Dynamic Energy Management Model: A Catalyst for Carbon Neutrality in Austrian Thermal Baths

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Abstract

Austrian thermal baths, significant energy consumers, primarily rely on fossil fuels, posing ecological and economic challenges. This research focuses on optimizing energy consumption by integrating renewable energy sources, such as deep geothermal energy, and enhancing efficiency through innovative technologies like heat pumps and dynamic optimization models. The performed baseline survey of thermal baths identified major energy consumers and potential areas for efficiency improvements. The developed Python-based dynamic simulation program uses Mixed Integer Linear Programming (MILP) to optimize the energy system, considering various energy sources, demands, and storage systems. Key strategies included waste heat utilization, efficiency enhancements in heating, ventilation, and cooling systems, and the integration of photovoltaic systems. The demonstration case in southeast Austria highlighted significant energy savings through the recovery of waste heat from thermal splashing water, air conditioning systems, and drinking water cooling. The optimized system configuration, featuring cascaded heat pumps and stratified storage systems, achieved substantial reductions in both heat and electricity demand. The results underscore the importance of dynamic simulation and optimization in achieving energy efficiency and sustainability in thermal bath operations. The research work provides a reference model for replication in other facilities, contributing to Austria’s broader decarbonization goals.

Keywords: decarbonization, energy management system, renewables, heat pumps, thermal storages, dynamic optimization, Python simulation

1. Introduction

Austria, with its extensive thermal spa landscape comprising a total of 42 facilities, is not only a popular tourist destination in Europe but also one of the regions where the use of deep hydrothermal geothermal energy (depths greater than 400 meters in water-bearing layers) is at the forefront (Goldbrunner and Goetzl 2019). From an ecological perspective, thermal baths in Austria are significant energy consumers, still relying on fossil fuels like natural gas. However, since the increase in electricity and gas prices, these thermal spas have been striving for more energy-efficient operations. To achieve a transition away from fossil energy sources, it's essential to focus on major energy consumers, as the adoption of renewable energy in thermal spas is generally easier to implement compared to other urban areas (Goetzl 2022). The complex producer/consumer dynamics at a thermal spa site, with varying supply and demand profiles and external conditions, offer substantial potential for the efficient use of deep geothermal energy. This can be realized through innovative integration concepts involving heat pump technologies, efficiency enhancement measures within the internal energy system, and a real-time, innovative energy management system that provides flexibility with both the electricity and heat networks.

Energy Supply in Austrian Thermal Baths

The energy supply of Austrian thermal baths utilizes a combination of hydrothermal energy, biomass-based district heating, fossil fuels, and electricity. Most of the heat demand—60-70%—is dedicated to maintaining pool water temperatures, while 30-40% is used for hot water and heating requirements for thermal bath buildings, wellness facilities, and hotel complexes (Novakovits, 2018). Major electricity consumers include ventilation systems, which ensure optimal indoor air comfort, as well as cooling systems for hotel and spa operations. Overall, energy costs in Austrian thermal baths account for at least 20% of total costs, classifying this sector as "energy intensive." The volatility or increase in energy prices, particularly for electricity and fossil fuels like natural gas, poses significant challenges for these businesses, leading to substantial cost and price pressures. Decarbonizing thermal baths therefore requires a comprehensive approach that considers technological, economic, political, and societal factors.

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Key strategies include:

- Reducing dependence on fossil fuels
- Implementing technological adjustments and conversions in heating, ventilation, and cooling systems
- Adapting existing infrastructure and integrating with future or existing electricity and heat networks
- Addressing cost pressures and exploring financing options
- Establishing clear regulatory frameworks to incentivize and support investments
- Enhancing public and stakeholder acceptance and awareness

Baseline Survey of Thermal Baths in Austria

The baseline survey confirms the energy-intensive nature of thermal baths. Table 1 below shows exemplary the heat and electricity consumption by energy source for two demonstration sites and the transfer site.

Table 1: Energy Consumption by Energy Source for Demonstration and Transfer Sites (Seidnitzer-Gallien et. al. 2024a)

Energy Consumption	Demo Case 1	Demo Case 2	Demo Case 3
Electricity	6 [GWh/a]	3,4 [GWh/a]	4 [GWh/a]
Biomass	-	6,4 [GWh/a]	4,5 [GWh/a]
Natural Gas	16 [GWh/a]	-	8,5 [GWh/a]

To reduce the high energy consumption and associated carbon footprint, a diverse combination of measures is planned, focusing on waste heat utilization in conjunction with heat pump technologies. Additionally, efficiency improvements in hot water preparation as well as ventilation and air conditioning systems will be implemented. These measures are intended to lay the groundwork for a complete decarbonization.

