, 5], # Priority order specifically for Charging.
        'dis_strat': "proportional", # For Modulated HP Distribution (Congestion)
        'dis_prio': [1, 2, 3, 4, 5], # Priority order specifically for Discharging.
        'tes_first': [False] * 5, # True = Use TES to keep T_SET. False = Drift to T_MAX.
        'delta_t': 8.0, # Temperature difference for Cooling.
        'manual_kwh': None # Set size in kWh to bypass optimization, or None.
    }
}

# Physical & System Constants
CONSTANTS = {
    's': 1.2, # Safety factor.
    'rho': 1000, # Density of water (kg/m3).
    'cp': 4.18, # Specific heat capacity of water (kWh/kg.K).
    'eta_str': 0.95, # Stratification efficiency of the tank.
    'dead_zone': 0.20, # Unusable fraction of the tank capacity.
    'drift_rate': 0.0001, # Hourly thermal loss (e.g., 0.01%).
    'utilization_factor': 1.2
}

# Grid & Distribution Control
GRID_CONTROL = {
    'split_mode': 'proportional', # Options: 'fixed' or 'proportional'.
    'heating_share': 0.5, # Master Knob: % of grid/PV to this tank when 'fixed'.
    'show_flow_rates': True # Set to 'True' to show the flowrates per zone.
}
```

F.2 Data Loading Section

This section handles the ingestion and alignment of heterogeneous data sources required for the simulation. It calculates thermal mass properties from architectural specifications, sanitizes demand profiles to ensure simulation stability, and synchronizes periodic environmental and grid availability data with the simulation time-frame. Finally, it executes the integration handshake by aggregating zone-specific thermal demands and mapping the resulting heating and cooling potentials onto the primary simulation dataframe to establish operational constraints for each time-step.

```
# =====
# 2. DATA LOADING & PRE-PROCESSING
# =====
try:
    # --- Thermal Mass Processing ---
    df_mats = pd.read_csv(PATHS['materials'])
    # Convert material specs to thermal mass [kWh/K]
    df_mats['kWh_per_K'] = (df_mats['FloorArea'] * df_mats['SpecCapacity'] * 1000) / 3.6 / 1_000_000
    zone_masses = df_mats['kWh_per_K'].tolist()

    # --- Demand Profile Loading ---
    df_input = pd.read_csv(PATHS['thermal_data']).fillna(0) # Critical: Handle NaNs to prevent bisection failures
    df_input['Hour'] = df_input.index + 1
    demand_cols = [col for col in df_input.columns if 'Demand' in col]
    num_zones = len(demand_cols)
    sim_length = len(df_input)

    # --- Environmental & Grid Alignment ---
    # Loads external factors and aligns periodicity with the simulation length
    df_solar = pd.read_csv('Input PV - NEN5060-B2 1%.txt')
    df_temp = pd.read_csv('Input Temp - NEN5060-B2 1%.txt')
    df_grid = pd.read_csv('Output - total kVA - Hour, Grid_kVA.csv')

    # Align inputs to match simulation length (looping periodic data)
    df_grid_aligned = df_grid.iloc[np.arange(sim_length) % len(df_grid)].reset_index(drop=True)
    df_weather = df_solar.iloc[np.arange(sim_length) % len(df_solar)].reset_index(drop=True)
    df_weather['T'] = df_temp['T'].values[np.arange(sim_length) % len(df_temp)]

    # --- Engine Integration: The Combined Handshake ---
    # Aggregate heating/cooling demands to determine power split
    h_dem_series = df_input[demand_cols].apply(lambda x: x[x > 0].sum(), axis=1)
    c_dem_series = df_input[demand_cols].apply(lambda x: abs(x[x < 0].sum()), axis=1)

    df_potentials = calc_combined(
        df_weather,
        df_grid_aligned,
        split_mode=KVA_SPLIT_MODE,
        h_demand=h_dem_series,
        c_demand=c_dem_series,
        manual_share=HEATING_SHARE_INPUT,
        hp_max_h=HP_MAX_CAPACITY_H,
        hp_max_c=HP_MAX_CAPACITY_C
    )

    # Map potentials to input dataframe
    # We maintain separate columns for heating and cooling constraints
    df_input['Available_kVA_H'] = df_potentials['Elec_kVA_Heating'].values
    df_input['COP_H'] = df_potentials['COP_Heating'].values
    df_input['Max_Supply_kW_H'] = df_potentials['Potential_Heating_kW'].clip(upper=HP_CAPACITY['heating']).values

    df_input['Available_kVA_C'] = df_potentials['Elec_kVA_Cooling'].values
    df_input['COP_C'] = df_potentials['COP_Cooling'].values
    df_input['Max_Supply_kW_C'] = df_potentials['Potential_Cooling_kW'].clip(upper=HP_CAPACITY['cooling']).values
```

F.3 Main Simulation Loop

The simulation engine acts as the temporal orchestrator for the entire system, processing sequential thermal demand profiles across multiple zones. It employs a multi-strategy logic to manage thermal energy storage (TES) and heat pump dispatch concurrently for both heating and cooling circuits. At each time-step, the engine evaluates energy balances, prioritizes thermal comfort through either structural mass interaction or active TES discharge, and dynamically reallocates output based on infrastructure congestion and system efficiency constraints. This parallel execution ensures that heating and cooling demands are balanced against available thermal energy and grid availability.

