A tailored model for sustainable control of ATES systems using mixed-integer programming

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Abstract

Aquifer thermal energy storage (ATES) systems are used to temporarily store heat or cold in open aquifers in order to regulate building temperatures. Although the basic concept of storing heat in summer for winter (and vice versa) is simple, the efficient operation of ATES is non-trivial. For instance, ATES are necessarily combined with conventional heating systems or heat pumps to handle peak loads, which complicates their efficient operation. Moreover, it is important to maintain a certain heat balance in the underground to ensure long-term operation of ATES. Both challenges can be addressed with modern control technologies. In particular, model predictive control (MPC) enables to optimize the current operation while taking constraints and long-term requirements into account.

The performance of MPC crucially depends on the quality of the model. In fact, the model should accurately capture the dominant system dynamics while being numerically cheap to evaluate. Existing approaches often address only one of these aspects. For instance, Rostampour et al. [1] consider a simplistic battery-like model whereas Beernink et al. [2] build on a complex MODFLOW model. In our contribution, we present a novel MPC scheme which reflects a sweet-spot between these extremes. More precisely, our model builds on linearizations of the heat transport equation for the three operation modes injection, extraction, and storing (or inactivity). Incorporating these modes in the MPC leads to a mixed-integer (optimization) program, which can be solved efficiently compared to an MPC utilizing a MODFLOW model. This is illustrated with a numerical case study showing the effectiveness of our approach.

1. Introduction

According to the International Energy Agency, building operation still accounts for 30% of the worlds primary energy consumption and 26% of the global energy-related emissions [3]. Thus, sustainable and low-CO_2-emitting heating, ventilation, and air conditioning (HVAC) technology for buildings have growing demand and constitute a focus of research for climate change mitigation. In this context, industry and research are already presenting a wide range of new, environmentally friendly HVAC technology. With the use of thermal energy storage systems, fossil fuel-based HVAC technology may be replaced reducing CO_2-emissions of building operation.

1.1 Aquifer thermal energy storage systems

ATES systems reflect a prominent form of geothermal thermal energy storages. The basic idea is to store heat from summer in aquifers to heat with during winter period; in winter cold is stored and used in summer for cooling. Storing the energy results in local temperature changes. The operational modes of ATES systems can be subdivided into heating, storing (or inactivity), and cooling. They depend on the pumping flow direction between the aquifers. Extracted fluid is injected into the subsurface again. ATES systems reduce heating and cooling operations of fossil fuel-based HVAC technology saving CO_2-emissions and cost (EUR) [4]. Amplifying heating and cooling power of ATES systems, heat pumps are employed. To maximize ATES' CO_2 saving potential and even abandon fossil burning technology, ideas about autarkic ATES systems are already discussed by [5].

Optimal operation of ATES systems is crucial for achieving significant and dynamic contributions to the energy demand of buildings lowering total CO_2-emissions. However, the subsurface must be protected from non-sustainable operations, focusing on preserving potable groundwater sources. Certainly, the operation of ATES underlies challenging restrictions. For instance, large temperature changes in the subsurface may trigger geo-chemical or -biological reactions, leading to groundwater quality mitigation or clogging. Monitoring results of chemical and microbial processes in the cold storage of an ATES system indicate that temperature changes are responsible for clogging [6, 7, 8]. Further, Hartog et al. [9] conclude in their field study that temperatures above $300\,\mathrm{K}$ may lead to significant negative groundwater quality changes. However, profound experimental field studies on possible chemical or biological reactions are not yet presented by research [10, 11]. As a consequence, legal institutions in Germany and the Netherlands require energy balanced operation of such systems as a preventive measure against the aftermath of temperature changes in the subsurface [12, 13]. Usually, this refers to storing equal amounts of heat and cold in the subsurface within a certain time horizon. Similar rules also apply to other systems, such as borehole heat exchangers, which store heat and cold at the same time [14]. Additionally, a recent study by Beernink et al. [2] indicates that an balanced operation of ATES systems results in less mutual interactions of several ATES aquifers in, e.g., urban ares such as Utrecht, the Netherlands. Further, persistent energy imbalances of ATES operation may lead to negative impacts of ATES viability and may result in a shut down of operation [15]. A prominent example is the Reichstag building of the German parliament, where the operation of deployed ATES system was ceased due to ongoing imbalanced operation [16, 17].