Aim and Methodology

The research work focuses on evaluating the current technical, energy, and environmental status of thermal spas in Austria. The goal is to identify realistic opportunities for decarbonization and energy transformation, while also developing innovative approaches such as the optimal utilization of renewable energy, maximizing energy efficiency, and integrating digital, predictive control and regulation systems. These strategies will be applied in real-world settings and will serve as reference models for replication in other thermal spa operations.

To achieve a sustainable transition to energy-efficient and renewable energy supply in Austrian thermal spas, an integrated methodological approach is employed.

- **Assessment of Energy Framework Conditions**: Initially, the basic energy data of the thermal spas were collected through a combination of surveys and a detailed energy audit. This assessment provided a comprehensive overview of the current energy consumption and existing energy use structures within the facilities.

- **Identification of Waste Heat and Efficiency Potentials**: Technical potentials were analyzed through targeted measurement series to identify possible sources of waste heat and areas with efficiency improvement potential. These analyses helped to recognize untapped energy sources and evaluate the efficiency of existing systems.

- **Energy Demand Simulation and PV System Analysis**: The optimization was based on a detailed energy demand simulation of the thermal spa's major consumers, created through a dynamic building simulation in IDA ICE. Additionally, simulations for the future use of a photovoltaic (PV) system were conducted to assess its integration into the energy system.

- **Comprehensive Energy System Optimization**: Finally, the entire energy system of the thermal spas was optimized using a Python-based dynamic simulation program, built on the optimization model of the Pyomo library. This model employed Mixed Integer Linear Programming (MILP) and distinguished four functional components: energy sources, energy demands, heat pumps (HPs), and energy storage systems. The core of this phase was the dynamic optimization of the energy system on a technical and energetic level, aimed at identifying the most energy-efficient system configuration and developing a sustainable, efficient overall system.

2. Demonstration Case

The demonstration case 2, situated in the southeast of Austria, is a significant energy consumer. It operates a geothermal well (depth: 498 m, production: 9 m³/h at 32°C) and is connected to a local district heating network. The annual heat demand is 6.4 GWh, and the electricity demand is 3.4 GWh. At the current energy system there is considerable potential to recover waste heat from thermal splashing water, climate cooling supply, and drinking water cooling. Establishing bidirectional use of the waste heat with the district heating network (for both heat and cold) aims to conserve biomass resources and enhance the heating plant's efficiency during summer and transitional operation.

Waste Heat Potential

Potential of Splashing Water: The daily backwash water generated by the thermal spa operation amounts to approximately 60 m³ at a temperature of 30°C. Before being discharged into the receiving waters, this water is cooled to around 9°C, allowing the residual energy of the thermal water to be fully utilized. This process enables the recovery of around 670 MWh per year of waste heat.

Potential of Cooling Water from Air Conditioning Systems: Waste heat from the cooling water of the air conditioning systems and the exhaust air from the ventilation systems offers a potential of approximately 1 GWh per year from both the spa and the hotel.

Potential of Drinking Water Cooling: The new drinking water source for the local supply, with a flow rate of 18 m³/h, must be cooled from 21.3°C to around 9°C before being introduced into the drinking water network. This energy source is available 24 hours a day, 365 days a year, providing a waste heat potential of 2.7 GWh per year.

Efficiency Measures

In parallel with identifying waste heat potentials, the overall energy demand for heating and electricity was analyzed for efficiency improvements. The analysis reveals that more efficient use of hot water systems (both treatment and customer facilities) could save 125 MWh per year for the spa and the connected hotel. Optimizing the system temperatures of the pool water heat exchangers aims to effectively supply the pools with water temperatures in the range of 32-38°C, making them usable. Furthermore, optimizing the ventilation systems with a heat recovery system enables near year-round dehumidification in the swimming hall using outdoor air. Overall, efficiency measures could reduce the heat demand by 884 MWh per year and the electricity demand by 150 MWh per year.

Derived Innovation Concept for Utilizing Potentials

A schematic overview (Figure 1) illustrates the elements integrated into the innovation concept. The local heating supply, provided by a biomass heating plant (BIOS), serves both the thermal spa and the hotel. The geothermal heat source, with temperatures of 32°C, is directed into the pools and heated to 34°C to 36°C. (Seidnitzer-Gallien et al., 2024b) The identified waste heat potentials from splashing water, the optimization of ventilation systems (including exhaust air and cooling water from air conditioning systems), and the required cooling of the drinking water source form the basis for utilizing an integrated heat pump system used at three temperature levels (30 °C splashing water; 20°C drinking water, 14°C climate cold water)

The plan involves implementing a cascaded use of two to three compression heat pumps to optimally utilize the different temperature levels and maximize the coefficient of performance (COP). The goal is to minimize the mixing of high and low return temperatures. Additionally, optimized stratified cold and heat storage systems are intended to enhance system efficiency and operational flexibility while ensuring high exergy efficiency.