```
# =====
```

```

# 3. SIMULATION ENGINE (PARALLEL DUAL-HP MODE)
# =====

def simulate_merged_multi_zone(
    df_input, demand_cols, zone_masses, T_starts, T_sets, T_swings,
    tank_cap_h, tank_cap_c,
    # --- Heating ---
    reh_strat_h, dis_strat_h, reh_prio_h, dis_prio_h, tes_h, zone_dt_list_h,
    # --- Cooling ---
    reh_strat_c, dis_strat_c, reh_prio_c, dis_prio_c, tes_c, zone_dt_list_c,
    # --- Constants ---
    min_mod_kva_h, min_mod_kva_c, drift_rate
):
    # Initialization and Boundaries
    T_mins = [s - sw for s, sw in zip(T_sets, T_swings)]
    T_maxs = [s + sw for s, sw in zip(T_sets, T_swings)]
    current_temps = list(T_starts)
    current_tank_kwh_h = tank_cap_h if TES_STRATEGY['heating']['manual_kwh'] is None
    else TES_STRATEGY['heating']['manual_kwh']
    current_tank_kwh_c = tank_cap_c if TES_STRATEGY['cooling']['manual_kwh'] is None
    else TES_STRATEGY['cooling']['manual_kwh']

    EPSILON = 1e-7
    num_steps = len(df_input)
    num_zones = len(demand_cols)

    # Transform pandas to NumPy arrays for faster access in the loop
    hour_arr = df_input['Hour'].values
    demand_arr = df_input[demand_cols].values

    # Heating Infrastructure Data
    max_supply_arr_h = df_input['Max_Supply_kW_H'].values
    cop_arr_h = df_input['COP_H'].values
    available_kva_arr_h = df_input['Available_kVA_H'].values
    cong_indices_h = np.where(max_supply_arr_h < (np.where(demand_arr > 0, demand_arr, 0).sum(axis=1) -
    EPSILON))[0]
    next_cong_map_h = np.searchsorted(cong_indices_h, np.arange(num_steps), side='right')

    # Cooling Infrastructure Data
    max_supply_arr_c = df_input['Max_Supply_kW_C'].values
    cop_arr_c = df_input['COP_C'].values
    available_kva_arr_c = df_input['Available_kVA_C'].values
    cong_indices_c = np.where(max_supply_arr_c < (np.where(demand_arr < 0, abs(demand_arr), 0).sum(axis=1) -
    EPSILON))[0]
    next_cong_map_c = np.searchsorted(cong_indices_c, np.arange(num_steps), side='right')

    # Prep Matrix (Adjusted for dual results)
    num_base_cols = 9
    num_per_zone = 4 if GRID_CONTROL['show_flow_rates'] else 3
    num_individual_cols = num_base_cols + (num_zones * num_per_zone)

    # We create TWO separate matrices so they match your individual script output
    results_matrix_H = np.zeros((num_steps, num_individual_cols))
    results_matrix_C = np.zeros((num_steps, num_individual_cols))

    strat_h_hist, strat_c_hist = [], []

    for idx in range(num_steps):
        # A. Drift (Both tanks lose potential)
        current_tank_kwh_h *= (1 - drift_rate)
        current_tank_kwh_c *= (1 - drift_rate)

        demands = demand_arr[idx]
        current_time_val = hour_arr[idx]

        # Separates the combined demand array into positive (heating) and absolute negative (cooling) values
        h_demands = np.maximum(0, demands)
        c_demands = np.abs(np.minimum(0, demands))

        total_demand_h = np.sum(h_demands)
        total_demand_c = np.sum(c_demands)

        # 1. Constants for the Floor calculation (Split for H and C)
        available_kva_limit_h = available_kva_arr_h[idx]
        available_kva_limit_c = available_kva_arr_c[idx]
        current_cop_h = cop_arr_h[idx]
        current_cop_c = cop_arr_c[idx]

        # 2. Strategy Variables
        delta_t_window_h, tsat_tes_h, tsat_struct_h = 0.0, 0.0, 0.0
        delta_t_window_c, tsat_tes_c, tsat_struct_c = 0.0, 0.0, 0.0

        tsats_per_zone_h = [0.0] * num_zones

```

```

tsats_per_zone_c = [0.0] * num_zones
active_strat_h = "Discharge"
active_strat_c = "Discharge"

current_zone_flows_h = [0.0] * num_zones
current_zone_flows_c = [0.0] * num_zones
actual_hp_out_h = 0.0
actual_hp_out_c = 0.0
deficit_to_track_h = 0.0
deficit_to_track_c = 0.0

results_matrix_H[idx, 0] = current_time_val
results_matrix_H[idx, 1] = total_demand_h
results_matrix_C[idx, 1] = total_demand_c

