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Modeling and Integration of a Reversible Multi-Circuit Heat Pump for Flexible Operation in Thermal Source Networks

Shariq Akbar[a*], Simon Müller[a], David Schmitt[a], Tobias Schrag[a]

[a]Institute for new Energy Systems, Technische Hochschule Ingolstadt, 85049, Ingolstatd, Germany

Abstract

Reversible heat pumps (HPs) capable of providing simultaneous heating and cooling are well known at component level, but their role within Thermal Source Networks (TSNs) is still insufficiently explored with fast, system-level simulation models. This paper presents what we believe to be the first implementation of a modular, reversible multi-circuit heat pump model explicitly designed for integration into thermal source network (TSN) simulations with annual horizons. A reversible multi-circuit HP model is developed for a representative building sub-station at incampus in Ingolstadt, Germany. The MATLAB/Simscape model represents three hydraulic circuits (TSN, building heating, building cooling) and five active operating modes plus standby, using a quasi-steady Carnot-based formulation that is lightweight enough for year-long dynamic simulations.

The sub-station is embedded in a simplified TSN boundary model and driven by hourly heating and cooling demand profiles. Annual results show that the reversible HP supplies about 93% of the building's 223 MWh heating demand and 93% of its 244 MWh cooling demand, with auxiliary district heating and district cooling covering the remaining peaks. During dual operating modes, internal heat recovery from the cooling to the heating circuit contributes around 100 MWh, i.e. almost half of the annual heating demand, substantially reducing extraction from the TSN.

A comparison with a reference concept using a separate heating HP and chiller indicates that the reversible multi-circuit configuration can reduce TSN heating/cooling extraction by more than half while keeping total compressor electricity almost same. The model therefore provides a practical tool for assessing building-substation design and control strategies in TSNs with simultaneous heating and cooling demands.

Keywords: Thermal source network; reversible multi-circuit heat pump; Building sub-station; MATLAB/Simscape modelling;

1. Introduction

Modern cities face a critical challenge in decarbonizing building heating and cooling, which together account for 40% share of energy use and 36% of emissions [1]. Heat pump technology has emerged as a cornerstone solution, enabling the use of renewable electricity and ambient or waste heat to supply thermal demands with high efficiency. However, maximizing the benefits of heat pumps requires rethinking not only individual devices, but how entire districts exchange thermal energy [2].

One emerging concept is the Thermal Source Network (TSN), previously known as fifth-generation district heating and cooling (5GDHC) [3] – which is designed to simultaneously supply heating and cooling to multiple connected buildings. Unlike conventional district heating, which delivers hot water in one direction, a TSN is designed to simultaneously supply heating and cooling to multiple connected buildings, allowing them to share energy with each other [4]. The network operates at near-ambient temperatures, and each building is equipped with a decentralized heat pump that improves the temperature to meet the building's needs. In this way, each

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building becomes a prosumer: it consumes heat from the network when it has heating demand and injects excess heat into the network when it has cooling demand [5]. Surplus thermal energy from one building can thus be reused by another, which increases overall efficiency and facilitates the integration of low-exergy and renewable heat sources [6].

Further flexibility arises inside each building [7]. Many industrial or mixed-use buildings have separate heating and cooling circuits and experience simultaneous heating and cooling demands in different zones or for different end-uses [8]. Conventional systems often treat these as independent loads: chillers reject heat to the environment while boilers or district heating provide heat, even at the same time [9]. By contrast, a reversible heat pump capable of simultaneous heating and cooling recovers waste heat from the cooling circuit and uses it to cover heating demand within the same building. If such a heat pump is connected to a TSN, thermal demands are therefore balanced on two levels: first at the building level, by internal heat recovery between the building's heating and cooling circuits [8], and second at the network level, by exchanging any remaining surplus or deficit with other prosumer buildings via the TSN.

Several studies have modelled heat pumps for simultaneous heating and cooling, where a single refrigerant cycle serves both a hot-water circuit and a chilled-water circuit in parallel. Byrne *et al.* (2012,2019) developed and validated the model of air-source heat pump for simultaneous heating and cooling, showing that the same vapor-compression cycle can provide hot and chilled water concurrently [10,11]. Ghoubali *et al.* (2014) used TRNSYS simulations to study a heat pump for simultaneous heating and cooling in different building types and climates, showing that such systems can achieve higher overall COP than separate boiler–chiller solutions [12]. Shin *et al.* (2021) investigated simultaneous heating and cooling systems with thermal storage and flexible indoor temperature control, and reported substantial energy savings [9]. Detailed dynamic models for such heat pumps have been implemented in TRNSYS and Modelica to analyse refrigerant choices, component sizing and control strategies [13,14]. These high-fidelity models include explicit representations of compressors, heat exchangers and expansion devices, making them suitable for component-level design but computationally expensive for long-horizon or multi-building simulations. In system-level studies, the widely used approach is Carnot-based modelling, where the COP is represented as a fixed fraction of the ideal Carnot COP as a function of evaporator and condenser temperatures [15]. This formulation is also implemented in the Modelica Buildings library.

For TSNs, several recent works have demonstrated the feasibility and benefits of low temperature networks with decentralised heat pumps. Bilardo et al. (2021) developed a Modelica model of a bidirectional 5GDHC network to show substantial potential for demand balancing and primary energy savings [16]. Abugabbara et al. (2021, 2022) presented Modelica-based simulations of decentralised substations in 5GDHC networks and a design model for a real system with simultaneous heating and cooling demands, demonstrating that the shared energy flows between buildings cover 40% of the total carried heat [15,17].