For time-independent operation of the HPs from waste heat offer there will be installed a cold-water storage in between. A second water storage will be used to decouple the heat supply of the HPs and biomass heating plant from the consumers. Due to different operation modes of the HPs, the heat supply can occur at two distinct temperature levels, with the ejection of hot gas occurring at a higher temperature. Following the warm water storage is getting charged at 55°C and 70°C or 70°C and 80°C. The consumers require a temperature level of 70°C therefore the highest temperature layer of the thermal storage is around 70°C and any heat load at 80°C will be transferred to this layer as well. To ensure the coverage of the heat demand independently from the availability of waste heat and the operation of the HPs, the biomass heating plant is connected to the warm water storage. This allows the heating of returns from the thermal bath and district heating network from 45°C to 70°C, or the raising of the temperature level of the 55°C-water to the required 70°C. To enable a sustainable electricity supply too, a photovoltaic system will be installed above the thermal baths car park. This system will be used primarily to meet the electricity demand of the thermal bath itself, with any additional generation being used to cover the demand of the HPs. In the event of insufficient solar energy generation, the current electrical demand will be met through grid-based electricity supply.

The deployment of cascaded heat pumps enables the utilization of water at temperatures between 40°C and 50°C from various sources, including wastewater from the thermal spa, waste heat from the cooling water, and heat from the drinking water source. An integrated smart control strategy will allow for high self-consumption of photovoltaic (PV) electricity generated by the thermal spa, hotel, and heating plant, or for grid-supportive operation. This heat is used to preheat both the thermal water and domestic hot water.

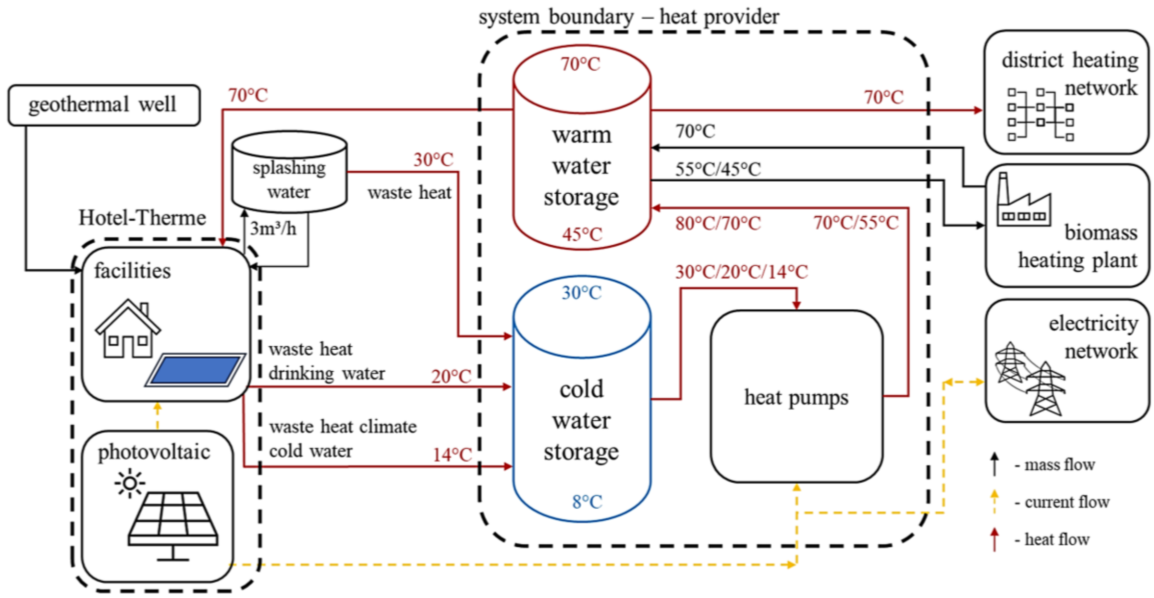

Figure 1: Simplified schematic overview of the innovative system concept at demo 1

The concept is further enhanced by expanding the connection between two heating plants (BIOW and BIOS) to enable bidirectional heat utilization. This allows waste heat from the thermal spa, using heat pumps, to also supply the second district heating grid (BIOW).

3. Dynamic Energy Management System

The development of a robust and efficient energy management system (EMS) is essential to effectively manage this complex system. This objective can be achieved through dynamic optimization using a Python-based programming tool. Dynamic modeling allows for the optimal configuration of the heat pumps and storage sizes, enabling efficient year-round control of the energy system. The model considers the different temperature levels and operating modes of the heat pumps, as well as the variable demands for cold and hot water. This ensures that the system can continuously adapt to changing conditions, minimize energy consumption, and maximize the use of available renewable energy sources.

The energy system was modeled with the optimization model built with the Pyomo library and distinguishes four functional components: sources, demands, HPs (heat pumps), and storages.