# B. HEATING HP BRANCH
available_power_h = max_supply_arr_h[idx]
if available_power_h >= (total_demand_h - EPSILON):
    # REHEAT / SURPLUS MODE
    current_zone_flows_h = [(d * 3600) / (CONSTANTS['rho'] * CONSTANTS['cp'] * zone_dt_list_h[i]) if d
    > EPSILON else 0.0 for i, d in enumerate(h_demands)]
    surplus_h = max(0.0, available_power_h - total_demand_h)
    actual_hp_out_h = total_demand_h + surplus_h

    map_idx_h = next_cong_map_h[idx]
    if map_idx_h < len(cong_indices_h):
        next_event_idx_h = cong_indices_h[map_idx_h]
        delta_t_window_h = float(hour_arr[next_event_idx_h] - current_time_val)
    else:
        delta_t_window_h = float(hour_arr[-1] - current_time_val)

    hunger_h = [max(0, T_sets[i] - current_temps[i]) * zone_masses[i] for i in range(num_zones)]
    total_hunger_h = sum(hunger_h)

    tsat_struct_h = (total_hunger_h / surplus_h * CONSTANTS['utilization_factor']) if surplus_h >
    EPSILON else 0.0
    tsats_per_zone_h = [(h / surplus_h * CONSTANTS['utilization_factor']) if surplus_h >
    EPSILON else 0.0 for h in hunger_h]
    tank_gap_h = max(0, tank_cap_h - current_tank_kwh_h)
    tsat_tes_h = (tank_gap_h / surplus_h) if surplus_h > EPSILON else 0.0

    if delta_t_window_h >= (tsat_struct_h - EPSILON):
        active_strat_h = "STRUCT"
        e_to_zones_h = min(surplus_h, total_hunger_h)
        e_to_tank_h = min(surplus_h - e_to_zones_h, tank_gap_h)
    else:
        active_strat_h = "TES"
        e_to_tank_h = min(surplus_h, tank_gap_h)
        e_to_zones_h = min(surplus_h - e_to_tank_h, total_hunger_h)

    if e_to_zones_h > EPSILON:
        if reh_strat_h == "proportional":
            for i in range(num_zones):
                if hunger_h[i] > EPSILON:
                    share_surplus_h = hunger_h[i] / total_hunger_h
                    zone_pwr_share = share_surplus_h * e_to_zones_h
                    tsats_per_zone_h[i] = (hunger_h[i] / zone_pwr_share * CONSTANTS['utilization_factor'])
                    current_temps[i] += (zone_pwr_share / zone_masses[i])
                    current_zone_flows_h[i] = ((h_demands[i] + zone_pwr_share) * 3600) /
                    (CONSTANTS['rho'] * CONSTANTS['cp'] * zone_dt_list_h[i])
                elif reh_strat_h == "sequential":
                    remaining_e_h = e_to_zones_h
                    for p_idx in reh_prio_h:
                        i = p_idx - 1
                        if hunger_h[i] > EPSILON and remaining_e_h > EPSILON:
                            give_h = min(remaining_e_h, hunger_h[i])
                            tsats_per_zone_h[i] = (hunger_h[i] / give_h * CONSTANTS['utilization_factor'])
                            current_temps[i] += (give_h / zone_masses[i])
                            current_zone_flows_h[i] = ((h_demands[i] + give_h) * 3600) /
                            (CONSTANTS['rho'] * CONSTANTS['cp'] * zone_dt_list_h[i])
                            remaining_e_h -= give_h
                        current_tank_kwh_h += e_to_tank_h
        else:
            # DISCHARGE MODE
            actual_hp_out_h = max(min_mod_kva_h * current_cop_h, available_power_h) if total_demand_h > 0
            else 0.0

    hp_shares_kw_h = [0.0] * num_zones
    if total_demand_h > EPSILON:
        if dis_strat_h == "proportional":
            for i in range(num_zones):
                share_h = h_demands[i] / total_demand_h
                hp_shares_kw_h[i] = actual_hp_out_h * share_h
        elif dis_strat_h == "sequential":

```

```

        rem_hp = actual_hp_out_h
        for p_idx in dis_prio_h:
            i = p_idx - 1
            give_h = min(rem_hp, h_demands[i])
            hp_shares_kw_h[i] = give_h
            rem_hp -= give_h
    for i in range(num_zones):
        if h_demands[i] > EPSILON:
            deficit = h_demands[i] - hp_shares_kw_h[i]
            actual_from_tank = 0.0
            if tes_h[i]:
                actual_from_tank = min(deficit, current_tank_kwh_h)
                current_tank_kwh_h -= actual_from_tank
                unmet_energy_h = deficit - actual_from_tank
                if unmet_energy_h > EPSILON: deficit_to_track_h += unmet_energy_h
                current_temps[i] -= (deficit - actual_from_tank) / zone_masses[i]
            else:
                t_pred = current_temps[i] - (h_demands[i] / zone_masses[i]) +
                    (hp_shares_kw_h[i] / zone_masses[i])
                if t_pred < (T_mins[i] - EPSILON):
                    needed = (T_mins[i] - t_pred) * zone_masses[i]
                    actual_from_tank = min(needed, current_tank_kwh_h)
                    current_tank_kwh_h -= actual_from_tank
                    current_temps[i] = t_pred + (actual_from_tank / zone_masses[i])
                    if current_temps[i] < (T_mins[i] - EPSILON):
                        deficit_to_track_h += (T_mins[i] - current_temps[i]) * zone_masses[i]
                else:
                    current_temps[i] = t_pred
            zone_pwr = hp_shares_kw_h[i] + actual_from_tank
            current_zone_flows_h[i] = (zone_pwr * 3600) / (CONSTANTS['rho']
                * CONSTANTS['cp'] * zone_dt_list_h[i])

