Integrating a seasonal thermal energy storage FMU in a MATLAB/Simscape thermal source network model

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Abstract

The integration of Functional Mock-up Units (FMUs) enables effective multi-domain co-simulation and model exchange, offering new possibilities for energy systems modelling considering thermo-hydraulic aspects. This paper presents a case study on incorporating an FMU of a seasonal thermal energy storage (sTES), developed in Modelica/Dymola, into a MATLAB/Simscape model of a thermal source network (TSN). While traditional thermo-hydraulic models are typically confined to a single simulation environment, this study demonstrates the feasibility and advantages of FMU-based interoperability between Modelica/Dymola and MATLAB/Simscape.

A key focus is the methodological approach for integrating FMUs into Simscape, addressing interface requirements, solver settings, and model coupling challenges. To illustrate the impact of FMU integration, the authors present simulation results for exemplary operation scenarios: TSN operation with and without an sTES. Additionally, our simulation results offer valuable insights into the influence of sTES on TSN operation and system layout.

Keywords: Functional Mock-up Unit (FMU), Thermal Source Network (TSN), Seasonal Thermal Energy Storage (sTES), MATLAB/Simscape, Modelica/Dymola, Thermo-Hydraulic Modelling

1 Introduction

The ongoing development of heating and cooling networks, such as district heating systems, requires constant integration of emerging technologies and components. Carefully planning these evolving systems demands flexible modelling approaches, which can be challenging when specialized models for new components reside in different software environments. For instance, an advanced sTES model might be developed in Modelica, whereas other system elements or advanced control libraries might only be available in MATLAB/Simscape. In many research and industrial settings, software licensing constraints further limit the ability to adopt multiple environments simultaneously, constraining researchers and engineers to a single “in-house” simulation tool.

To overcome this shortcoming, FMUs have recently gained traction as an enabling technology for sharing tailored simulation models across diverse platforms. By exporting a component from one domain and importing it into another, FMUs allow modelers to exploit specialized models without having to re-produce or re-validate them. This interoperability is particularly valuable in modelling of thermal source networks, where accurate representations of devices such as sTES units are essential for analysing and optimizing network performance.

This paper aims to demonstrate the feasibility of integrating a sTES model, originally developed in Modelica, into a TSN model built in MATLAB/Simscape using the Functional Mock-up Interface (FMI) standard. This approach enables the reuse of a validated sTES model, thereby avoiding the need for reimplementation and validation in Simscape. The study focuses on two core aspects of feasibility: (1) the technical effort required to set up the interface and configure the inputs and outputs, and (2) the stability and computational efficiency of the resulting co-simulation. Two realistic operational scenarios are evaluated as use cases: first, TSN operation without an sTES, and second, TSN operation where the sTES is coupled via a heat exchanger. Overall, this study shows how FMU-based co-simulation can increase the flexibility of thermo-hydraulic modelling across tools and domains, reducing software-related barriers in academic and industrial contexts.

2 Background and Related Work

The planning and design of sTES systems is a highly interconnected and complex process, requiring the evaluation of multiple parameters such as volume, geometry, insulation quality, and system integration (Dahash et al. 2019b). To mitigate risks associated with real-world implementation and to ensure feasibility and effectiveness, modelling and simulation have become integral to sTES system planning. Moreover, energy system simulations are well-suited for evaluating integration strategies and control approaches that optimize system operation. Commonly used energy system simulation (ESS) tools include TRNSYS, EnergyPlus, Modelica/Dymola, MATLAB/Simulink, and Simscape.

Among these, TRNSYS has been widely adopted for modelling buried water-based TES, owing to its modular structure and availability of specific models like XST and ICEPIT, which facilitate coupling with buildings, heating plants, and other system-level components. For instance, (Li et al. 2019) used the Type 534 model to simulate a 3000 m³ pit sTES in a solar-assisted district heating system, evaluating different control strategies.

On a bright note, other environments have also explored buried sTES modelling. For example, (Dahash et al. 2020) developed and validated a buried tank sTES model in Modelica/Dymola, coupled with a ground model. However, this work was limited to component-level simulations and did not address the broader energy system context. Similarly, (Bott et al. 2022) developed an underground sTES model in MATLAB/Simscape, benefiting from its multi-domain capabilities. Yet, this model also focused exclusively on component-level analysis.

Consequently, validated sTES models integrated into full energy system simulations remain rare. In this context, co-simulation emerges as a promising solution, allowing the integration of component-level sTES models into broader system-level simulations. (Lyden et al. 2022) highlighted this gap, especially for borehole and aquifer TES models, while (Dahash et al. 2019b) noted a similar lack for pit and tank TES technologies.

To address this gap, the present work focuses on two key objectives:

1) Co-simulation of sTES and energy systems through the integration of an sTES Functional Mock-up Unit (FMU) into a top-level model of a real-world energy system, and
2) Optimization of system operation by evaluating the impact of sTES integration compared to a reference case without sTES.

3 Description of the Thermal Source Network

The TSN at the incampus site in Ingolstadt, Germany, serves as the case study in this work.

3.1 Overview of the Case Study

The TSN at the incampus in Ingolstadt (DE), is a pioneering energy system designed to facilitate CO_2-neutral industrial energy supply. The system's core principles include sustainability, modularity, and long-term viability (Müller et al. 2024). Due to the lower system temperature, the TSN offers a significant flexibility in integrating renewable and low-temperature energy sources, unlike conventional district heating systems. Key components in this system approach are decentralized heat pumps, which enable each building to extract or reject heat from/into the system independently from the TSN temperature level.

The incampus TSN undergoes development in multiple construction phases, eventually spanning 9 km of piping and connecting approximately 70 buildings, including:

- Offices, laboratories, and test benches, each with their own decentralized heat pump.
- A data centre acting as a major source of waste heat.
- Energy storage and distribution components, including an sTES and firefighting water tanks repurposed as thermal buffers.