Technical and Operational Specifications

The utilization of the **waste heat sources** is contingent upon their availability. The new system will cool drinking water and feed it into the public drinking water network, thereby ensuring a waste heat capacity of up to 257 kW. Equally, the climate cold water always provides up to 500 kW. However, the waste heat from splashing water must be taken over night from 10 pm to 6 am when the thermal bath is closed to the public. Therefore, the water from the backwashing process is collected in a separate tank throughout the day, accumulating a volume of 60 m³.

Heat demand is met from the warm water storage. The biomass heating plant operates by drawing from the lower temperature levels in the storage and feeding heated water into the highest temperature zone. The biomass heating plants have a total capacity of 4 MW. The heat demand of the district heating network is defined based on measurement series from 2023, and the heat requirement of the thermal spa is simulated with the prospective efficiency measures with a comprehensive IDA ICE simulation.

The **electrical energy system** will also be expanded and made more sustainable, complementing the thermal energy improvements. A new 2 MW photovoltaic system will be installed at the thermal baths site. Any surplus electricity generated beyond the facility's needs will be used to power the thermal energy system, primarily the heat pumps. In case of a power outage, additional electricity will be sourced from the grid. The photovoltaic system's power generation is modeled using ASHRAE weather data in an IDA ICE simulation, while the thermal spas electricity demand data is based on measurements from 2023 and 2024.

Heat Pump Model

Each HP can choose from three different heat sources with different temperature levels. These temperature levels are 14°C, 20°C and 30°C. Regarding the condensation side, the heat can be released at 55°C with hot gas ejection at 70°C or 70°C with hot gas ejection at 80°C. These two options are labelled as operation modes. Each HP is capable of operating with every possible combination of the different operational points and modes. The schematic of the HP model can be seen in Figure 2.

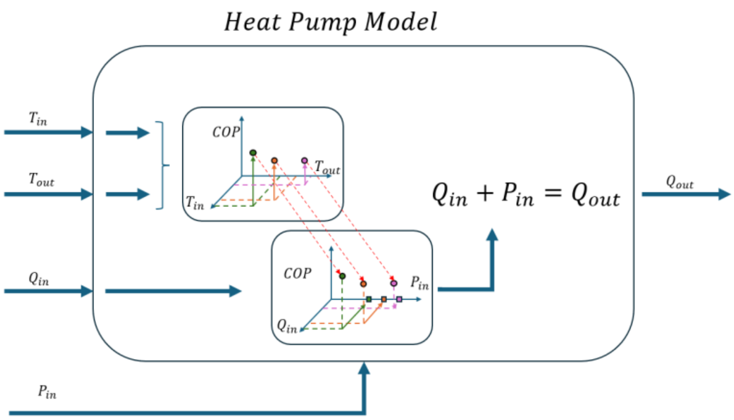

Figure 2: Schematic of the HP Model

Each pairing of inlet and outlet temperatures is defined as an operating point, with its own COP. A lower inlet temperature results in a lower COP, while a higher outlet temperature also leads to a lower COP. The optimizer can freely choose between these operating points. Each HP can switch between operating points in each timestep. The optimizer specifies an operating point for each timestep, and the HP model sets the associated COP. This COP dictates the electricity necessary to fulfill the heat demand. With a higher COP, more heat can be transferred from the cold side to the warm side with reduced electricity consumption.

Hot and Cold-water Storage Tank

The storages are implemented as layered storages (Figure 3). Each layer is defined by its own temperature level. Each layer can fully utilize the storage volume.

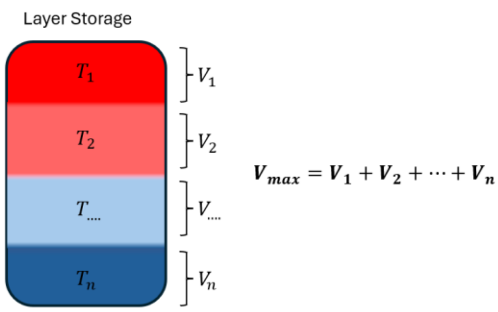

Figure 3: Schematic of the Layer Storage Model

Within the energy system, there are two separate storages: a cold-water storage and a hot water storage.

The cold-water storage has a capacity of 200 m³ and is consistently filled, always maintaining a constant volume of 200 m³. It has four different temperature levels. These temperature levels are 8°C, 14°C, 20°C and 30°C. The cold-water storage has four inlets. These inlets are the splashing water with a temperature of 30°C, the drinking water with a temperature of 20°C, the climate cold water at 14°C and cold water with a temperature of 8°C. This storage is connected to all HPs. All HPs can independently access all temperature levels at the same time. This cold-water storage is used as a heat source for the HPs. If a HP accesses one heat level, the water from the heat level is not cooled down to 8°C. Instead, it is cooled down to the next lower heat level. For example, if one HP accesses water with a temperature level of 30°C it gets cooled down to 20°C. Therefore, the usable temperature difference for each HP is dependent on the temperature level it accesses.

$$V_{max} = V_{30}(t) + V_{20}(t) + V_{14}(t) + V_{8}(t) = 200\ m^3$$
$$V_{30}(t) = \dot{V}_{spw}(t) - \dot{V}_{HP\ 30\rightarrow 20}(t) + V_{30}(t-1)$$
$$V_{20}(t) = \dot{V}_{dw}(t) - \dot{V}_{HP\ 20\rightarrow 14}(t) + V_{20}(t-1)$$
$$V_{14}(t) = \dot{V}_{cw}(t) - \dot{V}_{HP\ 14\rightarrow 8}(t) + V_{14}(t-1)$$

There is one specific restriction for the cold-water storage. For cooling purposes, it must always contain at least 20% of the total storage capacity of 8°C water.