Remarkably, solely requiring a balanced heat and cold demand of buildings is not sufficient for guaranteeing energy balanced operation of ATES systems. Studies have shown that buildings in climate regions with equally long winter and summer periods do not necessarily have balanced heat and cold demands, as the demand also depends on the building's construction, its use and weather [2, 18]. As a result, provided heat and cold of ATES systems are not balanced for purely heat demand-driven operations. To nevertheless obtain a balanced operation, one must actively control the power output of ATES systems. The development of adequate (automatic) control schemes is an active research area [2, 5, 19].

1.2 Existing control schemes for ATES systems

In the literature, a wide range of control solutions for ATES systems is presented. The range spreads from manual (human) interaction with the system [19] to periodically or constantly monitoring model predictive control (MPC) algorithms tracking supplied energy and demand. Since MPC for ATES is also in the focus of this paper, we given an overview on various MPC solutions next. MPC determines control inputs by recurringly solving an optimal control problem on a receding prediction horizon subject to model dynamics as well as input and state constraints [20]. After applying the first element(s) of the optimal input sequence for the current horizon, the optimal control problem is solved again using updated state measurements and so forth. Proposed MPC schemes mostly differ with respect to the modeling detail of stored energy in aquifers and considerations of uncertainties.

A simple linear model for the amount of energy stored by an ATES system is presented by Rostampour et al. [1]. Battery-like first principle equations describe the stored energy in the subsurface and the energy delivered to the building. Heat loss by mixing with the surrounding groundwater is considered by a time-invariant constant. Added enthalpy to the subsurface is mixed perfectly, assuming a spatially constant temperature in the aquifer. Introduced integer variables engage a heat pump depending on the energy demand of the building avoiding mixed-integer programming. The basic ideas about mixed-integer programming are further explained in Section 3. Another publication by Rostampour and Keviczky [13] is based on a similar ATES model. It describes an MPC algorithm for smart thermal grids that is capable of constantly monitoring the supplied energy by ATES and heading for balanced operation with slacked inequality constraints that apply only at the end of the prediction horizon. The authors state that balanced operation can be reached when the prediction horizon has an appropriate length of one year. Uncertainties of the building's heat demand are considered by a robust-randomized approach.

Enabling a better modeling detail the stored amount of energy by an ATES and dropping time-invariant subsurface temperatures, Rostampour et al. [21, 22] propose a new control oriented modeling framework leading to a nonlinear first principle mixed-logical dynamical model. This model class is further explained in Section 3. Perfect mixing of stored and injected fluid is still assumed and lumped loss coefficients approximate the heat loss based on results of the aquifer specific simulation software MODFLOW [23]. The authors indicate large computational cost solving derived optimization problem since it is mixed-integer multi-dimensional polynomials nonlinear programming. A follow-up publication by Rostampour et al. [22] lowers computational times with pre-defining operational modes depending on outside temperatures.

Known for having the best model accuracy, tailored software, such as MODFLOW simulates the storing status and future extraction temperature of aquifers. Using these capabilities, MODFLOW is combined with an hierarchical distributed MPC scheme for ATES smart grids to simulate system feedback and (further) extraction temperatures in [15]. An upper-layer MPC coordinates the coupling of neighboring agents and determines constraints for a lower-layer MPC that is linked to every agent's HVAC and ATES technology.

Presented predictive controllers either depend on models with coarse modeling detail of subsurface's temperatures [1, 13] or are computationally expensive [15, 21, 22]. Literature shows that the temperature distribution in the subsurface drifts relative to extraction wells due to ambient groundwater fluxes, anisotropic material properties, and ATES pumping actions [6, 24]. Assuming perfect mixing of injected enthalpy with present fluid, such drifts cannot be captured resulting in wrong predictions of extracted temperatures and too conservative operation of ATES systems. Thus, a more detailed model for MPC capturing heat transport in groundwater saturated aquifers with moderate computational needs is proposed by the present publication. Given ideas in [22] to lower computational run times by pre-definition of operational modes forces the system to operate against common sense of sustainable operation of ATES systems, i.e.: injection temperature into cold aquifer are warmer than ambient temperature. This annihilates stored energy in the aquifer and ATES viability. The presented control scheme is able to decide based on the objective function which operational mode is chosen. The objective function combines terms aiming for a sustainable and cost-efficient operation of ATES systems. The operational focus can be easily tuned by the user.