In summary, the literature shows that reversible, multi-circuit heat pumps and TSNs have been studied separately, but rarely together. We found no fast heat pump model that both captures simultaneous heating–cooling operation and is light enough for district-scale simulation. To fill this gap, our work develops a modular MATLAB/Simscape model of a reversible multi-circuit heat pump designed for use in a TSN. The model explicitly includes three hydraulic circuits (building heating, building cooling, and network) and supports five operating modes (heating, mechanical cooling, free cooling, and two hybrid modes). We then integrate this into a district simulation to show how building-level heat recovery and network exchange interact.

Therefore, our study focuses on: (i) A novel yet computationally efficient model of a dual-circuit reversible heat pump, suitable for embedding in TSN studies. (ii) Demonstration of how such a unit can internally balance heating and cooling loads while flexibly sourcing from or sinking to the ambient network. (iii) Simulation results illustrating the effects of different modes on building performance and network operation. These results are purely simulation-based; we note that future work will include validating the model against field data.

2. Methodology

2.1. Incampus thermal energy system

The case study for this work is the thermal energy system of the incampus industrial park in Ingolstadt, Germany. The site is a 75-ha brownfield redevelopment on a former refinery area, jointly developed by AUDI AG and the city of Ingolstadt as a highly energy-efficient and low-carbon industrial park [18]. Figure 1 provides photographs of key infrastructure elements, including buildings, energy installations and the seasonal storage basin, all of which are already built and in partial operation. The long-term development is organized in four construction phases, during which both the buildings and the energy infrastructure are gradually expanded while the system must remain fully operational from the first connected consumers onwards [18].

Figure 1: Aerial views of the incampus site showing various connected buildings, energy hub, and thermal storage areas.

At the heart of the energy concept is a Thermal Source Network. The TSN is a bidirectional water network that interconnects non-residential buildings, central energy sources and several storage components. In its final expansion stage, the network is expected to reach a total length of about 9 km and supply up to 70 buildings, including office buildings, laboratories, test benches, a data center and an energy hub [19]. All connected buildings are equipped with decentralized water-to-water heat pumps that interface with the TSN and with the building-internal heating and cooling circuits. These units allow each building to operate as a thermal prosumer. A simplified schematic of the Incampus TSN is shown in Figure 2.

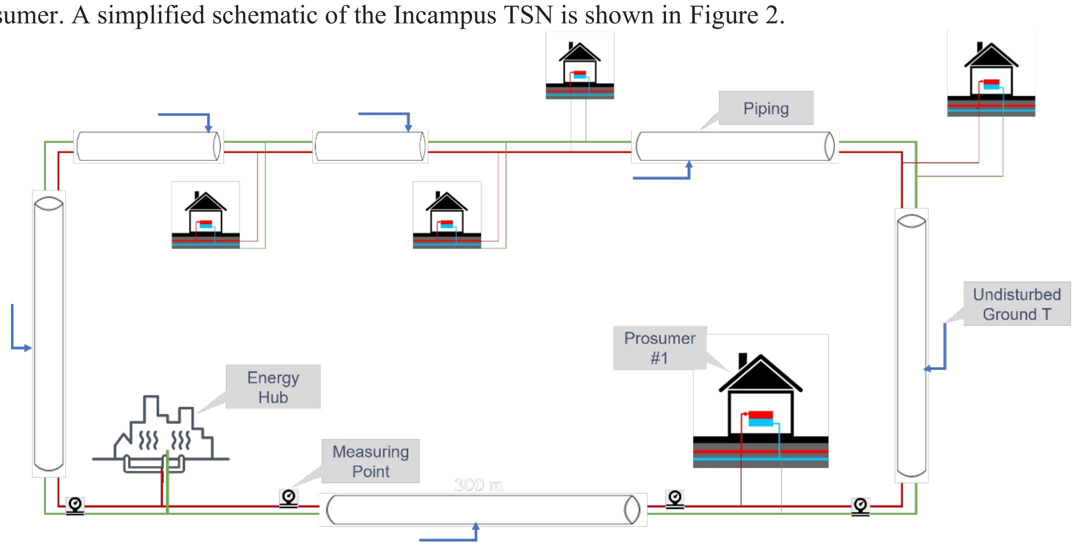

Figure 2: Schematic layout of the Incampus Thermal Source Network (TSN) with energy hub, and prosumer.

Planning studies defined allowable TSN supply temperatures of roughly 5 °C in winter and up to 30 °C in summer, and the main thermal sources and sinks were dimensioned accordingly: data-center waste heat (≈1.8 MW), groundwater wells (≈1 MW), the Danube River (≈10 MW) and an air-based re-cooling plant (≈2.25 MW) [20]. To support flexible operation, the system also uses the TSN water volume itself (≈2,200 m^3) and existing sprinkler tanks (≈3,150 m^3, ≈130 MWh) as short-term storage, while a large sTES in repurposed basin structures is currently under construction and is designed to provide 400+ MWh of seasonal storage.

Previous modelling studies have shown that this combination of TSN, local sources and storages can substantially reduce primary thermal energy demand by balancing heating and cooling both at building level and across the network. For the first construction phase, Müller et al. report a potential reduction of the net external thermal demand from 32.5 GWh/a to about 19.3 GWh/a when TSN-level balancing and local renewable sources are fully exploited [18].