A distinguishing feature of this TSN is that its pipes are uninsulated, allowing for thermal interaction with the surrounding ground. Unlike conventional district heating, where insulation is used to prevent energy loss, this TSN leverages its thermal environment as part of the storage and distribution system, potentially gaining heat or dissipating excess energy depending on the operational strategy. This can be attributed to the temperature levels foreseen in this TSN.

3.2 Energy Flows and System Operation

The TSN operates by balancing local, renewable, and waste heat sources with building-level heating and cooling demands. Unlike conventional heating networks, it functions bidirectionally, meaning buildings can both consume and supply heat leading to the so-called "prosumers." For this, each building is equipped with a decentralized heat pump, which allows it to either extract heat from the TSN for heating or reject excess heat into the network for cooling when operating in reverse operation.

The key energy sources include:

- Waste heat from the data centre (initially 1.83 MW, expandable to 3 MW), a stable and continuous source of low temperature heat in in the range of 18 to 38°C.
- Groundwater wells (1 MW thermal power), originally installed for remediation purposes and later adapted for thermal energy exchange.
- The Danube River (up to 10 MW thermal potential) as an additional cooling and heating source.
- Re-cooling plants (6 MW cooling capacity) for peak load scenarios.
- A seasonal thermal energy storage, designed as a water-gravel pit storage, re-purposing existing basin infrastructure, which reduces investment costs.

The primary objective of the system's control strategy is to balance and manage energy flows dynamically while minimizing operational costs, which for example depend on thermal losses or electricity consumption of heat pumps. The primary challenge in operating the TSN is finding the optimal strategy for system-wide efficiency. Accordingly, decisions shall be made regarding:

- The optimal TSN supply temperature levels to minimize losses while maximizing heat pump efficiency.
- The selection of thermal sources at different times considering cost, availability of renewable energy or other factors.
- The charging and discharging strategy of the sTES.

3.3 Motivation for FMU-Based Modelling of the TSN

To evaluate and validate different control strategies for the described system, a physical simulation model is a valuable tool. In general, FMUs can be utilized to integrate advanced, pre-existing simulation models of key components, which gives greater flexibility in testing and validation. Herein, this approach also might allow for faster and more accurate simulations, as an existing state-of-the-art sTES model developed in Modelica was directly incorporated rather than recreated in MATLAB/Simscape.

4 MATLAB/Simscape Model Development

4.1 Overall Model Structure

The MATLAB/Simscape implementation is encapsulated in a single .slx file, referencing a custom library to emulate the incampus with four main categories: Energy Hub, Pipes, Substations/Heat Pumps, and Buildings/ Loads.

All basic components which are used in the main subsystems have been taken from the two Simscape libraries *Fluids/Thermal Liquid* and *Foundation Library/Thermal.* The Simscape Toolbox is a MATLAB/Simulink add-on with a physically based, acausal modelling approach. It differs from the causal MATLAB/Simulink approach but is similar to the philosophy of Modelica/Dymola or other tools. This structure automatically derives the governing equations from the topology of the system, making it well suited to multi-domain energy systems. However, this approach has rarely been explored in Simscape (Dahash et al. 2019a).

In the base model, the sTES FMU is not yet included. However, an additional heat exchanger is already integrated into the Energy Hub to facilitate future FMU connections. Specific interface details are provided in Section 5.2 FMU integration.

4.2 Sub-Model Groups and Assumptions

Energy Hub

The Energy Hub comprises separate Simscape blocks for its centrifugal pump, heat exchangers, flow-coefficient valves, and a buffer tank (see Figure 1):

- **Pump:** A variable-speed centrifugal pump, parameterized with reference head/capacity curves, maintains the required volume flow in the TSN.
- **Heat Exchangers:** Two standard Simscape exchanger blocks connect the TSN to data centre waste heat and groundwater wells. A third exchanger is reserved for integrating the sTES FMU. Other heat exchangers to additional thermal sources were omitted.
- **Valves:** Simple flow-coefficient valves direct water through the appropriate heat exchanger or buffer tank, depending on an on/off control signal.