# C. COOLING HP BRANCH
available_power_c = max_supply_arr_c[idx]

if available_power_c >= (total_demand_c - EPSILON):
    # --- REHEAT / SURPLUS MODE (COOLING) ---
    current_zone_flows_c = [(d * 3600) / (CONSTANTS['rho'] * CONSTANTS['cp'] * zone_dt_list_c[i]) if d
        > EPSILON else 0.0 for i, d in enumerate(c_demands)]
    surplus_c = max(0.0, available_power_c - total_demand_c)
    actual_hp_out_c = total_demand_c + surplus_c

    # Identify next congestion for delta_t_window
    map_idx_c = next_cong_map_c[idx]
    if map_idx_c < len(cong_indices_c):
        delta_t_window_c = float(hour_arr[cong_indices_c[map_idx_c]] - current_time_val)
    else:
        delta_t_window_c = float(hour_arr[-1] - current_time_val)

    # AGNOSTIC HUNGER: Energy gap to reach T_set from above
    hunger_c = [max(0, current_temps[i] - T_sets[i]) * zone_masses[i] for i in range(num_zones)]
    total_hunger_c = sum(hunger_c)

    tsat_struct_c = (total_hunger_c / surplus_c * CONSTANTS['utilization_factor']) if surplus_c >
        EPSILON else 0.0
    tsats_per_zone_c = [(h / surplus_c * CONSTANTS['utilization_factor']) if surplus_c >
        EPSILON else 0.0 for h in hunger_c]

    tank_gap_c = max(0, tank_cap_c - current_tank_kwh_c)
    tsat_tes_c = (tank_gap_c / surplus_c) if surplus_c > EPSILON else 0.0

    # HIERARCHICAL STRATEGY
    if delta_t_window_c >= (tsat_struct_c - EPSILON):
        active_strat_c = "STRUCT"
        e_to_zones_c = min(surplus_c, total_hunger_c)
        e_to_tank_c = min(surplus_c - e_to_zones_c, tank_gap_c)
    else:
        active_strat_c = "TES"
        e_to_tank_c = min(surplus_c, tank_gap_c)
        e_to_zones_c = min(surplus_c - e_to_tank_c, total_hunger_c)

    # COOLING TEMPERATURE & FLOW UPDATE
    if e_to_zones_c > EPSILON:
        if reh_strat_c == "proportional":
            for i in range(num_zones):
                if hunger_c[i] > EPSILON:
                    share_surplus_c = hunger_c[i] / total_hunger_c
                    zone_pwr_share_c = share_surplus_c * e_to_zones_c
                    current_temps[i] -= (zone_pwr_share_c / zone_masses[i])
                    current_zone_flows_c[i] = ((c_demands[i] + zone_pwr_share_c) * 3600) /
                        (CONSTANTS['rho'] * CONSTANTS['cp'] * zone_dt_list_c[i])
        elif reh_strat_c == "sequential":
            remaining_e_c = e_to_zones_c
            for p_idx in reh_prio_c:

```

```

        i = p_idx - 1
        if hunger_c[i] > EPSILON and remaining_e_c > EPSILON:
            give_c = min(remaining_e_c, hunger_c[i])
            current_temps[i] -= (give_c / zone_masses[i])
            current_zone_flows_c[i] = ((c_demands[i] + give_c) * 3600) /
                (CONSTANTS['rho'] * CONSTANTS['cp'] * zone_dt_list_c[i])
            remaining_e_c -= give_c
        current_tank_kwh_c += e_to_tank_c

    else:
        # --- DISCHARGE MODE (COOLING) ---
        actual_hp_out_c = max(min_mod_kva_c * current_cop_c, available_power_c) if total_demand_c > 0
        else 0.0
        hp_shares_kw_c = [0.0] * num_zones

        if total_demand_c > EPSILON:
            if dis_strat_c == "proportional":
                for i in range(num_zones):
                    share_c = c_demands[i] / total_demand_c
                    hp_shares_kw_c[i] = actual_hp_out_c * share_c
            elif dis_strat_c == "sequential":
                rem_hp_c = actual_hp_out_c
                for p_idx in dis_prio_c:
                    i = p_idx - 1
                    give_c = min(rem_hp_c, c_demands[i])
                    hp_shares_kw_c[i] = give_c
                    rem_hp_c -= give_c

        for i in range(num_zones):
            if c_demands[i] > EPSILON:
                deficit = c_demands[i] - hp_shares_kw_c[i]
                actual_from_tank = 0.0
                if tes_c[i]:
                    actual_from_tank = min(deficit, current_tank_kwh_c)
                    current_tank_kwh_c -= actual_from_tank
                    unmet_energy_c = deficit - actual_from_tank
                    if unmet_energy_c > EPSILON: deficit_to_track_c += unmet_energy_c
                    current_temps[i] += unmet_energy_c / zone_masses[i]
                else:
                    t_pred = current_temps[i] + (c_demands[i] / zone_masses[i]) -
                        (hp_shares_kw_c[i] / zone_masses[i])

                    if t_pred > (T_maxs[i] + EPSILON):
                        needed = (t_pred - T_maxs[i]) * zone_masses[i]
                        actual_from_tank = min(needed, current_tank_kwh_c)
                        current_tank_kwh_c -= actual_from_tank
                        current_temps[i] = t_pred - (actual_from_tank / zone_masses[i])
                        if current_temps[i] > (T_maxs[i] + EPSILON):
                            deficit_to_track_c += (current_temps[i] - T_maxs[i]) * zone_masses[i]
                    else:
                        current_temps[i] = t_pred
                zone_pwr = hp_shares_kw_c[i] + actual_from_tank
                current_zone_flows_c[i] = (zone_pwr * 3600) /
                    (CONSTANTS['rho'] * CONSTANTS['cp'] * zone_dt_list_c[i])

