

Investigating Aquifer Thermal Energy Storage for Demand-Side Flexibility in Great Britain

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ABSTRACT

Aquifer Thermal Energy Storage (ATES) occupies a unique role in modern energy systems, relying on both groundwater resource availability and electrical power to provide seasonal thermal energy storage for heating and cooling services. In an increasingly integrated energy system, understanding these interdependencies creates opportunities for synergies across energy vectors and resources. In Great Britain, the growing share of intermittent renewable generation is driving grid system operators to seek flexible demand solutions capable of supporting peak load management and reducing renewable energy curtailment. The work herein makes use of the combined power-to-heat and thermal energy storage characteristics of ATES to explore the synergy of heat and electricity vectors through demand-side response. An energy system modelling framework is developed to explore control options of commercial-scale greenhouses with low-temperature ATES. This uses implicit price signals as a key decision variable. Machine learning models are applied to generate day-ahead forecasts of wholesale electricity prices, enabling risk-based scheduling of energy use in electricity flexibility markets. Using a receding forecast horizon, predictive control aims to reduce the levelised cost of heating and cooling through low-cost improvements to storage efficiency. A Python-FEFLOW modelling framework is developed to assess the impact of demand-side response on key indicators of technical, economic and environmental performance for conceptual energy system designs.

1 INTRODUCTION

Innovative heating and cooling systems are central to a sustainable and just energy transition. Vast cross-sectoral electrification of heating and cooling services is poised to replace incumbent systems, catalysed by integration with intermittent renewable energy sources (iRES). This energy system transformation is challenging traditional energy market controls. The relative non-dispatchable nature of iRES and need to reduce a reliance on dispatchable fossil-fuel based generation has raised important questions on the use and storage of energy across sectors and vectors. This multi-vector, multi-sector holistic perspective on future energy systems calls for innovation on integrated modelling across viable energy demand-side and energy storage technologies. As iRES continue to constitute a greater portion of the energy mix, grid system operators are increasingly seeking means to mitigate against power demand spikes. This has led to increased consumer engagement for demand-side response (DSR). Within this context, smart control of power-to-heat (P2H) and thermal energy storage (TES) is a proposed component of grid flexibility (Kohlhepp et al., 2019).

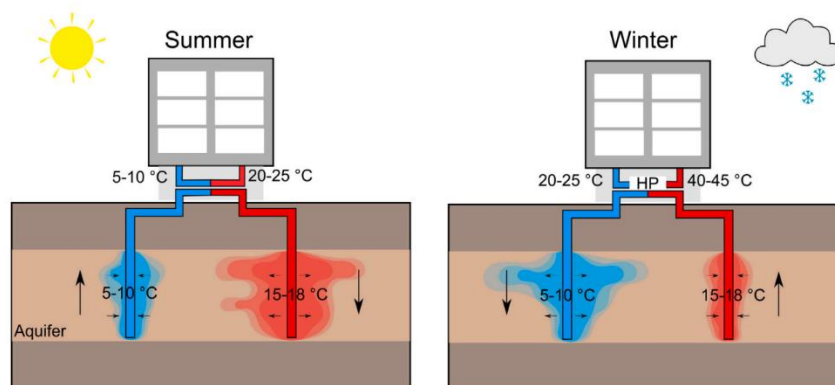


Figure 1. Aquifer thermal energy storage system (Regnier et al., 2022).

The strain on power grids is implicitly reflected in wholesale electricity prices and flexible time-of-use tariffs. This incentivises electrified energy systems to shift demand to low-cost periods through energy storage and peak shaving. This has the combined benefits of reduced energy system operation costs, reduced curtailment requirements and reduced cumulative demand peaks. Aquifer thermal energy storage (ATES) combines P2H, through heat pump and chiller dependency, and TES, through the use of subsurface aquifers (porous, permeable, water-bearing formations) for the seasonal storage and retrieval of thermal energy in an aqueous form. In the more common low-temperature design (heat storage less than 25°C) in shallow aquifers (less than 500 m beneath surface), abstracted groundwater must act in conjunction with industrial heat pumps to raise the working temperature and add value to the stored resource. It is this DSR potential in ATES systems as part of multi-vector energy systems that the work herein seeks to investigate.