The energy system features a hot water storage with a capacity of 100 m³, consistently filled to maintain a constant volume throughout the entire timeseries. This storage unit operates at three distinct temperature levels: 45°C, 55°C, and 70°C. The HPs can increase the water temperature from 45°C to either 55°C or 70°C, but they cannot raise the temperature from 55°C to 70°C. This specific temperature increase can only be achieved using the biomass boiler.

The hot water storage is utilized to meet the 70°C demand of the energy system, which can be supplied by either the biomass boiler or the HPs. Both the biomass boiler and the HPs can operate simultaneously to fulfill this demand.

$$V_{max} = V_{70}(t) + V_{55}(t) + V_{45}(t) = 100\ m^3$$
$$V_{70}(t) = \dot{V}_{HP\ 45\rightarrow 70}(t) + \dot{V}_{BHP\ 45\rightarrow 70}(t) + \dot{V}_{BHP\ 55\rightarrow 70}(t) + V_{70}(t-1)$$
$$V_{55}(t) = \dot{V}_{HP\ 45\rightarrow 55}(t) + \dot{V}_{BHP\ 45\rightarrow 55}(t) + V_{55}(t-1)$$

The hot water storage must always contain at least 15 m³ of 70°C water for heating purposes.

Optimization Scenarios

The optimization model aims to determine the optimal HP configuration for the specified energy system. This configuration is characterized by two main parameters: the number of HPs and the power of each HP. Up to three HPs are considered. Multiple optimization runs are conducted to compare the objective values and identify the best configuration. The optimization process, which does not factor in the installation cost of each HP, seeks to maximize system revenue.

The impact of adding an extra HP or additional power is assessed by comparing the objectives of multiple runs. Significant differences in objectives suggest that such investments could be financially beneficial, while minimal differences indicate that additional power or an extra HP may not substantially reduce costs.

The HP configurations are determined for four representative weeks throughout the year, each representing a typical week for the thermal bath. The selected weeks start on the following dates:

1. 2023.01.22
2. 2023.04.01
3. 2023.07.01
4. 2023.08.22

The optimization is executed on an hourly basis. The means that there are 168 timesteps for each week.

4. Results

In total, over 5,000 scenarios with various heat pump (HP) configurations were calculated for several representative weeks throughout the year. These scenarios were designed to assess the impact of adjusting the maximum compressor power of each HP on the entire system's performance over the course of the year. Compressor power variations were specifically analyzed for four distinct representative weeks in 2023.

In the following plot (Figure 4), each axis represents the maximum available compressor power for a heat pump. The color of the dots indicates the objective values, with brighter dots representing better outcomes. It is important to note that the objective values are normalized for each representative week, meaning that values from different weeks cannot be directly compared across plots.