    # --- HEATING LOGGING (Populate Results Matrix H) ---
    results_matrix_H[idx, 0:9] = [current_time_val, total_demand_h, total_demand_c,
        available_power_h, actual_hp_out_h, current_tank_kwh_h, deficit_to_track_h,
        delta_t_window_h, tsat_tes_h]
    strat_h_hist.append(active_strat_h)

    col_ptr_h = 9
    for i in range(num_zones):
        results_matrix_H[idx, col_ptr_h] = h_demands[i]
        results_matrix_H[idx, col_ptr_h + 1] = current_temps[i]
        results_matrix_H[idx, col_ptr_h + 2] = tsats_per_zone_h[i]
        col_ptr_h += 3
        if GRID_CONTROL['show_flow_rates']:
            results_matrix_H[idx, col_ptr_h] = current_zone_flows_h[i]
            col_ptr_h += 1

    # --- COOLING LOGGING (Populate Results Matrix C) ---
    results_matrix_C[idx, 0:9] = [current_time_val, total_demand_h, total_demand_c,
        available_power_c, actual_hp_out_c, current_tank_kwh_c, deficit_to_track_c,
        delta_t_window_c, tsat_tes_c]
    strat_c_hist.append(active_strat_c)

    col_ptr_c = 9
    for i in range(num_zones):
        results_matrix_C[idx, col_ptr_c] = c_demands[i]
        results_matrix_C[idx, col_ptr_c + 1] = current_temps[i]
        results_matrix_C[idx, col_ptr_c + 2] = tsats_per_zone_c[i]
        col_ptr_c += 3
        if GRID_CONTROL['show_flow_rates']:

```

```

        results_matrix_C[idx, col_ptr_c] = current_zone_flows_c[i]
        col_ptr_c += 1

# Final DataFrame Construction
cols = ["Sim_Timestep", "Total_Demand_H_kW", "Total_Demand_C_kW", "Max_Supply_kW",
        "HP_Out_kW", "Tank_kWh", "Deficit_kW", "Window_h", "Tsat_TES"]
for i in range(num_zones):
    cols.extend([f"Demand_Z{i+1}_kW", f"Temp_Z{i+1}", f"Tsat_Z{i+1}_h"])
    if GRID_CONTROL['show_flow_rates']: cols.append(f"Flow_Z{i+1}_m3h")

df_h = pd.DataFrame(results_matrix_H, columns=cols)
df_h["Strategy"] = strat_h_hist
df_c = pd.DataFrame(results_matrix_C, columns=cols)
df_c["Strategy"] = strat_c_hist

return df_h, df_c, T_mins, T_maxs

```

F.4 Optimised Volume Check

This final section automates the system sizing through an iterative bisection search method. The engine executes multiple simulation passes to find the minimum Thermal Energy Storage (TES) capacity required to maintain zone temperatures within their defined comfort boundaries, effectively eliminating thermal violations. Following this optimization, the engine performs a hydraulic stability analysis, calculating the peak net flow requirements for both heating and cooling circuits. This ensures the system remains robust during periods of high demand deficit, sizing the necessary buffer volumes to prevent infrastructure instability.

This concludes the documentation for the core simulation framework. Please let me know if you would like me to review or format any additional components of your project.

```

# =====
# 4. RUN & OPTIMIZE (BISECTION SEARCH) & VIOLATIONS CHECK
# =====

def check_violations(df, T_mins, T_maxs, T_sets, tes_first_list):
    """
    Checks for thermal violations across both heating and cooling demands.
    - For Heating: Temp must not drop below (T_set if TES-first, else T_min).
    - For Cooling: Temp must not rise above (T_set if TES-first, else T_max).
    """
    for i, (t_min, t_max, t_set, tes_first) in enumerate(zip(T_mins, T_maxs, T_sets, tes_first_list)):
        # --- Heating Violation Check ---
        # If TES-first, floor is the setpoint; otherwise, it's the absolute minimum.
        floor = t_set if tes_first else t_min
        if (df[f"Temp_Z{i+1}"] < (floor - 1e-6)).any():
            return True