The study focuses on one representative building sub-station at incampus. The building is connected to TSN via a decentralized reversible heat pump and interfaces with separate heating and cooling circuits on the building side. By modelling this sub-station and embedding it into a simplified representation of the TSN boundary conditions, we can analyze how a reversible multi-circuit heat pump contributes to local balancing of heating and cooling demands while remaining consistent with the overall incampus energy system concept. The current study is based on planning data; future work will incorporate measured operational data from the live system to further validate and calibrate the model.

2.2. Architecture of building sub-station (incampus specific)

The detailed model in this study represents one non-residential incampus building with both heating and cooling demand, similar in size and use to the "functional building", as given in Figure 3. The building is connected to the TSN via a decentralized reversible heat pump which interfaces with two separate building circuits: heating circuit supplying space heating and domestic hot water, and cooling circuit serving the building's chilled-water system. Both building circuits are coupled to the heat pump through buffer tanks that act as hydraulic and thermal interfaces. Each circuit has one well-mixed buffer tank with a simple thermostat logic: the heating tank is controlled between 35 °C and 45 °C, while the cooling tank is operated between 14 °C and 18 °C. Hourly heating and cooling load profiles for the building are derived from incampus planning data and imposed as time-varying thermal loads on the buffer tanks. In this way, the tank temperatures and mass flows reflect the dynamic interaction between building demand and sub-station operation over a full year.

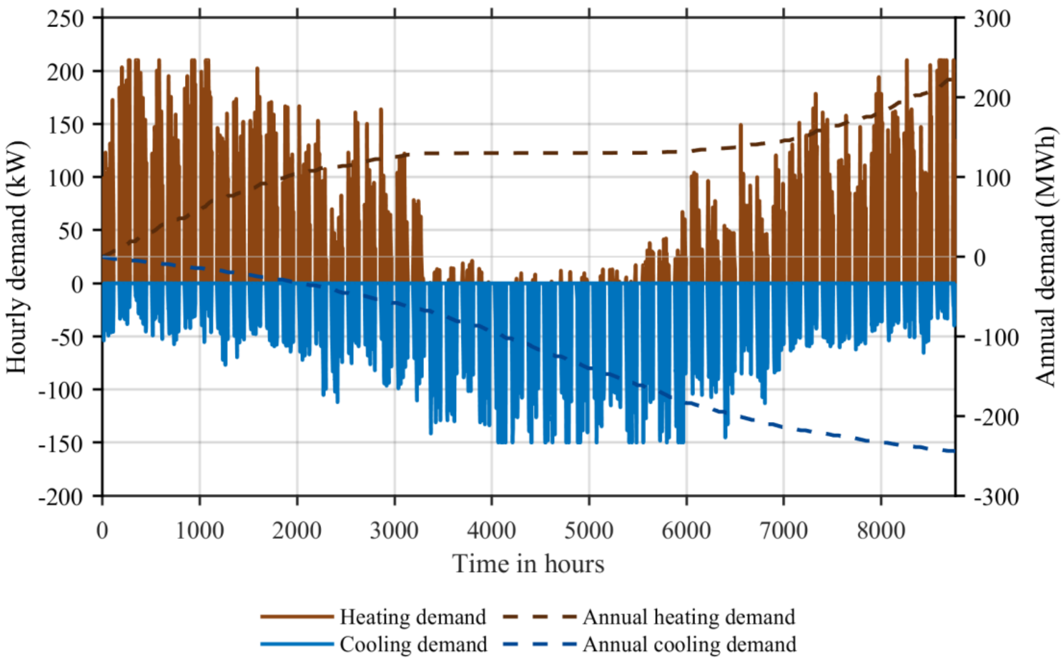

Figure 3: Hourly and annual heating and cooling demands

Hydraulically, the building sub-station comprises three external thermal-liquid circuits connected to the reversible heat pump: (i) the TSN circuit, (ii) the building heating circuit, and (iii) the building cooling circuit. Physically this yields six ports: supply and return for each circuit. The heat pump mediates energy flow between these circuits depending on the selected operating mode, either transferring heat between the two building circuits and/or exchanging heat with the TSN. A schematic view of the MATLAB/Simscape implementation, highlighting the three circuits and buffer tanks, is shown in Figure 4. This figure is intended to illustrate the overall signal and energy flow paths rather than every individual component detail.