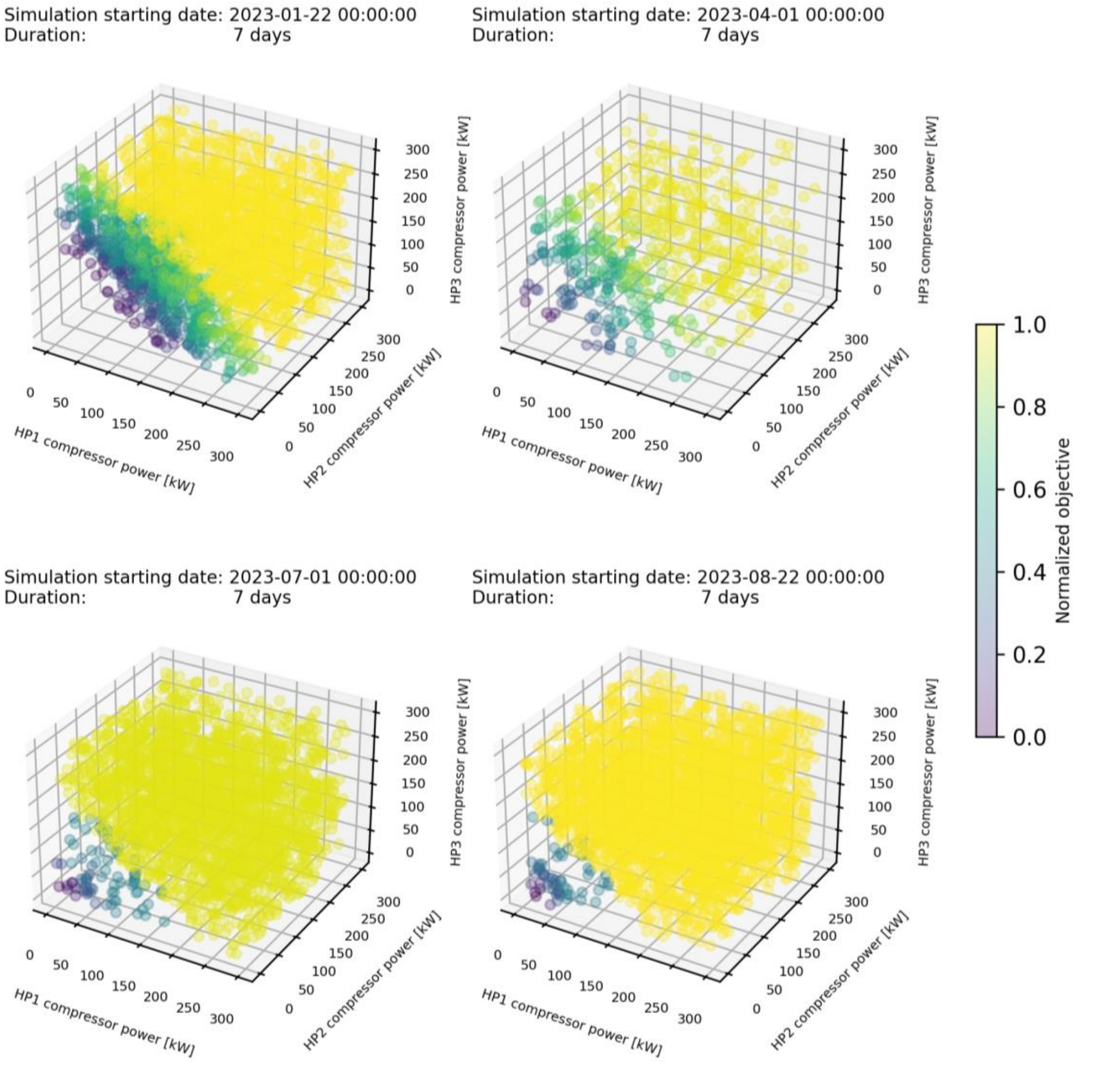

Figure 4: Impact HP power on energy system objective

These diagrams illustrate that the energy system gains more from larger heat pumps (HPs) in winter than in summer. They also suggest that increasing the HP size beyond a certain threshold offers no additional advantage.

Figure 5 depicts the relationship between the objective value and the maximum combined electrical power of the three HPs. It shows that improving the objective value by increasing HP power is only effective up to a certain point. Beyond this threshold, further increases in power yield no significant benefit.

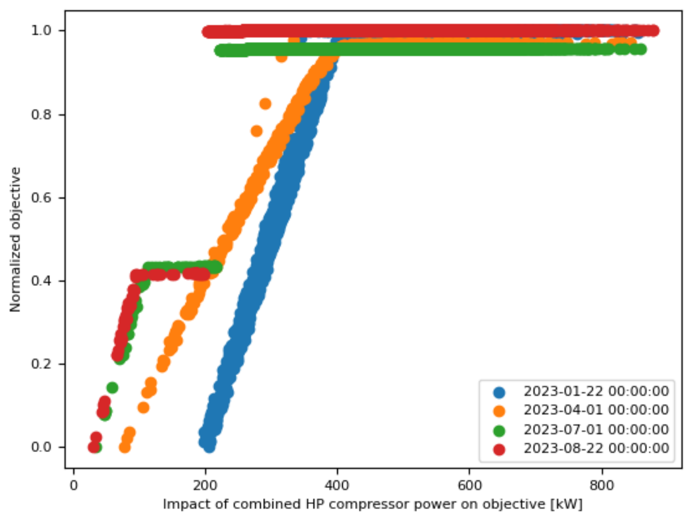

Figure 5: Effect of the combined compressor power of the three HPs on the normalized objective.

An analysis of the graph showing results from four representative weeks throughout the year indicates that the system gains no advantage from a combined maximum electrical power exceeding 400 kW for the three HPs. Furthermore, the results reflect only successful optimization runs, suggesting that a combined electrical power of at least 200 kW is necessary to meet winter demand. During the summer months, there is no benefit to having a combined power output above 200 kW. The minimum combined electrical power during the summer period is 100 kW. This indicates that the advantage of larger HPs is less pronounced in summer than in winter, as expected.

Based on data collected from over 5,000 configuration runs across multiple weeks during the year, one HP configuration emerged as particularly promising. For the subsequent run, the HPs will be configured as follows:

- HP1: 170 kW
- HP2: 100 kW
- HP3: 100 kW

The next phase of the analysis involves performing an optimization run over the course of a month, with January selected for this purpose. The resulting aggregated energy flows for this optimization run are depicted in Figure 6.