Energy system modelling frameworks (ESMFs) have been developed for applications ranging from short-term ancillary services to long-term national energy planning. Yet few have integrated ATES within the suite of available system components. On the occasion that ATES is included it is often represented by a highly simplified analytical model or surrogate model. Furthermore, the black-box nature of many ESMF makes the modelling approach difficult to validate through a lack of transparency. Meanwhile, examples of UTES modelling in open-source energy system modelling frameworks (OS-ESMFs) are severely limited and often rely on a constant coefficient of performance (COP) while treating the aquifer store akin to a short-term buffer hot water storage tank. The work herein thus seeks to numerical modelling of ATES and ESMFs for the purposes of investigated sector-coupled demand response.

2 METHODS

The core ESMF herein has been developed in the Python programming language with object-oriented programming. This decision was made in favour of commercially-available energy system modelling software in order to draw from a range of open-source packages which improved system design flexibility and modularity.

2.1 Energy System Components

A typical arrangement of energy system components simulated in the ESMF is shown in Figure 2. Central to the ATES integration in the framework is the modelling of the heat pump, chiller and heat exchanger. The accuracy in simulating these components is fundamental to control decisions related to ATES storage temperatures. The Python-based TESPpy modelling framework, accounts for the operating conditions of these components by reflecting working fluid temperature-pressure dependency through the CoolProp library (Witte and Tuschy, 2020). The COP of the heat pump and chiller thus goes beyond the simplified approach to energy system modelling in other ATES studies. For example, for an ATES with warm storage ranging from 10 to 25°C, a sensitivity analysis of heat pump found the COP varied from 3.0 to 3.6 when operating at an evaporator inlet flow rate of 40 kg/s. The relationship between temperature and COP also varies with operating mass-flow rates, often ignored in high-level energy system models. For example, an ATES with cold side storage of 10°C, the chiller COP varied from 3.3 to 10.3 as mass flow into the condenser ranged from 40 to 2 kg/s. Low storage temperatures (<6 °C) in the cold side of the ATES are assumed to provide free-cooling, bypassing the need for the chiller and interacting with the cooling bus directly via a heat exchanger.

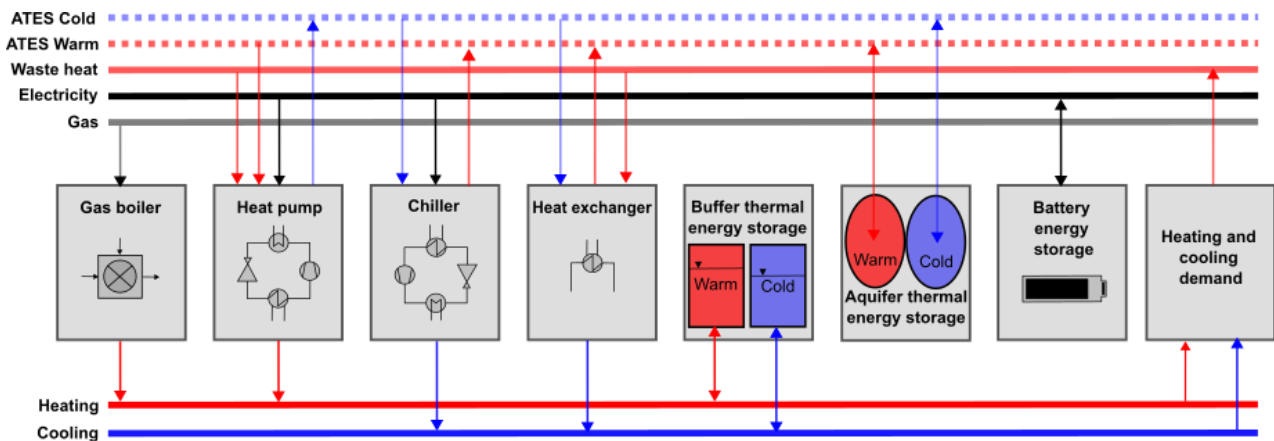


Figure 2. An example of an integrated energy system that can be implemented through the proposed framework.