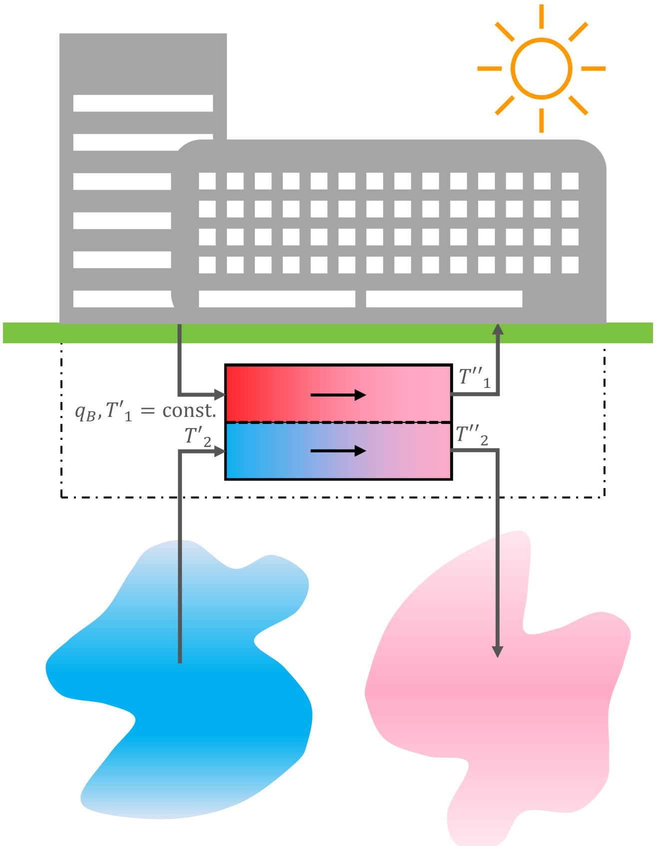

Figure 1: Considered system with ATES and cocurrent heat exchanger during cooling season.

2. Novel model

The storing status of the aquifers is modeled focusing on convective and conductive energy transport. A cocurrent heat exchanger connects the aquifers with the building's HVAC piping system exchanging energy from the subsurface with the building. Heat exchangers are useful to connect and combine other competing HVAC technology (heat pumps, chillers, gas/oil boilers) to the ATES system. In the present model, other HVAC technology is comprehensively considered by the energy demand of the building.

2.1 Governing partial differential equation for subsurface temperature profile

Two physical effects dominate energy propagation in the subsurface: conduction and advection. Material properties depend on present mix of solids, e.g., rock, sand, and fluids, e.g., water. Effective (mixed) material properties of aquifers, thermal conductivity λ_m or heat capacity c_m are usually determined by an on-site thermal response test [25]. It is assumed that the aquifer is saturated, homogeneous and non-transient. Energy advection is defined by groundwater's motion, whereas ambient groundwater flow is neglected. The magnitude of advection depends on the pumping activities of the ATES system. An adapted version of general equation of energy transport (1) in aquifers captures both physical effects, assuming a Newtonian fluid (water) with constant density ρ and heat capacity c_w as medium for advection [26, 27]. Change of inner energy and heat conduction rely on effective material properties of the aquifer $(\lambda_\mathrm{m}, c_\mathrm{m})$. The viscous dissipation function is neglected,

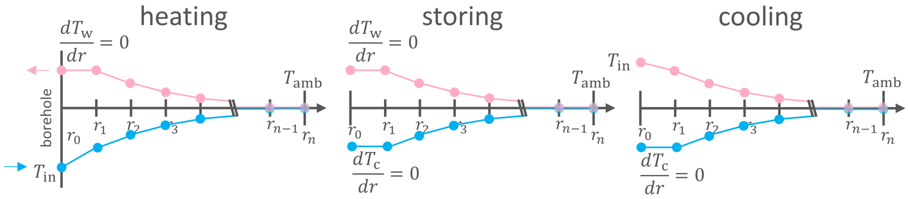

Figure 2: Schematic overview of chosen boundary conditions to solve governing partial differential equation based on operational mode

as viscosity and shear stresses are assumed to be low [28]. The acting energy transport equation

$$c_{\mathrm{m}} \frac{\partial T(r,t)}{\partial t} + c_{\mathrm{w}} v_{\mathrm{r}}(r,t) \frac{\partial T(r,t)}{\partial r} = \frac{\lambda_{\mathrm{m}}}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T(r,t)}{\partial r} \right) \tag{1}$$