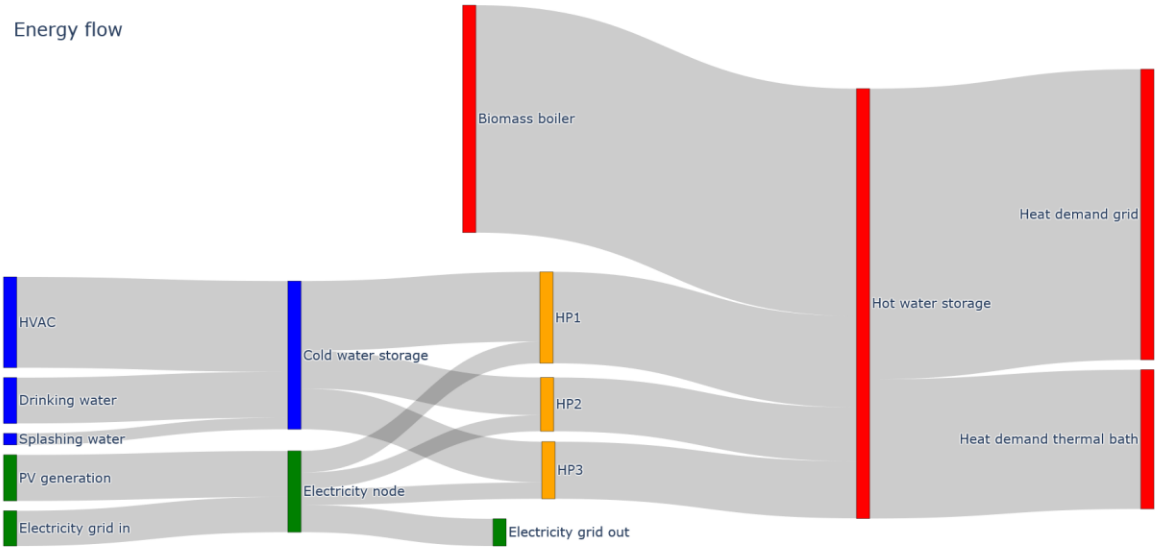

Figure 6: Energy flow of the system for the month January

As illustrated in the Sankey diagram above, the results of this run demonstrate that the HPs are capable of meeting approximately 47% of the heat demand in January. However, this percentage decreases during the winter months due to the higher heat demand, causing the HPs to frequently operate at their power limits to maintain this level of coverage. Additionally, the heat sources for these pumps are also constrained by power limitations. A similar month-long run was conducted for July, during which the HPs were able to fully meet the heat demand.

The following diagrams (Figure) provide an evaluation of the January optimization run results. The first diagram shows the supply from different energy sources. The waste heat from drinking water is fully utilized, and a significant portion of the waste heat from air conditioning is also harnessed. As per the specified requirements, the cooling of the splashing water is consistently maintained throughout the night. To meet the substantial heat demand during the winter period, the biomass boiler experiences significant fluctuations, reaching its maximum load.

To facilitate a more precise comparison of energy demand and supply, the second diagram depicts the heat demand of the thermal bath and the district heating network, as well as the excess electricity that cannot be utilized by the HPs.

The optimization run demonstrated that over the course of this month, the HP1 with the maximum electrical power of 170 kW operates for approximately 708 full load hours. The HP2 with 100 kW of electrical power operates with 714 full load hours, respectively. HP3, with a power of 100 kW, operates for 713 full load hours. Therefore, these three HPs are highly utilized while still providing comprehensive coverage of the heating demand.