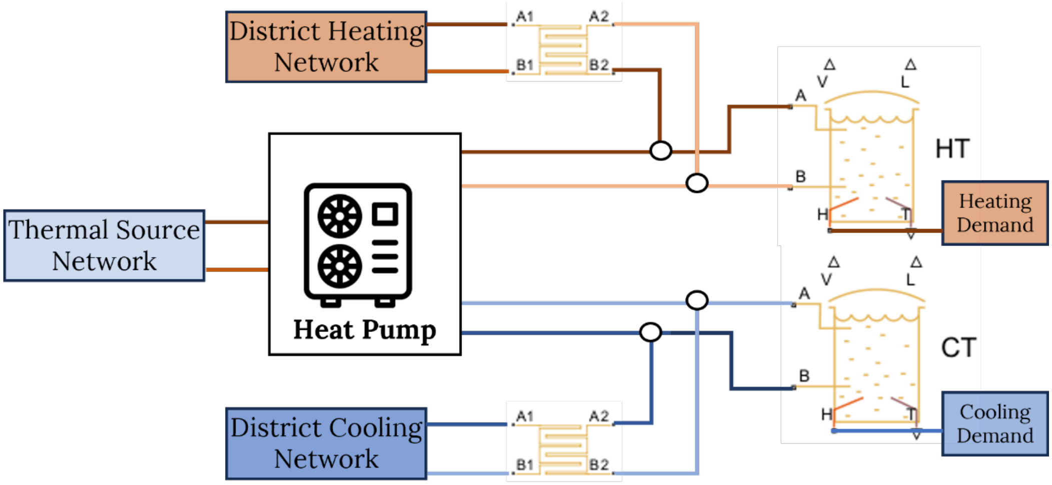

Figure 4: MATLAB/Simscape implementation of the incampus building sub-station with reversible multi-circuit heat pump, buffer tanks, and auxiliary district heating/cooling connections.

In addition to TSN, the building has auxiliary connections to the conventional district heating (DH) and district cooling (DC) networks. On the heating side, a heat exchanger couples the building heating circuit to the DH network; on the cooling side, a similar heat exchanger couples the building cooling circuit to the DC network. In the control scheme, the heat pump is the primary supplier for both circuits. The DH and DC connections are activated only when the heat pump cannot fully cover the heating or cooling demand (for example, when buffer tank temperatures fall outside their limits). In those cases, DH supports the heating circuit and DC supports the cooling circuit, while the TSN interface remains unchanged. This setup allows the sub-station to be analyzed under realistic conditions where the building can rely on DH/DC systems as backup, but the focus remains on the flexible operation of the reversible multi-circuit heat pump within the TSN.

2.3. HP model

The reversible multi-circuit heat pump is represented as a quasi-steady Carnot-based model implemented in MATLAB/Simulink. This approach, common in system-level studies, uses the ideal Carnot coefficient of performance (COP), scaled by a constant effectiveness factor ($\eta = 0.5$), to estimate realistic performance [15]. At each time step, the mean evaporating and condensing temperatures are computed from the respective inlet and outlet temperatures of the cold and hot sides of the heat pump, and are used to calculate the ideal COP via the Carnot relation. The real COP is then obtained by multiplying with the Carnot effectiveness factor.

The building heating and cooling circuits are dynamically coupled to the heat pump via buffer tanks, and their return temperatures are determined by the internal building loads. These return temperatures serve as the cold-side and hot-side inlets depending on the current operating mode. The supply temperatures to the building are fixed at 45 °C for heating and 12 °C for cooling. Based on the operating mode, the TSN may act as either a heat source or sink, and is connected to the evaporator or condenser side of the heat pump accordingly. The TSN inlet temperature is taken from the network boundary condition, while the TSN outlet is constrained by a minimum pinch of 5 K. Using this COP and the requested heating and cooling powers, the model determines the evaporator heat flow, the condenser heat flow and the corresponding electrical power consumption under the assumption of steady-state operation. The mass flow rate on the TSN side is derived from the calculated primary-side heat flow and the specified temperature spread, assuming constant specific heat capacity. The heat pump is simulated as a fixed-capacity unit with on/off operation logic. Part-load effects are not included in the current implementation.

The heat pump operates in five active modes—classical heating, mechanical cooling, free cooling, and two dual modes—plus a standby mode, depending on the building demand and temperature conditions. These modes and their energy flow characteristics are summarized in in Table 1.

Table 1: Operating modes of the reversible multi-circuit heat pump.

#	Mode	Building demands	TSN role	Compressor	Energy path
1	Classical heating	Heating > 0, Cooling ≈ 0	Source	On	TSN → HP → Heating circuit
2	Free cooling	Heating ≈ 0, Cooling > 0	Sink	Off	Cooling circuit → TSN (via HX), no HP
3	Mechanical cooling	Heating ≈ 0, Cooling > 0	Sink	On	Cooling circuit → HP → TSN
4	Dual mode (heating-dominated)	Heating > |Cooling| > 0	Source	On	Cooling circuit + TSN → HP → Heating circuit
5	Dual mode (cooling-dominated)	|Cooling| > Heating > 0	Source	On	Cooling circuit → HP → Heating circuit + TSN
6	Standby	Heating > 0, Cooling ≈ 0	-	Off	No heat transfer

3. Results

The annual heating and cooling demand profiles of the investigated incampus building (Figure 3) show a heating-dominated winter, with peak hourly loads above 200 kW, and a pronounced cooling season during summer with peak loads around 150 kW. Based on the simulated operation of the sub-station, the reversible heat pump can cover most of the building's heating and cooling demand, while the auxiliary district heating and district cooling connections are only activated during extreme peak periods. Over the full year, the combination of heat pump and DH meets a total heating demand of approximately 220 MWh, with the heat pump providing the dominant share. Similarly, the total annual cooling demand is about 250 MWh, of which most is supplied by the heat pump, supplemented by DC during the hottest periods.

The buffer tank temperatures illustrate how the reversible heat pump and the auxiliary networks interact with the building loads over the year. Figure 5 shows the heating buffer tank temperature together with the control thresholds. For most of the heating season, the tank temperature oscillates within the intended band between 35 °C (heat-pump start) and 45 °C (heat-pump stop), indicating stable thermostat operation. Only during a few high-load hours does the tank temperature approach the DH-enable threshold (around 32 °C), at which point the district heating connection is enabled to prevent further temperature drop and restore the setpoint range. During the summer period, the tank temperature gradually drifts downward due to negligible heating demand, so that the heat pump is rarely activated.