        # --- Cooling Violation Check ---
        # If TES-first, ceiling is the setpoint; otherwise, it's the absolute maximum.
        ceiling = t_set if tes_first else t_max
        if (df[f"Temp_Z{i+1}"] > (ceiling + 1e-6)).any():
            return True

    return False

T_mins_calc = [s - sw for s, sw in zip(T_SET_LIST, T_SWING_LIST)]
T_maxs_calc = [s + sw for s, sw in zip(T_SET_LIST, T_SWING_LIST)]

start_total = time.perf_counter()
run_count = 0

# --- 4.1 HOT TANK OPTIMIZATION (HEATING) ---
if MANUAL_TANK_KWH_H is None:
    print("Optimizing Hot Tank Size (Bisection Method)...")
    low_h, high_h = 0.0, 5000.0 # Search range in kWh
    best_tank_h = high_h

    for i in range(15):
        mid_h = (low_h + high_h) / 2
        # Run sim: Testing mid_h for heating, keeping cooling tank at 0 (or a safe high value)
        df_h, _, t_mins, t_maxs = simulate_merged_multi_zone(
            df_input, demand_cols, zone_masses, T_START_LIST, T_SET_LIST, T_SWING_LIST,
            mid_h, 5000.0, # Testing heating specifically
            REHEAT_STRATEGY_H, DISCHARGE_STRATEGY_H, REHEAT_PRIORITY_H,
            DISCHARGE_PRIORITY_H, ZONE_TES_FIRST_H, ZONES_DELTA_T_H,
            REHEAT_STRATEGY_C, DISCHARGE_STRATEGY_C, REHEAT_PRIORITY_C,

```

```

        DISCHARGE_PRIORITY_C, ZONE_TES_FIRST_C, ZONES_DELTA_T_C,
        MIN_MODULATION_KVA_H, MIN_MODULATION_KVA_C, DRIFT_RATE
    )

    # Check violations in Heating DataFrame
    if check_violations(df_h, t_mins, t_maxs, T_SET_LIST, ZONE_TES_FIRST_H):
        low_h = mid_h
    else:
        high_h = mid_h
        best_tank_h = mid_h
    print(f" Iter {i+1}: Testing {mid_h:.2f} kWh -> {'Violations' if low_h == mid_h else 'Pass'}")

    TANK_KWH_H_FINAL = best_tank_h
else:
    TANK_KWH_H_FINAL = MANUAL_TANK_KWH_H
    print(f"Using Manual Hot Tank Size: {TANK_KWH_H_FINAL} kWh")

# --- 4.2 COLD TANK OPTIMIZATION (COOLING) ---
if MANUAL_TANK_KWH_C is None:
    print("\nOptimizing Cold Tank Size (Bisection Method)...")
    low_c, high_c = 0.0, 5000.0
    best_tank_c = high_c

    for i in range(15):
        mid_c = (low_c + high_c) / 2
        # Run sim: Using the FINAL hot tank size, testing mid_c for cooling
        _, df_c, t_mins, t_maxs = simulate_merged_multi_zone(
            df_input, demand_cols, zone_masses, T_START_LIST, T_SET_LIST, T_SWING_LIST,
            TANK_KWH_H_FINAL, mid_c,
            REHEAT_STRATEGY_H, DISCHARGE_STRATEGY_H, REHEAT_PRIORITY_H,
            DISCHARGE_PRIORITY_H, ZONE_TES_FIRST_H, ZONES_DELTA_T_H,
            REHEAT_STRATEGY_C, DISCHARGE_STRATEGY_C, REHEAT_PRIORITY_C,
            DISCHARGE_PRIORITY_C, ZONE_TES_FIRST_C, ZONES_DELTA_T_C,
            MIN_MODULATION_KVA_H, MIN_MODULATION_KVA_C, DRIFT_RATE
        )

        # Check violations in Cooling DataFrame
        if check_violations(df_c, t_mins, t_maxs, T_SET_LIST, ZONE_TES_FIRST_C):
            low_c = mid_c
        else:
            high_c = mid_c
            best_tank_c = mid_c
        print(f" Iter {i+1}: Testing {mid_c:.2f} kWh -> {'Violations' if low_c == mid_c else 'Pass'}")

    TANK_KWH_C_FINAL = best_tank_c
else:
    TANK_KWH_C_FINAL = MANUAL_TANK_KWH_C
    print(f"Using Manual Cold Tank Size: {TANK_KWH_C_FINAL} kWh")

# --- 4.3 FINAL RUN & PERFORMANCE SUMMARY ---
run_count += 1
df_res_h, df_res_c, final_t_mins, final_t_maxs = simulate_merged_multi_zone(
    df_input, demand_cols, zone_masses, T_START_LIST, T_SET_LIST, T_SWING_LIST,
    TANK_KWH_H_FINAL, TANK_KWH_C_FINAL,
    REHEAT_STRATEGY_H, DISCHARGE_STRATEGY_H, REHEAT_PRIORITY_H,
    DISCHARGE_PRIORITY_H, ZONE_TES_FIRST_H, ZONES_DELTA_T_H,
    REHEAT_STRATEGY_C, DISCHARGE_STRATEGY_C, REHEAT_PRIORITY_C,
    DISCHARGE_PRIORITY_C, ZONE_TES_FIRST_C, ZONES_DELTA_T_C,
    MIN_MODULATION_KVA_H, MIN_MODULATION_KVA_C, DRIFT_RATE
)

end_total = time.perf_counter()
print(f"\nOptimization Complete.")
print(f"Total Simulation Runs: {run_count}")
print(f"Total Time Taken: {end_total - start_total:.2f} seconds")