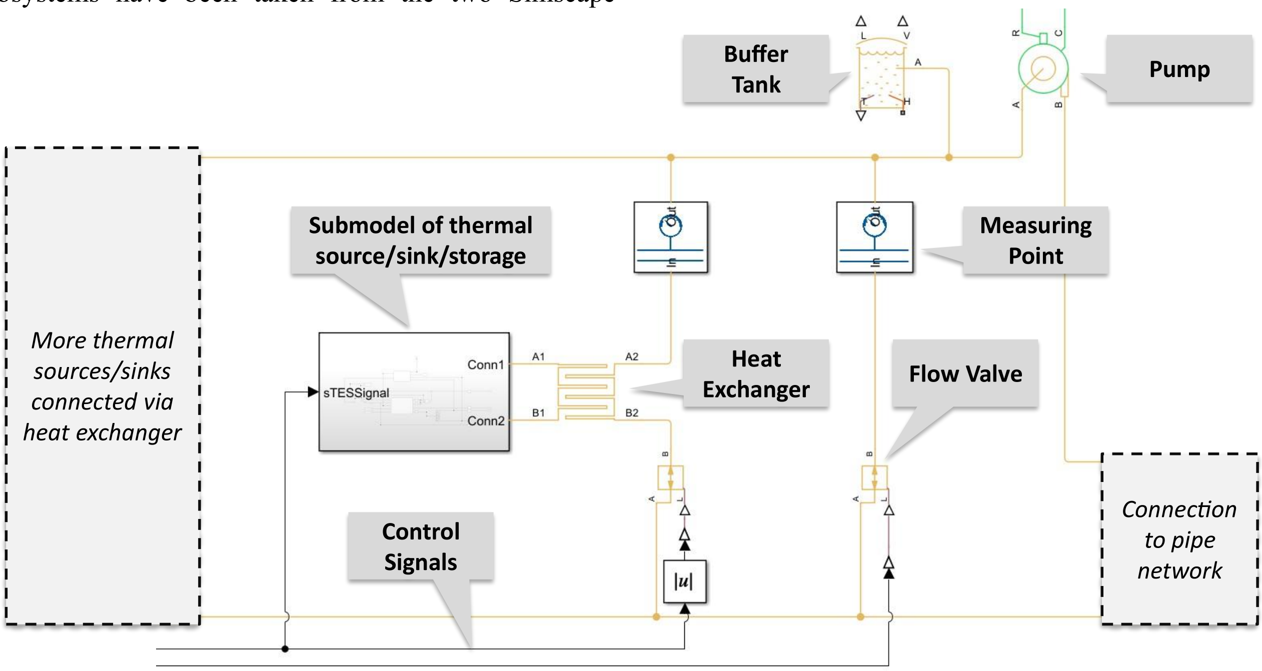

Figure 1. Components and Connections of the Energy Hub Sub-Model.

- **Buffer Tank:** Mainly accommodates thermal expansion (i.e. expansion vessel) in the simulated scenarios.
- **Measurement and Control:** The Hub's interfaces with the TSN piping and the thermal sources are monitored by thermal/hydraulic sensors (flow, pressure, temperature).

Pipes

The supply and return lines of the TSN are each represented by *Pipe (TL)* blocks from the Simscape *Fluids/Thermal Liquid* library, sized according to the incampus layout.

These blocks represent:

- Pressure Drop due to viscous friction.
- Heat Transfer with a seasonally varying ground temperature, using a fixed thermal resistance for the pipe wall.

To capture changes in diameter and branching points for buildings, the network is divided into multiple pipe segments. Thermal capacities of the pipe wall and ground are herein neglected. Flow is governed by the central pump in the Energy Hub, with no additional regulation in the pipes themselves. Pressure and temperature sensors placed at key nodes monitor conditions for system control and analysis.

Substations/Heat pumps

Each building in the TSN is equipped with a single heat pump block, which interfaces between the TSN and the building's heating and cooling circuits. Physically, this design yields six connection ports: supply and return lines for the TSN, and separate supply and return lines for both the heating and cooling circuits on the building side, all in the thermal liquid domain. In practice, the heat pump acts as a mediator, drawing energy from (or rejecting energy to) the TSN as required to satisfy the building's thermal demands.

Within the heat pump model, a Carnot-based approach is used to capture energy flows rather than simulating the full refrigeration cycle. In particular, the model measures the evaporator and condenser temperatures to calculate the theoretical Carnot efficiency, which is then scaled by a Carnot effectiveness factor (typically 0.4 to 0.5 for water-to-water heat pump units). This simplification emerges as a balance between realism and computational efficiency by focusing on overall heat exchange and compressor power, rather than diving into detailed phase-change processes and fluid properties.

From an operational perspective, the heat pump is capable of switching between four distinct modes: 1) heating (with the TSN serving as the heat source), 2) free cooling (where no compressor action is required and the TSN serves as the heat sink), 3) mechanical cooling (with the compressor actively dissipating heat into the TSN via the condenser), and 4) dual operation (with simultaneous building heating and cooling, using the TSN to cover any unbalanced demand).

The operation of these modes is governed by a local control scheme focusing on target supply temperatures in the building's heating and cooling circuits, along with the mass flow present in each loop. At instances where flow exceeds a pre-determined threshold, the heat pump starts automatically, with the objective of maintaining the selected supply temperature. The maximum power output is then limited by a rated thermal capacity. On the TSN side, the reference mass flow is calculated with respect to a prescribed temperature difference between TSN supply and return.

The heat pump model logs thermal energy flows and mass flow rates within the connected circuits, while alongside providing the COP and compressor power consumption as outputs.

Buildings/Loads

Currently, the incampus area is still under development and only two buildings from construction phase one are connected to the TSN (next to the Energy Hub and the Data Centre). Thus, this work simulates a future scenario where two more buildings are connected to the TSN.

The load profiles of the buildings are derived from planning documentation for the incampus energy system. This report provided the total floor area of each planned building, along with its annual heating and cooling energy demands (expressed in kWh/m^2a) and peak thermal loads (in kW/m^2). By virtue of this data, hourly heating and cooling profiles can be generated for each building and implemented as input signals for the heat flow sources.

Each building model comprises two separate circuits: one for heating and one for cooling. These circuits are each connected to an individual buffer tank, resulting in two tanks per building. Both tanks are connected to the heat pump's supply and return lines in the thermal liquid domain, while a thermal port on each tank interfaces with a controlled heat flow rate source. This source applies the building's time-varying thermal load, based on pre-defined demand profiles.

A key assumption in the building model is the exclusion of a specific thermal node or building capacity. The thermal inertia (i.e. thermal mass) of the buildings is implicitly included in the demand profiles, eliminating the need for detailed physical modelling of the building envelope. The tank serves to bridge the gap between the thermo-hydraulic domain of the heat pump and the demand-driven thermal domain of the load profiles. It is the interface point, facilitating heat exchange between the heat pump and the imposed thermal load. Each buffer tank is sized according to planning specifications (e.g. 1.8 m^3 for each tank in the functional building).

To maintain appropriate supply conditions, a thermostat logic governs each tank. In the heating circuit, the tank can be heated up to a maximum of 45°C and allowed to cool to 35°C. In the cooling circuit, the tank is cooled down to 14°C and permitted to warm up to 20°C.

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5 Functional Mock-up Units: Creation and Integration

5.1 FMU creation

The sTES FMU is based on a stratified thermal energy storage model integrated with thermo-hydraulic components – valves, pumps, and source/sink elements – from the Modelica Buildings library, enabling dynamic charging and discharging during simulations. The core sTES model is developed using the *PartialStratifiedTank* from the Buildings library. The model dividing the tank into *n* segments with uniform temperatures and allowing for multiple inlet and outlet streams. In the partial tank model, a key enhancement and modification is the adjustment of thermal conductivity to better represent diffusion effects. The model captures buoyancy-driven natural convection, caused by the temperature-dependent density of water, leading to internal recirculation between hot and cold regions. Notably, heat loss at the top of the tank may induce an inverse thermocline, a local stratification anomaly.