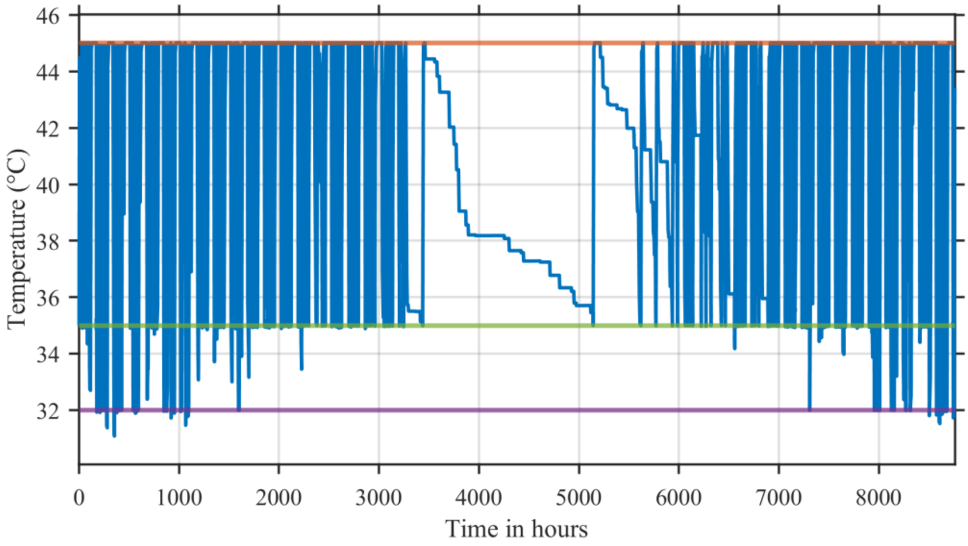

Figure 5: Heating buffer tank temperatures

The behavior of the cooling buffer tank is shown in Figure 6. The tank is controlled with a hysteresis band between 12 °C (heat pump off threshold) and 18 °C (heat pump on threshold), while 21 °C is defined as the enable threshold for district cooling. The tank temperature repeatedly cycles within the 12–18 °C band, indicating that the heat pump alone is sufficient to maintain the chilled-water conditions. Only during a limited period in mid-summer does the tank temperature occasionally rise above 18 °C and approach the 21 °C DC-enable threshold, reflecting sustained high cooling loads. The infrequent use of DC confirms that the cooling demand is largely covered by the reversible multi-circuit heat pump.

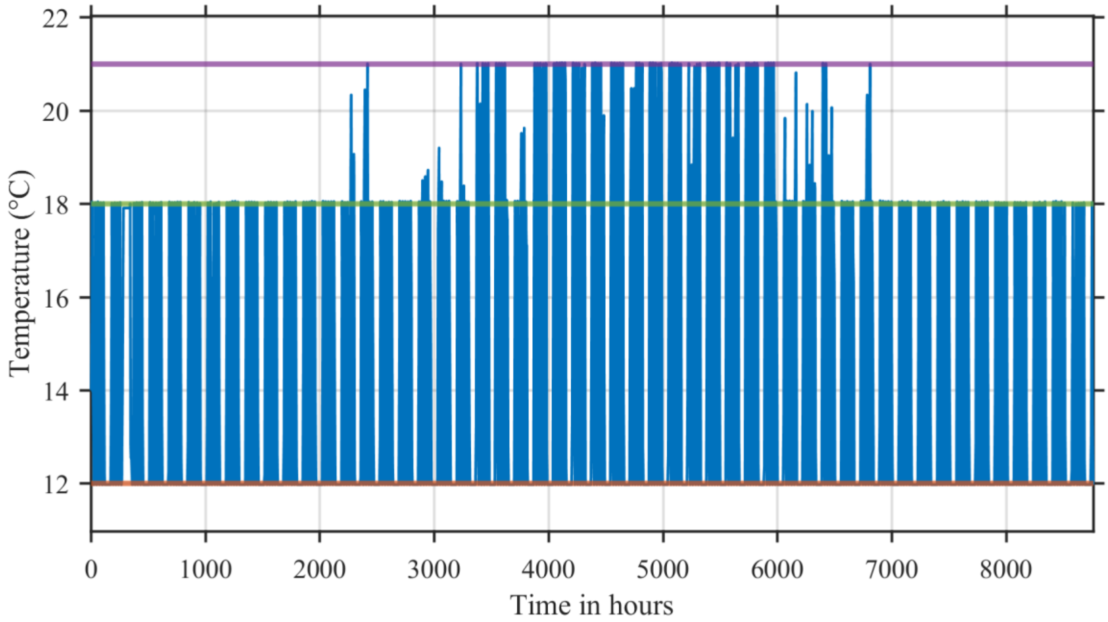

Figure 6: Cooling buffer tank temperatures

The utilization of the auxiliary district heating and district cooling connections over the simulation year is shown in Figure 7. District heating is only required during a few short periods at the beginning and end of the year, with peak powers of around 100 kW and a cumulative energy of roughly 15 MWh. District cooling is activated mainly during the central summer period, reaching up to about 70 kW and providing approximately 16 MWh of cold, corresponding to only 5–7 % of the total cooling demand of 260 MWh.