The ESMF allows buffer tank designs to interface with the heating and cooling buses, shown in Figure 2, which adds short-term load fluctuation support to the ATES by providing thermal power when demand drops below the minimum part-load constraints of the heat pump and chiller. The short-term buffers are defined as surface storage tanks, demanding that heat losses and gains dependent on ambient outdoor air temperature and specified insulation material properties are included in the modelling. The rate of charge and discharge is set by the buffer C-rating, which by default is set to one full charge or discharge cycle per hour.

Given the focus on sector-coupling and market integration in the framework, the option to include battery energy storage systems is available. As shown in Figure 2, the BESS system has a bidirectional interface with the electricity bus from which other system components draw power, such the compressor of the heat pump. As in the case of the buffer tanks, the capacity BESS can be set by the user (default set to 1 MW) and others fast response with a C-rating set to one full charge or discharge cycle per hour. The degradation of the BESS is modelled by accounting for the number of charge-discharge cycles as well as the total operational lifespan.

Back-up boilers have also been included in the framework set-up. By default, a gas boiler is added to the system with capacity to cover 70% of the expected peak demand from the load, estimated prior to full integrated model simulation. This delivers heat to the heating bus with an assumed efficiency of 85%. An auxiliary electric boiler can also be added to interface between the electricity bus and heating bus, while there is also the option for an air-source heat pump to interface between the electricity and cooling bus.

2.2 Aquifer thermal energy storage numerical model

The framework herein deploys numerical modelling of ATES. While analytical models may offer faster simulation, they compromise on the precision and accuracy of the underlying results. For the complex mode of operation anticipated when integrating ATES into dynamic multi-vector energy systems, the simplified charging, storage and discharging cycles assumed in the available analytical solutions further undermine their suitability as modelling approaches here. The challenge to produce bidirectional analytical solutions capable of simulating subsurface temperature distributions also remains and hurdle to their application. Recent surrogate models of high-temperature ATES for example have shown promising accuracy for simplified charging and discharging periodicity yet were found to differ significantly from the baseline numerical model when a more irregular short-term cycling was applied (Geerts et al., 2025).

Numerical modelling approaches, such as FEFLOW used herein, produce more accurate estimates of subsurface thermodynamic and thus more reliable temperature distributions around the wellheads of the ATES system. Nonetheless, such numerical approaches suffer from the need to iteratively solve a discretised 3D representation of the storage media, whether this is via finite volume methods (as in FEFLOW), finite element methods or finite difference methods. The numerical modelling software FEFLOW is chosen despite this significant drawback to ATES model integration with wider energy system modelling tools. It is an area for ongoing work within the field to create robust analytical models of ATES that can faithfully produce temperature distribution in heterogeneous geological strata while operating non-ideal charge-discharge cycles.

2.3 Time-series Forecasting

2.3.1 Electricity Price Forecasting

The framework supports forecasting models for day-ahead wholesale electricity prices as an implicit time-of-use signal for energy systems component scheduling. For the work presented herein, the deep learning NBEATS (Neural Basis Expansion Analysis for Time Series) is applied to wholesale prices (Olivares et al., 2023). This has been applied with bootstrapping of lag prices range to generate an ensemble of deterministic forecast of day-ahead prices. The ensemble mean is subsequently taken for each hour of the forecast to give the final deterministic forecast (Figure 3).