# --- HYDRAULIC STABILITY CALCULATION (Heating Side - Vh_h) ---
df_res_h['Net_Power_Deficit_kW'] = (df_res_h['Total_Demand_H_kW'] - df_res_h['HP_Out_kW']).clip(lower=0)
df_res_h['Net_Flow_m3h'] = (df_res_h['Net_Power_Deficit_kW'] * 3600) / (rho * cp * delta_t_H)

has_deficit_h = df_res_h['Net_Power_Deficit_kW'] > 1e-6
peak_net_flow_h = df_res_h.loc[has_deficit_h, 'Net_Flow_m3h'].max() if has_deficit_h.any() else 0.0
Vh_volume_m3_h = (peak_net_flow_h * TAU_STABILITY) / (1 - DEAD_ZONE)

# Identify worst index for Table 2 highlight (Heating)
worst_idx_Vh_h = df_res_h.loc[has_deficit_h, 'Net_Flow_m3h'].idxmax() if has_deficit_h.any() else 0

# --- HYDRAULIC STABILITY CALCULATION (Cooling Side - Vh_c) ---
df_res_c['Net_Power_Deficit_kW'] = (df_res_c['Total_Demand_C_kW'] - df_res_c['HP_Out_kW']).clip(lower=0)
df_res_c['Net_Flow_m3h'] = (df_res_c['Net_Power_Deficit_kW'] * 3600) / (rho * cp * delta_t_C)

has_deficit_c = df_res_c['Net_Power_Deficit_kW'] > 1e-6
peak_net_flow_c = df_res_c.loc[has_deficit_c, 'Net_Flow_m3h'].max() if has_deficit_c.any() else 0.0
Vh_volume_m3_c = (peak_net_flow_c * TAU_STABILITY) / (1 - DEAD_ZONE)

```

```

# Identify worst index for Table 2 highlight (Cooling)
worst_idx_Vh_c = df_res_c.loc[has_deficit_c, 'Net_Flow_m3h'].idxmax() if has_deficit_c.any() else 0

end_total = time.perf_counter()
total_ms = (end_total - start_total) * 1000

```

F.5 Display Section

This section defines the utility functions for visualizing simulation outputs, providing a clean and interpretable format for reviewing performance data. It includes a custom styling function that dynamically identifies and highlights periods of thermal demand exceeding heat pump supply, a critical feature for identifying infrastructure congestion, alongside formatting rules to ensure numerical results remain readable across both the heating and cooling datasets.

```

# =====
# 5. STYLED DISPLAY
# =====

# --- STYLED DISPLAY FUNCTION ---
def apply_styles(row):
    """Highlight rows where the active demand exceeds HP supply."""
    # Since both columns exist in the dataframe, we check which demand is active (non-zero)
    h_dem = row.get('Total_Demand_H_kW', 0)
    c_dem = row.get('Total_Demand_C_kW', 0)

    # Pick the active demand for the current row (works for both H and C tables)
    active_demand = max(h_dem, c_dem)

    # Logic: If the active demand is greater than HP capacity, highlight the row blue
    if active_demand > row['Max_Supply_kW'] + 1e-4:
        return ['background-color: #002b5e; color: white'] * len(row)
    return [''] * len(row)

def clean_format(x):
    """Clean formatting for display purposes."""
    if isinstance(x, (int, float)):
        if abs(x) < 1e-6: return "0"
        if x % 1 == 0: return f"{int(x)}"
        return f"{x:.2f}"
    return str(x)

```

F.6 Heating Side Summary Section

This section generates the final diagnostic summary for the heating infrastructure, providing a detailed overview of the optimized hot water storage capacity and operational strategies. It calculates and outputs the physical storage volumes required for both the energy capacity (V_C) and hydraulic stability (V_H), while detailing the specific discharge behaviour for each building zone. Finally, it produces two focused data visualizations: one isolating the system's tank charge exhaustion cycle for energy capacity verification and another highlighting peak flow events to validate hydraulic stability under maximum heating demand pressure.

```

# =====
# HEATING SIDE SUMMARY
# =====
delta_u_h = cp * delta_t_H
v_c_h = (TANK_KWH_H_FINAL * 3600 * S) / (rho * delta_u_h * TOTAL_EFFICIENCY)

print(f"HEATING SIDE:")
print(f"Optimized Tank (Vc): {TANK_KWH_H_FINAL:.2f} kWh")
print(f"Charging: {REHEAT_STRATEGY_H.title()} | Discharge: {DISCHARGE_STRATEGY_H.title()}")
print(f"Final Volume (Vc): {v_c_h:.2f} m3")
print(f"Final Volume (Vh): {Vh_volume_m3_h:.2f} m3")

print("ZONE DISCHARGE STRATEGIES (H):")
for i in range(num_zones):
    status = f"MAINTAIN T_SET at {T_SET_LIST[i]}C" if ZONE_TES_FIRST_H[i] else f"ALLOW DRIFT from {T_SET_LIST[i]}C down"
    print(f"Zone {i+1}: {status}")

# --- HEATING SECTION DISPLAY ---
print("\n" + "="*30 + " TABLE 1: ENERGY CAPACITY (Vc_H) " + "="*30)
# Locate the moment of lowest energy in the hot tank

```

```

min_tank_h = df_res_h['Tank_kWh'].min()
worst_idx_vc_h = df_res_h[df_res_h['Tank_kWh'] <= min_tank_h + 1e-6].index[0]