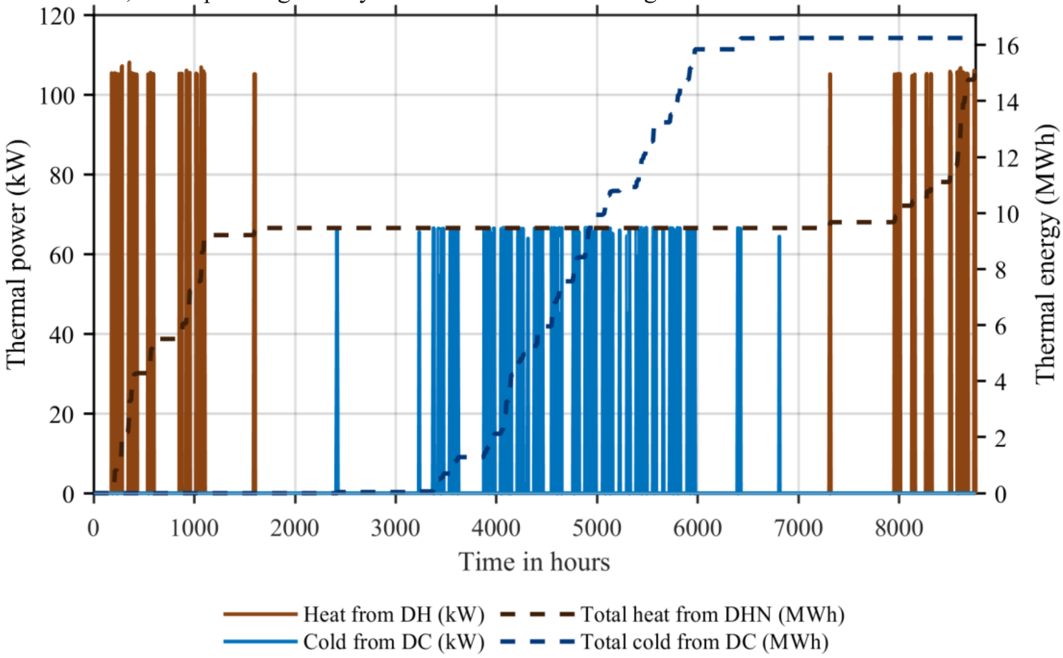

Figure 7: Power and annual energy from district heating (DH) and district cooling (DC) used by the incampus building sub-station.

4. Discussion

The annual distribution of heat pump operation modes is shown in Figure 8. Over the simulated year, the unit operates for 993 h in classical heating mode, 1,892 h in mechanical cooling mode, 636 h in dual heating-dominated mode and 1,303 h in dual cooling-dominated mode, while free-cooling mode is never activated and the heat pump remains off for 3,936 h. This indicates that the building spends roughly 55 % of the year with active heat-pump operation and that simultaneous heating-and-cooling conditions (dual modes) occur for about 1,939 h, corresponding to 40% of the operating hours. The absence of free-cooling operation informs that, with the current control thresholds and TSN temperature levels, the conditions where the network could directly satisfy the cooling demand without compression are not possible.

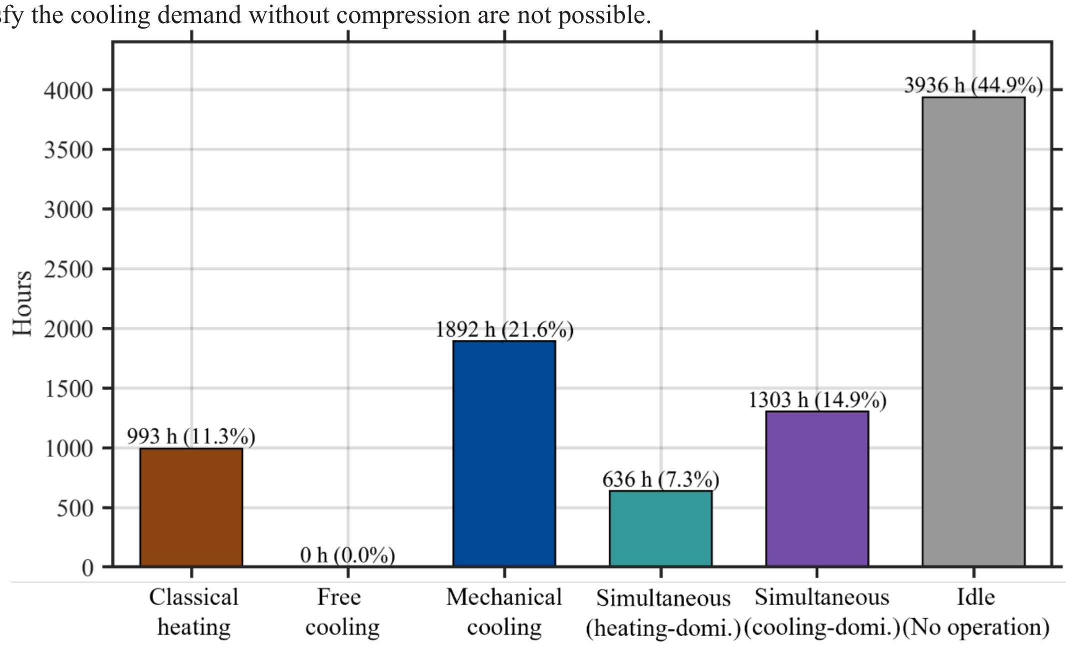

Figure 8: Annual distribution of operating hours of the reversible multi-circuit heat pump by operating modes.