The ensemble approach has also been applied in order to produce distribution-free prediction intervals for each hour of day-ahead electricity price. The conformal prediction algorithm EnbPI (Ensemble Batch Prediction Interval) is applied as a wrapper around the ensemble of deterministic NBEATS outputs to provide guaranteed forecast coverage at set confidence levels (Xu and Xie, 2021). This is formulated based on the prior accuracy of the deterministic forecast relative to the true electricity prices, with worse performing models (greater errors in conformity score) producing wider prediction intervals to maintain guaranteed coverage of the forecast thus revealing the uncertainty and inaccuracy in underlying price forecast model. The EnbPI approach was selected over other forms of conformal prediction for its recognition to maintain the sequential nature of time-series data by denying the exchangeability assumption during training and validation.

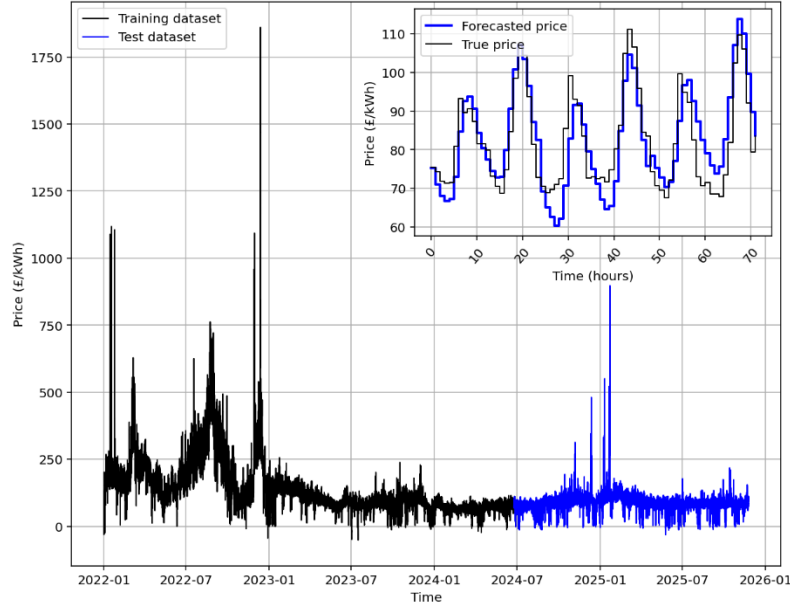


Figure 3. Electricity price dataset from Great Britain wholesale prices for tuning forecast model hyperparameters (LCCC, 2025). The inset figure shows the comparison between forecasted and true prices for an arbitrary three-day window, using the ensemble of NBEATS forecast model with a 24-hour prediction horizon and varying lag window lengths.

2.3.2 Greenhouse Thermal Power Demand Forecasting

The demand model is a deterministic forecast of greenhouse heating and cooling requirements dependent on the day-ahead weather conditions (data sources). The weather variables of interest to the model are solar irradiance, outdoor air temperature, outdoor relative humidity and outdoor wind speed at the greenhouse site (Open Meteo, 2025). Using the analytical greenhouse model of van Beveren et al. (2015), heating and cooling demand are set based on time of day, day of year and day of growth cycle for a tomato crop biannual rotation. The model includes the effects of evapotranspiration via the Penman-Monteith transpiration model and dynamic leaf area index to ensure the time-varying nature of plant growth is reflected in the thermal power demands. As with other components of the energy system, the design of the greenhouse allows for flexible design inputs. The heat flows (Q) and humidity flows (ϕ) are shown

2.4 Integrated model workflow and control

The interactions between the main model classes in the framework are shown in Figure 4. The three main inputs to the energy system model are (i) electricity price forecasts; (ii) greenhouse energy demands, and (iii) the FEFLOW ATES model which is interfaced using the FEFLOW-Python interface manager (IFM). Forecasts are made at the start of each day for the day-ahead electricity prices and greenhouse demand at an hourly resolution. At the same instance, the ATES well temperatures are imported from FEFLOW and assumed constant during the day to reduce the number of callbacks to FEFLOW. At the end of each 24-hour horizon block, the true price data from the day is appended to the current forecast training set while the ATES flow-rate and temperature controls are applied to the FEFLOW model in preparation of the next window.