This model is coupled to a 2-D, axisymmetric ground model in order to simulate underground sTES configurations. The sTES model was cross-compared against a valid model showing its credibility as reported in (Dahash et al. 2020).

The model allows individual specification of heat transfer coefficients at the top, side walls, and bottom of the tank, reflecting different insulation levels.

Subsequently, the sTES model – comprising both the storage tank and surrounding ground domain – is connected to the aforementioned thermo-hydraulic components to represent a hydraulically decoupled sTES system. In this configuration, the sTES can be integrated into a broader energy system via a heat exchanger interface. The complete model is exported from the Dymola simulation environment as an FMU with the type set to Model Exchange and Co-Simulation using CVode, compliant with FMI version 2.0. This FMU is license-free and allows user-defined inputs for key parameters, including storage volume, height, initial temperature, and insulation quality (top, sidewalls, and bottom). The number of thermal segments within the sTES tank is fixed at 15.

The surrounding ground is discretized into 15 axial segments, with a user-defined outer radius. The inner radius is automatically determined by the sTES tank radius. The radial discretization is fixed at 40 segments. Additionally, the model includes a bottom ground domain extending 15 m beneath the tank, discretized into 15 axial and 65 radial segments, with an inner diameter of zero. The model supports spatially inhomogeneous ground properties, allowing users to define thermophysical parameters independently for the lateral and bottom ground domains.

The FMU requires three primary inputs to operate: the injected mass flow rate (*mDot_in*), its temperature (*T_in*), and a control signal (*yDis*) indicating the charging or discharging phase. Based on the value of *yDis*, the model dynamically determines the appropriate injection port – either at the top or bottom of the sTES – reflecting the current operational mode. Additionally, the user can supply a time-series profile for ambient temperature as input, as well as define the undisturbed ground temperature, enabling realistic boundary conditions for long-term thermal simulations.

The FMU provides several outputs over the simulation period, including the evolution of the top, bottom, and mean temperatures of the sTES. Additionally, it reports the total thermal losses, along with a breakdown of these losses by location (e.g., top, sidewalls, bottom). The FMU also outputs the extraction temperature during both charging and discharging phases.

5.2 FMU integration into Simscape

The sTES model, which was developed in Modelica, was integrated into the TSN simulation environment via the *FMU block* from the Simulink *Extras* library. The FMU was coupled at the Simulink level rather than directly within the Simscape physical domain. This is due to the signal-based nature of FMI, which requires the conversion of acausal physical ports in Simscape to causal signal lines in Simulink, and vice versa, using standard *PS-Simulink* and *Simulink-PS* converter blocks. To prevent algebraic loops resulting from feedback between Simscape and the FMU (e.g. temperature and flow dependencies across the interface), *Unit Delay* blocks were introduced at the FMU outputs. To enable efficient multirate simulation, the FMU was imported in co-simulation mode. This allowed it to operate with its own internal solver and step size, decoupled from the Simulink solver. In contrast, model exchange mode forced Simulink to integrate the FMU dynamics at its global solver rate. This prevented multirate execution and resulted in simulation times that were approximately 300% longer in test runs. Co-simulation was therefore better suited to this application, where the TSN and sTES have dynamics with different timescales. The influence of the communication step size between the FMU and the main model/sample time of the FMU on computational time is shown in Chapter 7.

The sTES FMU was linked to the TSN via a heat exchanger in the Energy Hub. This component remains entirely within the Simscape thermal liquid domain and serves as the hydraulic interface for charging and discharging the storage. On the FMU side of the heat exchanger, a set of interface components was implemented as can be seen in Figure 2:

- A *controlled temperature source* (Simscape) defines the outlet temperature of the sTES.
- A *mass flow rate source*, governed by a custom sTES control block, imposes charging or discharging flow rates.
- A *reservoir* serves as a pressure and temperature reference node in the thermal liquid domain.

- *Mass flow rate sensors* and *temperature sensors* capture input data for the FMU.

The FMU inputs include:
- Mass flow rate measured downstream of the flow source.
- Inlet temperature, measured in the return line from the heat exchanger.
- A charging/discharging signal, generated by the sTES control block.
- Ambient air temperature and undisturbed ground temperature, provided as time series inputs.

The main output of the FMU is the outlet temperature. It is forwarded to the controlled temperature source connected to the supply line of the heat exchanger. Additional outputs—the top and bottom temperatures of the sTES—serve as inputs to the control function that determines which storage operational phase is possible.
Signal conversion and unit consistency between Simscape and the FMU were ensured using *Simulink-PS* and *PS-Simulink* Converter blocks, with units set to Kelvin for temperature and kg/s for mass flow.
The sTES control block was implemented as a MATLAB function block, receiving a high-level charge/discharge request from the Energy Hub controller. It evaluates temperature conditions within the sTES and TSN to determine if the requested action can proceed (as described in detail in Chapter 6).

The sTES FMU employed in this study is a water-based thermal energy storage system whose parameters, including volume, height, initial temperature, and thermal resistances of each boundary surface, can be adjusted. For all simulations, the system was configured with a volume of 10,000 m³ and a height of 5 m, resulting in a nominal thermal capacity of approximately 230 MWh based on a design temperature differential of 20 K. Thermal insulation was modelled by assigning thermal resistances of approximately 0.5 W/m²K for the top surface and 1.3 W/m²K for the sidewalls.