is a parabolic nonlinear partial differential equation (PDE) [29]. T represents the Temperature $[\mathrm{K}]$, c_{m} the specific volumetric heat capacity of the aquifer (material mix) $[\mathrm{J}/\mathrm{m}^3\mathrm{K}]$, c_{w} the specific volumetric heat capacity of water $[\mathrm{J}/\mathrm{m}^3\mathrm{K}]$, v_{r} the flow velocity $[\mathrm{m}/\mathrm{s}]$ in radial direction r $[\mathrm{m}]$, λ_{m} the heat conduction coefficient of aquifer $[\mathrm{W}/\mathrm{mK}]$. Given the assumptions, the temperature profile is radially symmetric and the energy equation may be formulated in one-dimensional cylindrical coordinates $(\frac{\partial}{\partial \theta}, \frac{\partial}{\partial z} \equiv 0)$. For the implementation of the energy equation, boundary conditions must be specified for all operating modes. Temporal and spatial finite difference methods are used to derive a time-discrete model. A first order Taylor expansion is used to avoid nonlinear system dynamics. The spatial domain of the PDE solution starts at the borehole radius r_0 and ends far away from the borehole, such that ambient temperature may be assumed at that point. The domain is discretized by $n+1$ states as illustrated in Figure 2.

2.1.1 Boundary conditions

As already discussed, an ATES system can operate in three different modes: injection, storing (or inactivity) or extraction. These modes are independent and defined by the direction of pump flow. Each operational mode requires unique boundary conditions for solving (1). The temperature of injected fluid T^{in} is given by the heat exchanger leading to a Dirichlet-Boundary condition $T(r_0, t) = T^{in}(t)$. For extraction, it is assumed that the extracted fluid is equal to the temperatures close to the well, resulting in a Neumann-Boundary condition [6, 10, 30]

$$\frac{\partial T(r_0, t)}{\partial t} = 0\,.$$

The same boundary condition applies for storing (or inactivity) assuming perfect insulation of well. For all modes, ambient temperature T_{amb} is considered time-invariant at the end of the spatial domain and the initial temperature profile is $T(r, t_0) = T_{t=0}(r)$. A unique solution with given boundary conditions for governing energy equation (1) is proven by Protter and Weinberger [29, Thm. 8]. Figure 2 illustrates discussed boundary conditions depending on the operational mode and location.

2.1.2 Affinization

First order Taylor expansion is used to derive affine system dynamics of the nonlinear energy equation (1). Since we consider one per operation mode, we obtain piecewise affine (PWA) system dynamics of the form

$$\begin{aligned}\boldsymbol{x}(t+1) =& \boldsymbol{A}^{i(k)}\boldsymbol{x}(k) + \boldsymbol{B}^{i(k)}\boldsymbol{u}(k) + \boldsymbol{f}^{i(k)} \\ \boldsymbol{y}(k) =& \boldsymbol{C}^{i(k)}\boldsymbol{x}(k) + \boldsymbol{D}^{i(k)}\boldsymbol{u}(k) + \boldsymbol{g}^{i(k)}\,,\end{aligned} \tag{2}$$

with three (non-overlapping) regions i. At each time-step k, one of the regions, i.e., $i(k)$, will be active. The regions i are usually described with polyhedrons of the form $\boldsymbol{S}^i\boldsymbol{x}(k) + \boldsymbol{R}^i\boldsymbol{u}(k) \leq \boldsymbol{b}^i$. The affinization is important to lower the computational cost for solving the optimal control problem. Considering some working point $T^\circ = T(r^\circ, t^\circ), v_\mathsf{r}^\circ = v_\mathsf{r}(r^\circ)$, a first order Taylor expansion yields

$$\begin{aligned} c_\mathsf{m}\frac{\partial T}{\partial t} \approx & \left.\frac{\partial T}{\partial r}\right|_{T^\circ} \frac{\lambda_\mathsf{m}}{r^\circ} + \lambda_\mathsf{m} \left.\frac{\partial^2 T}{\partial r^2}\right|_{T^\circ} - \left.\frac{\partial T}{\partial r}\right|_{T^\circ} c_\mathsf{w} v_\mathsf{r}(t) - \left.\frac{\partial T}{\partial r}\right|_{T^\circ} \frac{\lambda_\mathsf{m}}{r^{\circ 2}}\left(r(t) - r^\circ\right) \\ & + \left.\frac{\partial^2 T}{\partial r^2}\right|_{T^\circ} \left(\frac{\lambda_\mathsf{m}}{r^\circ} - c_\mathsf{w} v_\mathsf{r}^\circ\right)\left(r(t) - r^\circ\right) + \left.\frac{\partial^3 T}{\partial r^3}\right|_{T^\circ} \lambda_\mathsf{m}\left(r(t) - r^\circ\right)\,. \end{aligned}$$