Figure 9 summarizes the corresponding electricity consumption per mode. Classical heating accounts for 26 % of HP electricity, mechanical cooling consumes 20 %, heating-dominated dual operation uses 21 % and cooling-dominated dual operation is responsible for the largest share of 33%. The total annual electricity use of the reversible heat pump is 54 MWh, of which 25 MWh is associated with heating-focused modes and 29 MWh with cooling-focused modes. Taken together, the two dual modes represent around 54 % of the total heat-pump electricity consumption, even though they cover only about 22 % of the year in terms of operating hours.

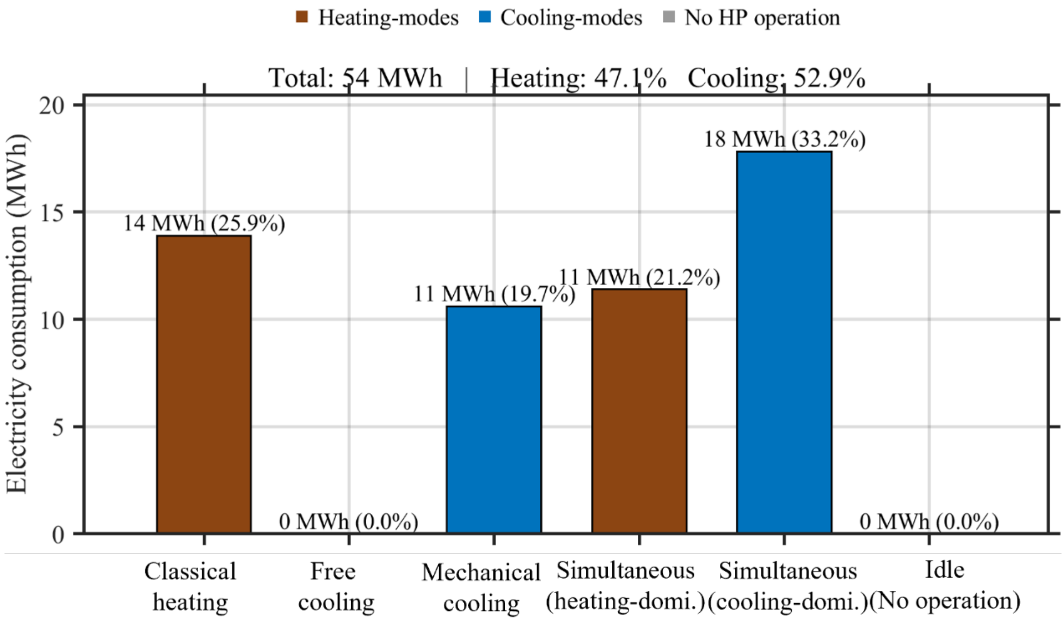

Figure 9: Annual electricity consumption of the reversible multi-circuit heat pump by operating mode, distinguishing between heating-oriented and cooling-oriented operation.

The annual energy balance of the reversible multi-circuit heat pump and its interaction with the TSN, DH and DC networks is summarized in Figure 10. On the heating side, the building requires 223.3 MWh of heat, of which 208.3 MWh (≈93 %) are supplied by the heat pump and 15.0 MWh (≈7 %) by district heating. The heat delivered by the heat pump combines three contributions: 83.4 MWh extracted from the hot branch of the TSN, 25.1 MWh of compressor electricity that is upgraded to useful heat, and 99.8 MWh recovered from the cooling side during dual operation. This internal heat recovery covers almost half of the annual heating demand and demonstrates the benefit of simultaneously serving the heating and cooling circuits with a single unit.

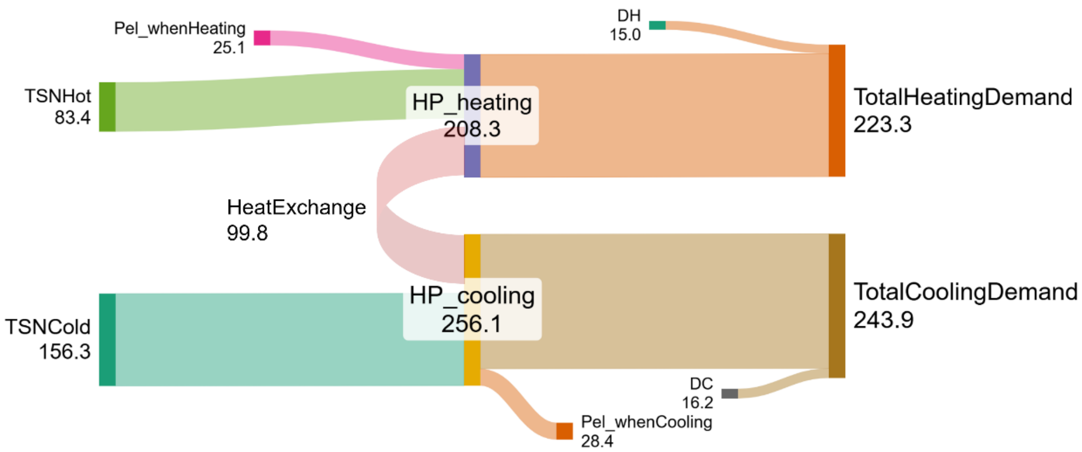

Figure 10: Annual energy balance of the reversible multi-circuit heat-pump sub-station, shown as a Sankey diagram distinguishing TSN hot/cold contributions, heat-pump electricity use, internal heat exchange between cooling and heating circuits, and auxiliary district heating/cooling in relation to total heating and cooling demands

On the cooling side, the building requires 243.9 MWh of cold, of which 227.7 MWh (≈93 %) are provided by the heat pump and 16.2 MWh (≈7 %) by the district cooling network. The compressor electricity during cooling increases the cooling duty of the evaporator. Thus the HP must provide 227.7 MWh to meet demand plus remove 28.4 MWh of compressor waste heat, totaling 256.1 MWh of cooling from the evaporator.