While FMU-based integration enables cross-platform modularity, it also introduces structural limitations. The internal structure of the FMU cannot be modified directly. Changes to core physical assumptions, such as converting from a water-based model to a water-gravel model, would require access to the original Modelica source code and regeneration of the FMU. Nevertheless, the parameterised interface provided sufficient flexibility for the simulation scenarios considered in this study. This integration approach is designed for modularity. If future FMUs follow the same interface logic (inputs for mass flow, inlet temperature, and control signal, and outputs for outlet temperature, top, and bottom temperatures) they can be easily integrated with minimal adjustments, allowing for rapid adaptation to other storage models or components.

6 Control Structures

The overall system is governed by four independent control schemes:
- A central controller in the Energy Hub regulates the TSN supply temperature by activating available thermal sources.
- In each building, a local controller maintains the temperature in the heating and cooling buffer tanks within a hysteresis threshold.
- A dedicated controller for the sTES manages its charging and discharging based on system state and surplus or shortage of energy.
- Additionally, a pump controller regulates the TSN mass flow by adjusting the speed of the main hydraulic pump to ensure stable network operation.

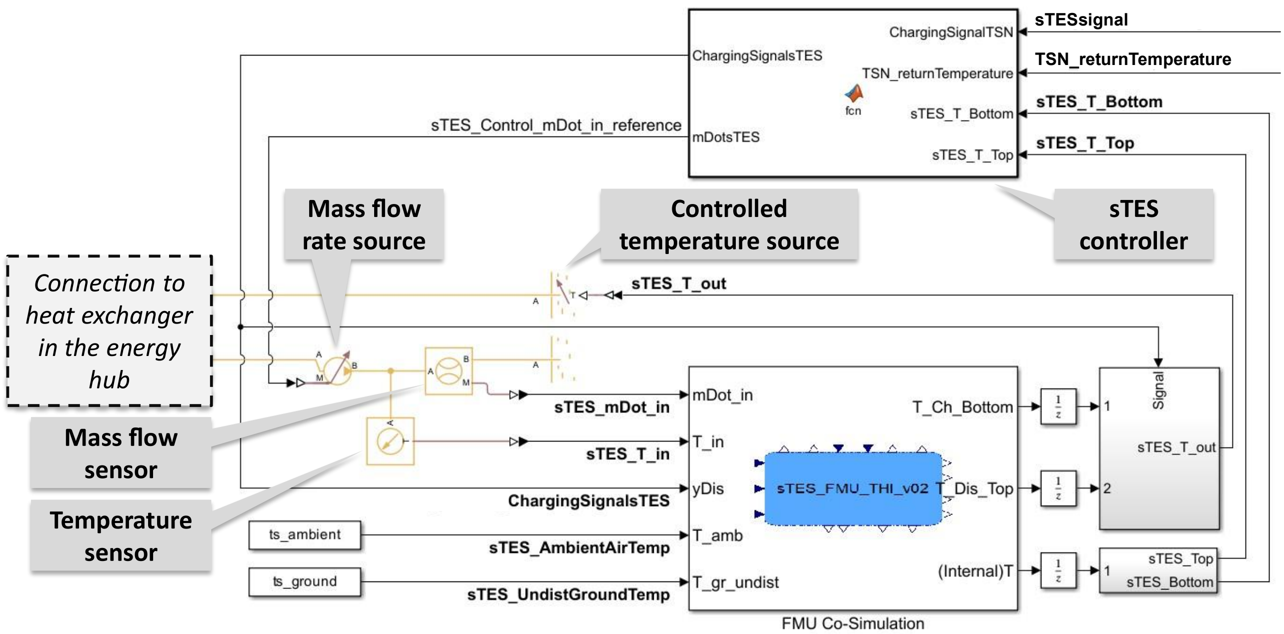

Figure 2. Connections and Interfaces of the sTES FMU.

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6.1 Energy Hub Control

The central control scheme ensures that the TSN supply temperature remains within defined limits, adjusting the activation of thermal sources accordingly as depicted in Figure 3. During summer, the supply temperature is maintained between 15°C and 35°C. While in winter, it is regulated within a range of 10°C to 20°C. In summer, a higher temperature reduces cooling losses to the warmer soil, while in winter, a lower temperature helps minimize heat losses to the colder ground. Additionally, the selected temperature bands consider the efficient operation of decentralized heat pumps. To achieve this, the controller can activate three thermal sources: waste heat from the data centre, groundwater wells, and, in future scenarios, the sTES. Herein, the selection follows a simple priority strategy. For both heating and cooling the sTES is prioritized. Only when the sTES cannot meet the demand, the waste heat from the data centre supplies heat as a secondary source, while for cooling, groundwater is used. This overall control logic is implemented using a Stateflow model, which allows for condition-based switching between sources.

6.2 sTES control

The sTES controller, depicted in Figure 4, receives a charging or discharging request from the central Energy Hub controller. Based on this input, it evaluates whether the current temperature levels in the TSN and the sTES allow for the requested operation. Charging is only activated if the bottom temperature of the sTES is at least 2 K below the TSN return temperature, while discharging is allowed if the top temperature of the sTES is at least 2 K above it. If the temperature conditions are met, the