2.2 Heat exchanger model

The considered cocurrent heat exchanger between ATES system and building connects warm and cold aquifer ensuring mass conservation (see Fig. 1). The injection temperature are approximated with the extraction temperatures and the delivered energy to the building. For simplicity and since no building model is considered, the inlet temperature at the building side is assumed to be constant for each operational mode. Further, the heat capacity stream $\dot{m}_\mathsf{B}(k)c_\mathsf{w}$ on the building side is assumed to be constant ($T'_{1,\text{heating}} = 293\,\mathrm{K}$, $T'_{1,\text{cooling}} = 274\,\mathrm{K}$, $u_\mathsf{B}(k) = 0.1\,\mathrm{m^3/s}$). The injection temperature is than defined by given nonlinear dynamics

$$T''_2(k+1) = \frac{u_\mathsf{B}c_\mathsf{w}}{u_\mathsf{B}c_\mathsf{w} + u_\mathsf{A}(k)c_\mathsf{w}}\left(T'_1 - T'_2(k)\right) + T'_2(k)\,,$$

where u_A and u_B denote the pump flow rates at ATES and building side, respectively. With a first order Taylor polynomial, the previous equation is linearized around the initial state ${T'_2}^\circ$ and input ${u_\mathsf{A}}^\circ$ that is measured every time step. Affine system dynamics $(A_\mathsf{H}, B_\mathsf{H}, F_\mathsf{H})$ are derived, where the superscript h indicates heating operating mode

$$T''_2(k+1) = A^\mathsf{h}_\mathsf{H}T'_2 + B^\mathsf{h}_\mathsf{H}u_\mathsf{A}(k) + f^\mathsf{h}_\mathsf{H}\,.$$

3. Novel predictive controller

Optimal control of mixed dynamical models, the discussed system dynamics in Sections 2.1 and 2.2, typically result in mixed-integer programming (MIP). An integer decision variable switches between different systems of form (2) depending on current state or input [31]. Here, the regions i simply depend on the flow direction (and rate). The solution of MIP is computationally expensive, since - in the worst case - all combinations of the integer variables are examined. However, solution algorithms, e.g., branch-and-bound, are well developed and robust [20,32]. The model is integrated in a mixed-integer quadratic program

$$\min_{\boldsymbol{u}_N,\boldsymbol{x}_N} J_\mathrm{U}(\boldsymbol{u}_N) + J_\mathrm{D}(\boldsymbol{x}_N,\boldsymbol{u}_N) + J_\mathrm{E}(\boldsymbol{x}_N,\boldsymbol{u}_N) \tag{3a}$$

subject to

$$\underline{\boldsymbol{u}}_N \leq \boldsymbol{u}_N \leq \overline{\boldsymbol{u}}_N \tag{3b}$$

$$\underline{\boldsymbol{x}}_N \leq \boldsymbol{x}_N \leq \overline{\boldsymbol{x}}_N \tag{3c}$$

$$\boldsymbol{x}(k+1) = \begin{cases} \boldsymbol{A}_\text{heating}\,\boldsymbol{x}(k) + \boldsymbol{B}_\text{heating}\,\boldsymbol{u}(k), & \text{if } u(k) > 0 \\ \boldsymbol{A}_\text{storing}\,\boldsymbol{x}(k) + \boldsymbol{f}_\text{storing}, & \text{if } u(k) = 0 \\ \boldsymbol{A}_\text{cooling}\,\boldsymbol{x}(k) + \boldsymbol{B}_\text{cooling}\,\boldsymbol{u}(k), & \text{if } u(k) < 0 \end{cases} . \tag{3d}$$

following the design structure of Bemporad and Morari [31]. The addends in the objective function (3a) are chosen to push the control towards sustainable operation of ATES systems with respect to energy balance and appropriate injection temperatures (see Sect. 1.1). Temperatures in the subsurface are constrained by (3c) to avoid exceeding upper and lower boundaries given by f.i.: VDI 4640 [14] or Degenhart et al. [10]. Input constraints (3b) may be set according to the deployed pump capacity. The first addend of objective function focuses on lowering pump cost of ATES system with