The initial control strategy of the ATES-integrated ESMF is rules-based. The justification for this decision lies in the non-linearity of the energy system components, an important distinguishing factor between ESMFs that demand a linearization of the problem to solve a total system cost optimisation. Primarily this decision is taken to reflect the multiple dependencies of heat pump, and chiller, COP and thermal power output on the operating temperatures, mass flow rates and pressures. Sensitivity to these variables is important in reflecting the efficiency impacts of demand-side response, such as increased ATES temperature, while simulating ATES within realistic operating conditions, such as minimum and maximum reinjection temperatures to the subsurface in line with regulation. The advantage of the electricity price forecast is therefore derived from defining low price points for the day-ahead. Rather than optimise the energy system around these points, the forecast gives context to the current hourly electricity price with regards to the remaining hours of the day, alerting the energy system to take advantage of the low cost or to deploy BESS to avoid high price points. The control process for the ESMF at present follows the workflow shown in Figure 5.

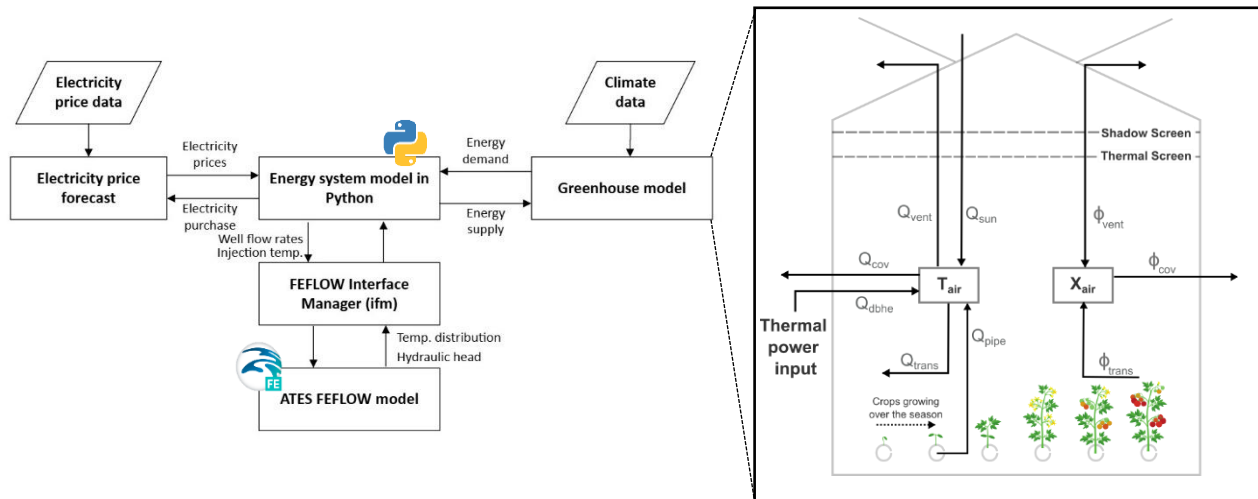


Figure 4: Schematic of the energy system modelling framework linking aquifer thermal energy storage and energy system control to time-of-use signals in power markets. The deterministic greenhouse energy demand model adapted from van Beveren et al. (2015) is dependent on weather conditions to calculate the heat flows (Q) and relative humidity (ϕ).