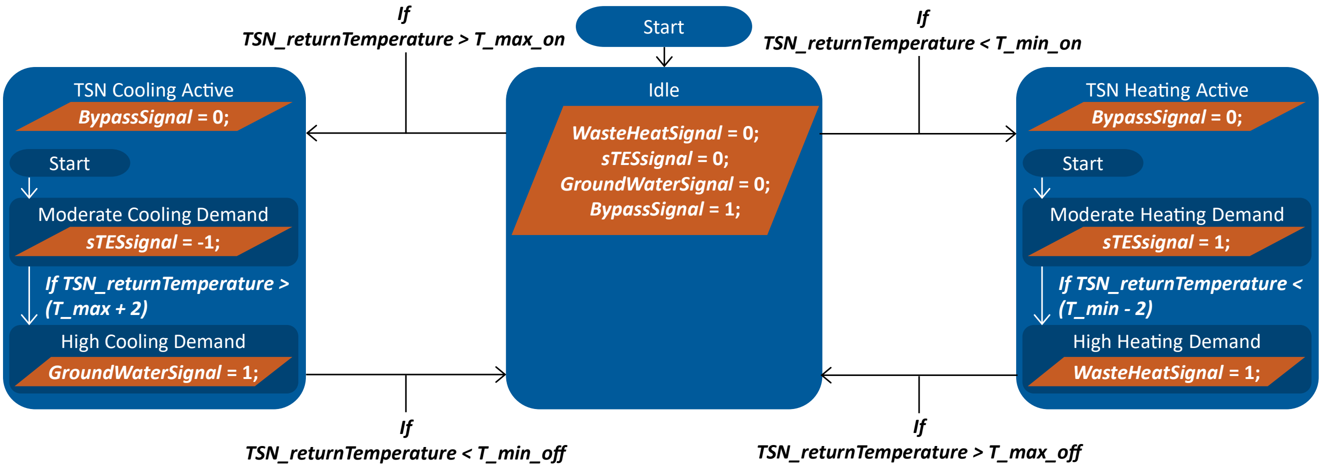

Figure 3. Energy Hub Control Strategy represented as a State Flow Chart.

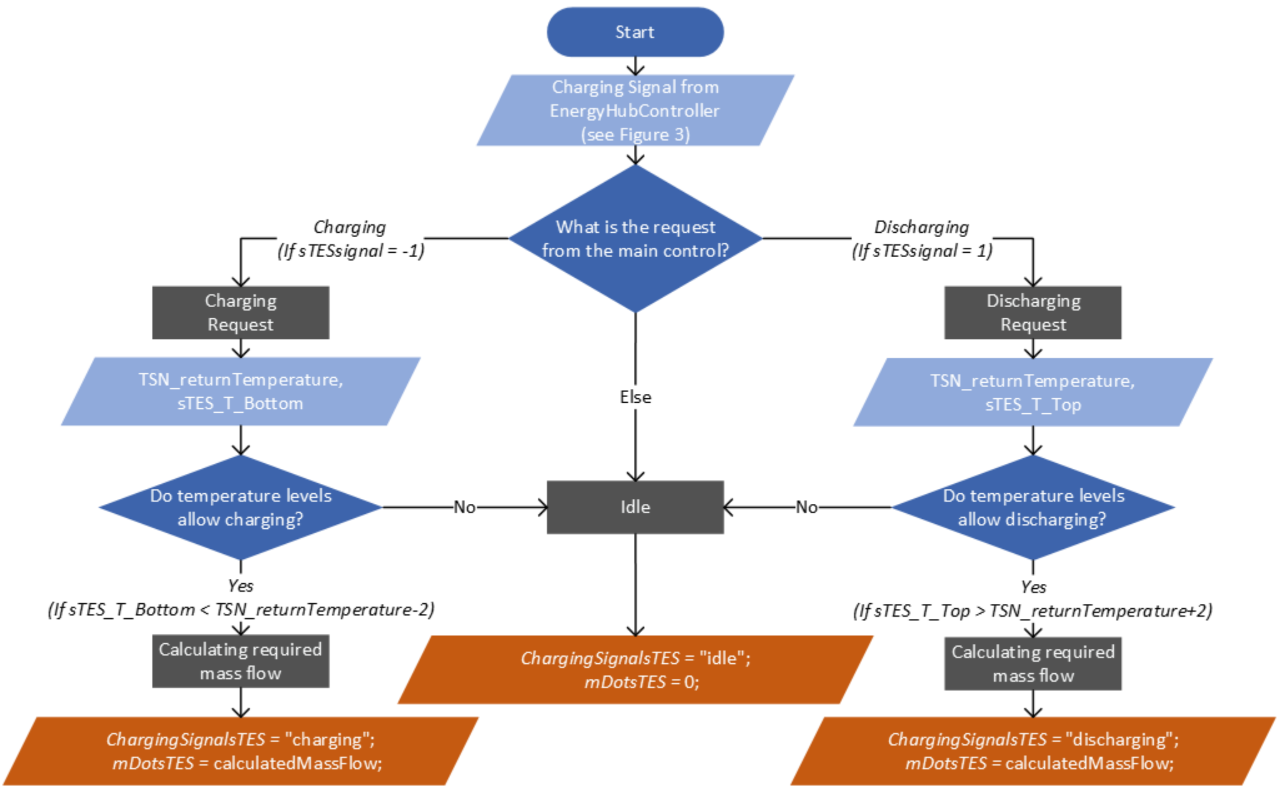

Figure 4. sTES Controller Flow Chart.

controller calculates the required mass flow and sets the operation mode accordingly. If not, the sTES remains idle and no flow is initiated.

6.3 Control Assumptions

To maintain model simplicity, idealized valve behaviour is assumed, and most control actions are treated as instantaneous. However, for pump control, a basic ramp-up function is applied to the control signal to better reflect realistic system dynamics.

7 Results

7.1 FMU Integration Results and Solver Settings

To assess the impact of solver settings on simulation efficiency, the model was evaluated using different combinations of co-simulation step sizes and solver types over a simulation period of 24 hours. Across all configurations, ode23t consistently outperformed all others yielding the shortest simulation times for short-term simulations, while daessc produced the longest, in line with its role in fixed-step real-time applications. Although ode23t was slightly faster than ode15s, it was found to be less stable in long-term simulations, often resulting in errors or early termination. Thus, ode15s was selected for the final year-round simulations, as it provided greater numerical robustness. These outcomes are consistent with MathWorks' recommendations for physical simulations involving stiff systems (The MathWorks, Inc. 2025).

According to MathWorks recommendations, enabling the use of a local solver for Simscape networks can significantly improve simulation performance and numerical stability—particularly in models with complex dynamics or coupled components from different domains. This setup allows the physical network to be updated independently of the global solver, providing greater flexibility in tuning solver configurations for performance and robustness.