Sankey diagram in Figure 11 highlights how the choice of configuration affects the interaction with the TSN and the auxiliary DH/DC networks. For the same annual heating and cooling demands, separate HP and chiller of same capacities draw about 168 MWh of heat and 241 MWh of cold from the TSN respectively, whereas the reversible multi-circuit HP requires only around 83 MWh and 156 MWh from the TSN, respectively. The difference is explained by the internal heat-recovery path: in the multi-circuit configuration, roughly 100 MWh of cooling-side waste heat is upgraded and reused to cover almost half of the annual heating demand, reducing the need of TSN for heating and cooling support. Despite these different energy flows, the total compressor electricity remains similar in both concepts. These results suggest that the reversible multi-circuit heat pump is particularly advantageous in buildings with frequent overlap of heating and cooling loads.

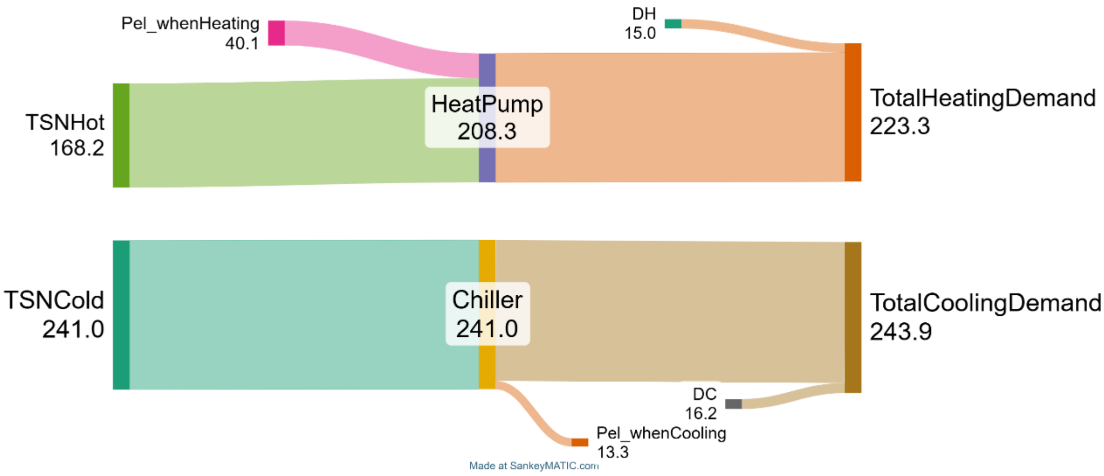

Figure 11: Annual energy balance of the heat-pump and chiller in sub-station.

5. Conclusion

This paper developed and applied a reversible multi-circuit heat pump model for use in a thermal source network, using a representative incampus building as case study. The MATLAB/Simscape model explicitly represents three hydraulic circuits (TSN, building heating, building cooling) and five active operating modes plus standby, while retaining a computationally efficient Carnot-based formulation. Embedded in a yearly simulation with realistic demand profiles and TSN boundary conditions, the model bridges the gap between detailed component-level heat pump models and highly simplified substation representations typically used in TSN studies.

The results show that the reversible multi-circuit heat pump can supply most of the building's heating and cooling demand. Auxiliary district heating and district cooling are required only during a limited number of peak-load hours. In dual modes, internal heat recovery between the building's heating and cooling circuits significantly reduces the need to extract heat/cold from the hot TSN and to purchase heat/cold from the district heating/cooling network.

A comparison with a reference concept using two separate units (a heating heat pump and a chiller) indicates that the reversible multi-circuit configuration can substantially reduce TSN extraction and district heating/cooling demand, while keeping the overall compressor electricity at a similar or slightly lower level. These benefits are most pronounced when the building exhibits high demand coefficient overlap. In such contexts, the reversible unit makes better use of local waste heat, alleviates stress on the TSN, and enhances the efficiency of the overall system.

The study also has several limitations. The heat pump model is based on a quasi-steady Carnot approach with a constant Carnot efficiency factor and does not resolve refrigerant-cycle phenomena, start-up transients or part-load behavior. Hydraulics are simplified: pump power, pressure drops and detailed stratification in the buffer tanks are not considered. Moreover, the analysis relies on planning data rather than calibrated measurements from the operating incampus system.

Future work will therefore focus on improving the heat pump model, and on optimizing its operation. This includes testing advanced control strategies, systematically varying mode-switch thresholds and TSN temperature levels and exploring the optimal sizing of the heat pump and buffer tanks under different demand patterns. Calibration against incampus monitoring data will be used to quantify uncertainties and to validate the model.

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