$$J_\mathrm{U}(\boldsymbol{u}_N) = \boldsymbol{u}_N^T \boldsymbol{Q}_\mathrm{U} \boldsymbol{u}_N ,$$

where $\boldsymbol{u}_N$ is the condensed input vector over the prediction horizon of length N. Second and third addend concentrate on delivering the building's energy demand and achieving a balanced operation as discussed in Section 1.1. The energy demand over the prediction horizon $\boldsymbol{D}_N$ is tracked by the quadratic cost

$$J_\mathrm{D}(\boldsymbol{u}_N,\boldsymbol{x}_N) = (\boldsymbol{D}_\mathrm{N} - \boldsymbol{E}_N(\boldsymbol{u}_N,\boldsymbol{x}_N))^T \boldsymbol{Q}_\mathrm{D} (\boldsymbol{D}_\mathrm{N} - \boldsymbol{E}_N(\boldsymbol{u}_N,\boldsymbol{x}_N)) .$$

$\boldsymbol{x}_N$ is the condensed state vector and $\boldsymbol{E}_N(\boldsymbol{u}_N,\boldsymbol{x}_N)$ denotes the delivered energy by the ATES system over the prediction horizon. For heating or cooling, $\boldsymbol{D}_N$ and $\boldsymbol{E}_N(\boldsymbol{u}_N,\boldsymbol{x}_N)$ are comprised of positive or negative values, respectively. To achieve sustainable operation of ATES system, energy balance cost

$$J_\mathrm{E}(\boldsymbol{u}_N,\boldsymbol{x}_N) = \left(E_\text{past} + \boldsymbol{1}_{1\times N}\boldsymbol{E}_N(\boldsymbol{u}_N,\boldsymbol{x}_N)\right) Q_\mathrm{E} \left(E_\text{past} + \boldsymbol{1}_{1\times N}\boldsymbol{E}_N(\boldsymbol{u}_N,\boldsymbol{x}_N)\right)$$

concentrate on balancing overall provided energy. E_past represents the sum of provided energy of all past operational time and $\boldsymbol{Q}_\mathrm{U}, \boldsymbol{Q}_\mathrm{D}, Q_\mathrm{E}$ are user-defined weighting factors. In balanced operation, positive (heating) and negative (cooling) values cancel out in the sum of provided energy of past operational time. The solution of (3) depends on the objective function and given (inequality) constraints, such that the decision on operational mode is independent of energy demand by building.

4. Numerical study

The behaviour of the proposed MPC scheme is tested on real data of an ATES system connected to a hospital in Brasschaat close to Antwerp, Belgium. The data is provided by Desmedt et al. [4]. The considered ATES system delivers energy to the ventilation system of the hospital. The building consists of 4 floors, 440 beds, surgery and, consultation rooms. It is known that such buildings have a strong alternating demand of heat and cold, especially during spring and autumn. Drilling tests showed that a water-saturated sand aquifer with a depth of about $100\,\mathrm{m}$ is separated by a clay-layer at about $80\,\mathrm{m}$. This geological configuration is considered preferable for ATES operation. The ATES system is capable of a maximal extraction rate of $100\,\mathrm{m^3/h}$ leading to a theoretical cooling