In line with this recommendation, a fixed-step local solver was implemented for the Simscape thermo-hydraulic network and evaluated in combination with varying FMU communication step sizes. Both the FMU communication step size and the Simscape solver sample time affected simulation runtime, as illustrated in Figure 5. Larger values for either parameter mostly led to shorter simulation times. However, this came at the risk of reduced numerical stability in long-term simulations.

In the region where the simulation remained stable (specifically including long-term simulations), the Simscape solver sample time was found to be the dominant factor influencing simulation time.

The simulation was stable for Simscape sample times up to 5 seconds and FMU communication step sizes up to 600 seconds, which is attributable to the high thermal inertia of the system. Beyond these values, the model increasingly exhibited temperature divergence and numerical errors, particularly when the Simscape solver was configured with a larger sample time.

For the final configuration, a Simscape solver sample time of 5 seconds and an FMU communication step size of 300 seconds were selected. This combination provided a good compromise between simulation speed and numerical stability and is indicated as the black dot in Figure 5.

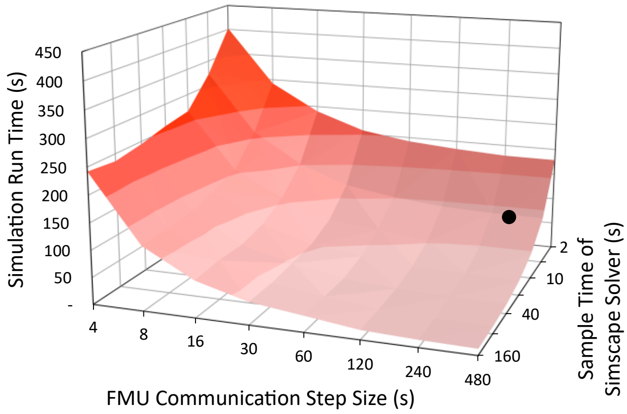

Figure 5. Simulation Run Time of Energy System Model (for 24 Hour Simulated Time) as a Function of FMU Communication Step Size and Simscape Solver Sample Time.

7.2 Energy System Simulation Results

The TSN is analysed in two scenarios:

- Scenario 1 – TSN without sTES: The thermal source network operates using only the available primary sources—waste heat from the data centre and cooling via groundwater wells.
- Scenario 2 – TSN with sTES: The same network configuration is used, but with the addition of a sTES connected to the TSN via a heat exchanger in the Energy Hub. In this setup, the sTES is treated as an integrated extension of the TSN, meaning it is only charged from and discharged to the network. It does not interface directly with any thermal sources or sinks. Charging and discharging occurs according to the control logic presented in Figures 3 and 4.

Figure 6 shows that the TSN return temperatures follow a similar trend in both scenarios. The control logic of the Energy Hub and available thermal sources were sufficient to maintain the requested temperature levels in the network. In the case without sTES, the network temperature fluctuated more drastically, reflecting the direct dependency on real-time availability from primary sources. By contrast, the inclusion of the sTES led to a noticeably smoother return temperature profile. These results showed that the sTES effectively dampened temperature peaks and maintained thermal stability in the network, acting as a buffer between fluctuating demands. The logged outputs of the sTES FMU provided further insights into the behaviour of the storage unit throughout the simulation year (Figure 7). During the first half of the year, the sTES is gradually charged with surplus heat from the TSN, as seen in the increasing top, bottom, and mean

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temperatures (see Figure 7.a). This stratified thermal profile indicates effective layering within the tank. In the second half of the year, the sTES transitions into discharge mode, providing additional thermal energy to the TSN during periods of increased demand. The corresponding thermal power curve (see Figure 7.b) confirms this pattern: negative values represent controlled discharging events, while positive values indicate charging of the sTES. Over the course of the simulation, a total of 289 MWh of heat was charged into the sTES, while 197 MWh was discharged back into the TSN.

8 Discussion

8.1 FMU Integration Results and Solver Settings

From a practical perspective, the integration process using Simulink's built-in FMU block was straightforward, requiring only signal conversion between physical and non-physical domains and careful attention to unit consistency. The most critical aspect was establishing reliable synchronization between the Simscape solver and the FMU co-simulation loop.

Importantly, performance benchmarks showed that the FMU was not a limiting factor in overall simulation time. Instead, simulation speed and stability were more strongly influenced by Simscape solver settings and the choice of global solver.

8.2 Energy System Simulation Results

The simulation results demonstrated that the thermal behaviour of the sTES is strongly influenced by the temperature level of the TSN itself. Since the sTES was connected to the network through a heat exchanger and can only be charged from the TSN, the maximum storage temperature was inherently limited by the network's supply conditions. As a result, the charging potential of the sTES was constrained, particularly during periods when TSN temperatures were suboptimal for storage loading. This limitation could be addressed in future system configurations by enabling charging from alternative sources or introducing a heat pump interface between the TSN and the sTES, thereby decoupling storage charging and discharging from the TSN temperature level leading to addressing sector coupling.

In terms of energy performance, the sTES received a total of 289 MWh of thermal energy during the simulation period and discharged 196 MWh into the TSN, yielding a storage efficiency of approximately 68%. This efficiency reflected the thermal losses to the surrounding ground and environment, as modelled within the FMU, and is within a reasonable range for seasonal storages (Bott et al. 2020).