# Define window: From last time tank was full before the dip, to next time it's full after
is_full_h = (df_res_h['Tank_kWh'] >= TANK_KWH_H_FINAL - 1e-6)
start_cand_vc_h = df_res_h.index[(df_res_h.index < worst_idx_vc_h) & is_full_h]
start_idx_vc_h = start_cand_vc_h[-1] if not start_cand_vc_h.empty else 0
end_cand_vc_h = df_res_h.index[(df_res_h.index > worst_idx_vc_h) & is_full_h]
end_idx_vc_h = end_cand_vc_h[0] if not end_cand_vc_h.empty else len(df_res_h) - 1

df_zoom_vc_h = df_res_h.iloc[start_idx_vc_h : end_idx_vc_h + 1].copy()
numeric_cols_h = df_zoom_vc_h.select_dtypes(include=['number']).columns
display(df_zoom_vc_h.style.format({col: clean_format for col in
numeric_cols_h}).hide().apply(apply_styles, axis=1))

print("\n" + "="*30 + " TABLE 2: HYDRAULIC STABILITY (Vh_H) " + "="*30)
# Center the view on the peak flow event calculated in Section 4.3
start_idx_Vh_h = max(0, worst_idx_Vh_h - 2)
end_idx_Vh_h = min(len(df_res_h)-1, worst_idx_Vh_h + 2)
df_zoom_Vh_h = df_res_h.iloc[start_idx_Vh_h : end_idx_Vh_h + 1].copy()
display(df_zoom_Vh_h.style.format({col: clean_format for col in numeric_cols_h}).hide().apply(lambda x:
['background-color: #5e0000; color:
white' if x.name == worst_idx_Vh_h else '' for i in x],
axis=1).set_caption("Peak Net Flow Heating Highlighted"))

```

F.7 Cooling Side Summary Section

This section generates the final diagnostic summary for the cooling infrastructure, providing a detailed overview of the optimized storage capacity and operational strategies. This section is a mirrored version of the heating side summary. Again, it calculates and outputs the physical storage volumes required for both the energy capacity (V_C) and hydraulic stability (V_H), while detailing the specific discharge behaviour for each building zone. Finally, it produces two focused data visualizations: one isolating the system's tank charge exhaustion cycle for energy capacity verification and another highlighting peak flow events to validate hydraulic stability under maximum demand pressure.

```

# =====
# COOLING SIDE SUMMARY
# =====
delta_u_c = cp * delta_t_C
v_c_c = (TANK_KWH_C_FINAL * 3600 * S) / (rho * delta_u_c * TOTAL_EFFICIENCY)

print(f"COOLING SIDE:")
print(f"Optimized Tank (Vc): {TANK_KWH_C_FINAL:.2f} kWh")
print(f"Charging: {REHEAT_STRATEGY_C.title()} | Discharge: {DISCHARGE_STRATEGY_C.title()}")
print(f"Final Volume (Vc): {v_c_c:.2f} m ")
print(f"Final Volume (Vh): {Vh_volume_m3_c:.2f} m ")

print("ZONE DISCHARGE STRATEGIES (C):")
for i in range(num_zones):
    status = f"MAINTAIN T_SET at {T_SET_LIST[i]} C " if ZONE_TES_FIRST_C[i]
    else f"ALLOW DRIFT from {T_SET_LIST[i]} C up to {final_t_maxs[i]:.2f} C "
    print(f"Zone {i+1}: {status}")

# --- COOLING SECTION DISPLAY ---
print("\n" + "="*30 + " TABLE 1: ENERGY CAPACITY (Vc_C) " + "="*30)
min_tank_c = df_res_c['Tank_kWh'].min()
worst_idx_vc_c = df_res_c[df_res_c['Tank_kWh'] <= min_tank_c + 1e-6].index[0]

is_full_c = (df_res_c['Tank_kWh'] >= TANK_KWH_C_FINAL - 1e-6)
start_cand_vc_c = df_res_c.index[(df_res_c.index < worst_idx_vc_c) & is_full_c]
start_idx_vc_c = start_cand_vc_c[-1] if not start_cand_vc_c.empty else 0
end_cand_vc_c = df_res_c.index[(df_res_c.index > worst_idx_vc_c) & is_full_c]
end_idx_vc_c = end_cand_vc_c[0] if not end_cand_vc_c.empty else len(df_res_c) - 1

df_zoom_vc_c = df_res_c.iloc[start_idx_vc_c : end_idx_vc_c + 1].copy()
numeric_cols_c = df_zoom_vc_c.select_dtypes(include=['number']).columns
display(df_zoom_vc_c.style.format({col: clean_format for col in
numeric_cols_c}).hide().apply(apply_styles, axis=1))

print("\n" + "="*30 + " TABLE 2: HYDRAULIC STABILITY (Vh_C) " + "="*30)
start_idx_Vh_c = max(0, worst_idx_Vh_c - 2)
end_idx_Vh_c = min(len(df_res_c)-1, worst_idx_Vh_c + 2)
df_zoom_Vh_c = df_res_c.iloc[start_idx_Vh_c : end_idx_Vh_c + 1].copy()
display(df_zoom_Vh_c.style.format({col: clean_format for col in
numeric_cols_c}).hide().apply(lambda x: ['background-color: #5e0000; color:
white' if x.name == worst_idx_Vh_c else '' for i in x],
axis=1).set_caption("Peak Net Flow Cooling Highlighted"))

```