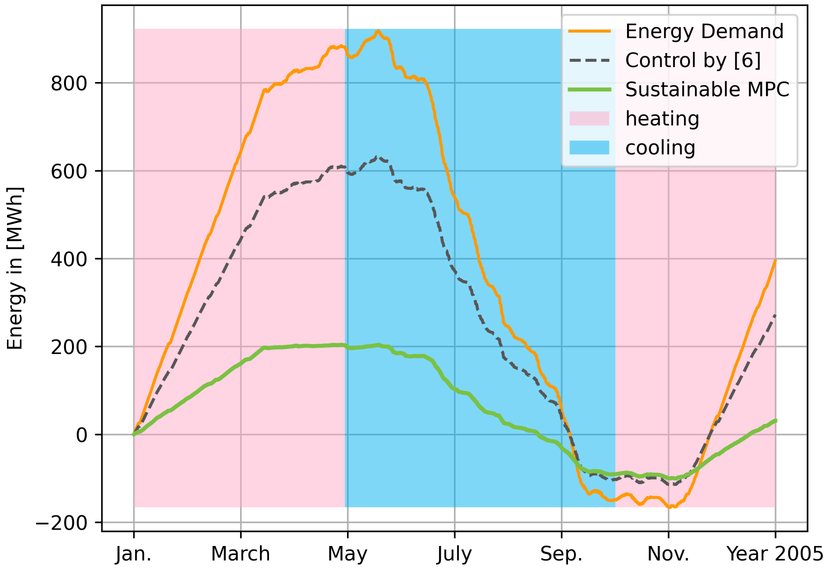

Figure 3: Total delivered energy by ATES system to building and building's energy demand in 2005 over time in comparison with the deployed controller in [4] and proposed MPC scheme.

power of $1.2\,\mathrm{MW}$. Operational data of three years from 2003 to 2005 show that the ATES system may have high investment cost, however, achieves a simple payback time after 8.5 years due to lower operational cost [33]. Compared to a reference HVAC system, discussed configuration with ATES system has saved 63% of CO_2-emissions ($11789\,\mathrm{GJ}$) with a drastically lower primary energy consumption [34].

In the long-term experimental evaluation of the operation of ATES system between 2003 and 2005, Vanhoudt et al. [33] have shown that the ATES system provided more heat ($12.3\,\mathrm{TJ}$) than cold ($9.8\,\mathrm{TJ}$). As a consequence, the warm aquifer could not be fully charged during summer period, and consequently approaching thermal exhaustion. The authors attribute the unbalanced operation to the manual control. Measures to prevent depletion of warm well by installing long term monitoring of operation and adjusted control strategies were proposed. The data contains information about the supplied energy by ATES system to the building. Building's energy demand is linearly extrapolated knowing that the energy demand tracking performance of deployed controller in [4] is 69%. Missing data is linearly extrapolated. State and input constraints for the mixed-integer quadratic program (3) are taken from [4] and VDI4640 [14]. Cost weights $\boldsymbol{Q}_\mathrm{U} = 1\boldsymbol{I}$ $\boldsymbol{Q}_\mathrm{D} = 1994\boldsymbol{I}$ $\boldsymbol{Q}_\mathrm{E} = 0.001$ are designed to balance the addends equally. Since past operational data is unknown, $\boldsymbol{E}_\mathrm{past}$ equals zero at start of simulation. The mixed-integer program is solved with Gurobi [32] in a Python environment. The entire simulation of one year (8746 time steps of $1\,\mathrm{h}$) runs on a standard Windows Desktop-PC (Intel Core i5-4690, $16\,\mathrm{GB}$ RAM) in about $50\,\mathrm{h}$. Demonstrated by simulation, the controller satisfies input and state constraints. Further, sustainable operation of ATES system has been improved in comparison to deployed controller in [4]. As illustrated by Figure 3, provided heat and cold nearly equal after the time period. In total $31.6\,\mathrm{MWh}$ of more heat is supplied to the building by the proposed sustainable MPC scheme. In comparison, the operation with the deployed controller in [4] resulted in an unbalanced operation with $300\,\mathrm{MWh}$ of more heat delivered to the building.

Comparing the contributed amount of energy, the sustainable MPC scheme supplies less energy to the building's energy demand (36.6%). Deployed controller in [4] achieved an energy contribution of 69%.

5. Conclusion

Motivated by the aim of mitigating climate change, ATES systems may play an important role to lower greenhouse gas emissions related to HVAC technology. Our literature review highlights two important requirements for sustainable use of ATES systems. First, injection temperatures may not exceed given bounds. Second, equal amounts of heat and cold should be stored in the subsurface within a certain time horizon for balanced operation [14]. We introduce a novel model and a corresponding MPC scheme with the aim of fulfilling the requirements for sustainable ATES use. The model focuses on the convective and conductive energy transport in the subsurface to capture the stored amount of energy in the ATES. It is shown that mixed dynamical models with PWA system dynamics can be used to model the stored amount of energy in ATES systems, resulting in MPC with mixed-integer programming. The optimal control problem (3) focuses on minimizing the operational cost of ATES systems, its heat demand tracking error and, unbalanced operations according to VDI 4640 [14]. A case study compares the performance of discussed MPC scheme with provided operational data from an ATES system in Belgium [4, 33, 34]. The MPC scheme fulfills the requirements of appropriate injection temperatures and balanced operation achieving sustainable control of ATES systems.

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