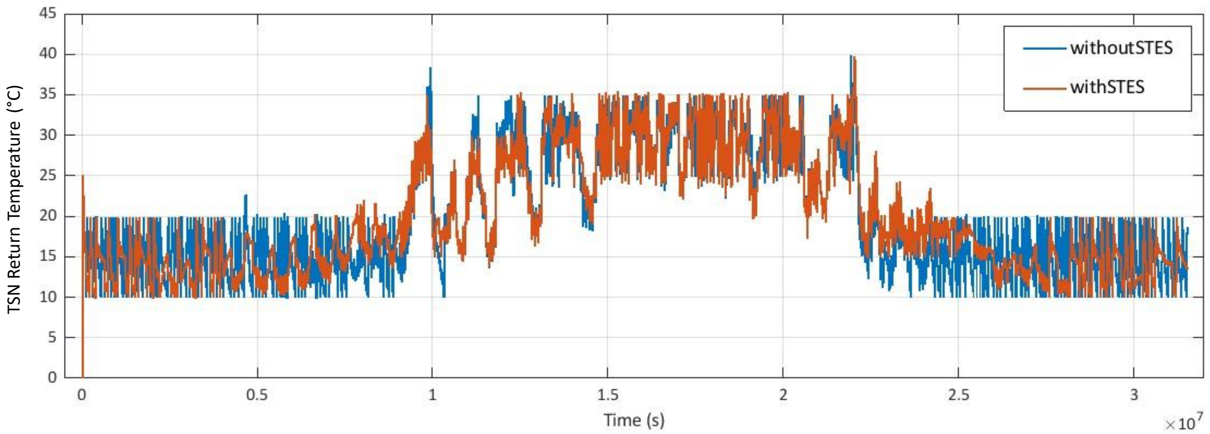

Figure 6. Comparison of TSN return temperature over time for two simulation scenarios.

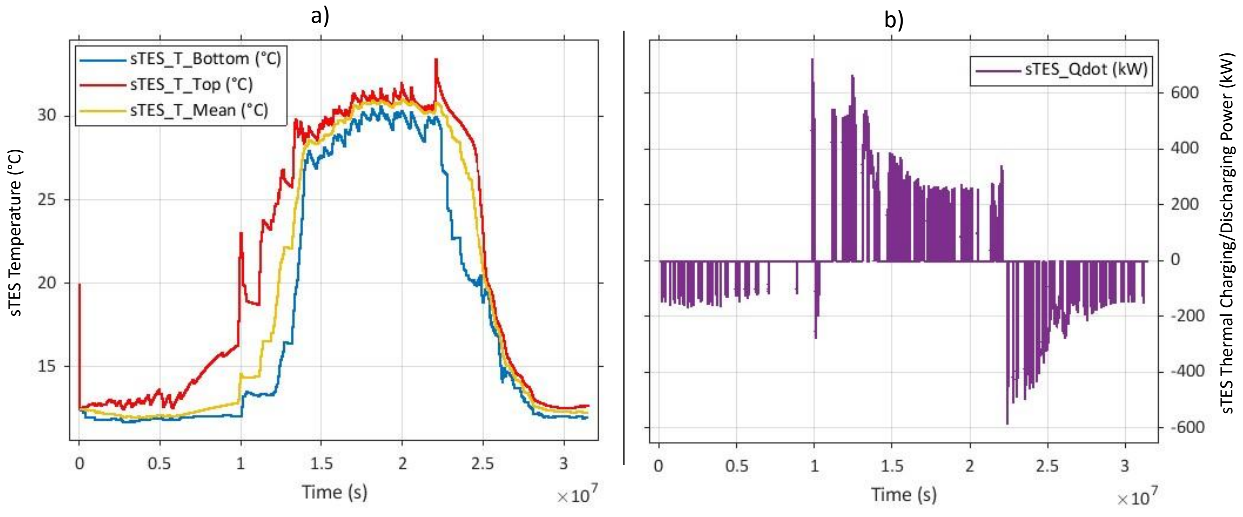

Figure 7. a) sTES temperatures and b) thermal power exchange between sTES and TSN.

8.3 Limitations

While the model successfully demonstrated the integration of an FMU-based sTES and its impact on TSN operation, several assumptions were made to keep the simulation tractable and focused. The pipe-ground interaction was considered using a static undisturbed ground temperature. Furthermore, the heat pump and building models were simplified, relying on Carnot efficiency and load profiles, respectively, rather than detailed thermodynamic or building physics. Additionally, the simulation was conducted over a single year, which limits the ability to fully assess long-term thermal interactions between the sTES and the surrounding ground. The implemented control strategies—both for the Energy Hub and the sTES—were designed for stability and clarity but do not include predictive or optimized logic, and the sTES was treated strictly as a passive TSN extension with no alternative source coupling. Additionally, while the study concentrated on runtime and stability, a more detailed evaluation of numerical precision and energy conservation across the FMI interface is yet to be conducted. Future work will include convergence studies and error analysis to quantify the consistency of energy between the FMU and Simscape subsystems.

9 Conclusion and Future Work

This paper presented a cross-platform simulation approach for modelling TSNs by integrating a Modelica-based FMU of an sTES into a MATLAB/Simscape environment. The co-simulation setup was implemented successfully, highlighting the interoperability potential between modelling domains and enabling the reuse of validated component models without reimplementation.

In the simulated case study, the sTES functioned as an integrated buffer within the TSN, helping to stabilize return temperatures and balance seasonal loads. With 289 MWh of thermal energy charged and 196 MWh discharged, the observed storage efficiency of approximately 68% reflects both thermal losses and current operational limitations, such as temperature coupling through a heat exchanger leading to indirect charging/discharging implying further thermal losses.

Future work will explore more advanced control strategies, such as model predictive control and reinforcement learning, with the aim of improving the operation of the TSN and the sTES. Annual simulations will be used to evaluate the long-term thermal interactions, particularly those with the surrounding ground. Additionally, coupling the sTES via a heat pump or enabling charging from alternative sources could increase flexibility, improve overall system performance, and address sector coupling. Finally, the approach could be extended in reverse by exporting the full TSN model as a MATLAB FMU for integration into Modelica, further demonstrating the bidirectional potential of FMI-based digital twins. It would also be valuable to compare FMU-based sTES integration with a simplified native Simscape implementation to evaluate trade-offs in terms of model fidelity, numerical performance, and cross-domain reusability. Similarly, a quantitative comparison of co-simulation and model-exchange FMUs could help assess the impact of FMU type on accuracy, stability, and energy consistency.

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