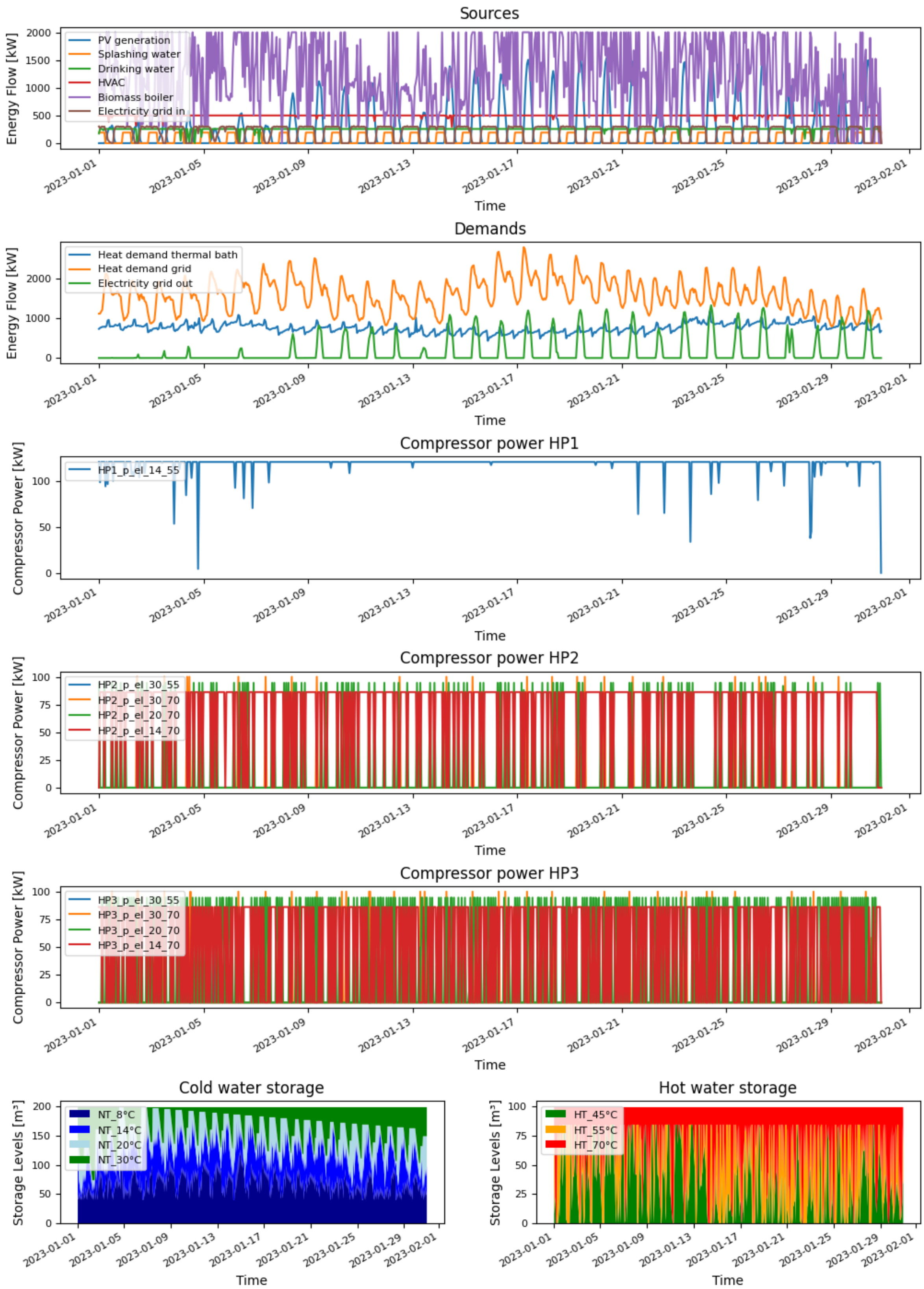

Figure 7: Results of the optimization run

Discussion & Conclusion

The exploration and implementation of innovative energy solutions in Austria's thermal bath facilities demonstrate significant potential for reducing carbon emissions and increasing energy efficiency. Through the optimization of existing infrastructure, utilization of untapped waste heat sources, and integration of renewable energy technologies, these facilities can play a pivotal role in the country's decarbonization efforts.

Especially, the heat pump (HP) configuration successfully met a significant portion of the heating demand during January, with each HP achieving over 700 full load hours. A similar performance was observed in July, where the

HPs operated extensively, accumulating 302, 469, and 480 full load hours for HP1, HP2, and HP3, respectively. The combined compressor power remained at 370 kW, below the previously defined limit of 400 kW, indicating the effectiveness of this configuration. However, further validation is needed through future optimization runs that include a cost model for the HPs.

Dynamic simulation and optimization play a main role in enhancing the overall efficiency and effectiveness of the energy system. By simulating various scenarios throughout the year, the model can account for fluctuating demands and environmental conditions, ensuring that the system operates at peak efficiency across different seasons. The ability to dynamically optimize HP configurations and energy flows allows for precise adjustments, minimizing energy consumption while maximizing the utilization of available renewable resources. This approach not only ensures reliable performance but also identifies the most cost-effective solutions, paving the way for sustainable energy management practices.

5. Outlook

The next phase will focus on refining the optimization model to autonomously determine the optimal installation power and number of HPs. To achieve this, price models for the initial costs of the HPs will be developed and integrated into the optimization process, enabling the model to independently identify the most efficient configuration.

Following the final dynamic optimization, detailed planning for the implementation of the demonstration site will be initiated. Simultaneously, the control strategy will be finalized, ensuring that the system operates efficiently under real-world conditions. The implementation phase will be closely monitored and accompanied by a dedicated optimization process to fine-tune system performance, ensuring that the goals of energy efficiency and sustainability are fully realized.

Through the integration of innovative technologies and optimization strategies, the project aims to revolutionize energy management in thermal bath complexes, paving the way for sustainable practices within the tourism industry.

6. Acknowledgments

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