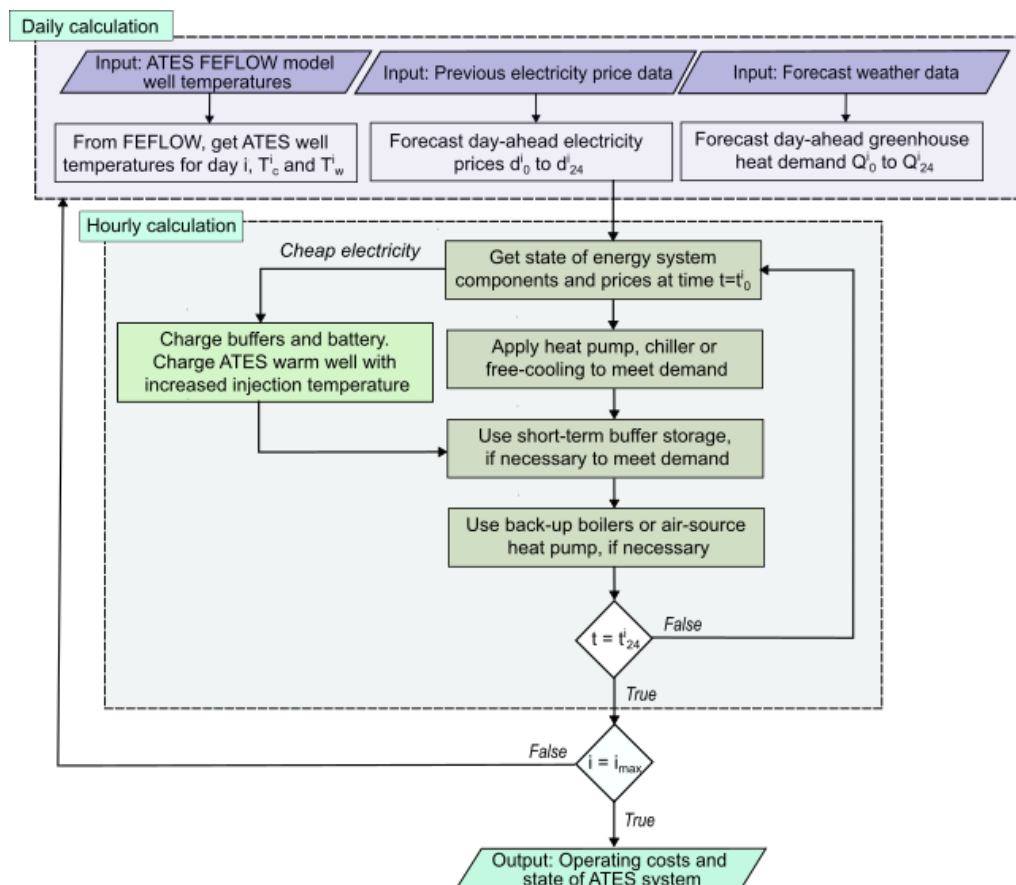


Figure 5: A high-level overview of the modelling workflow. The specific details pertaining to each process are specific to the framework set-up and components included.

3 INTEGRATED MODELLING RESULTS

An energy system arrangement is provided herein to illustrate the functionality of the modelling framework. The greenhouse is sited in north-west England, to coincide with the productive Sherwood Sandstone formation. Outdoor climatic data specific to this region are used in the greenhouse model. The greenhouse is specified as having a footprint of 5000m² with gutter and ridge heights of 4.5 m and 5.5 m, respectively. To protect crop growth in the greenhouse, assumed to be tomato growth, a thermal screen is deployed at solar irradiance values above Indoor temperature set points vary throughout the day to simulate a steady diurnal oscillation ranging from 18°C in the evening to 21°C during the day. Natural ventilation is included in the model in addition to the cooling provided by the energy system. Similarly, indoor relative humidity varied during the day from 75 % to 85%. The model is run for a one-week period in April 2024 as a demonstration of the framework. Long-run inter-seasonal models can be run with the framework but are beyond the scope of this paper.

The ATES is modelled in an unconfined aquifer, with properties based on a literature review on the area (Kingdon et al., 2017). The properties in the example case herein are the following: horizontal hydraulic conductivity (1.0 m/d); vertical hydraulic conductivity (0.1 m/d); porosity (0.2); volumetric heat capacity of solid (2.325 MJ/m³·K) and thermal conductivity of solid (2.5 W/m·K). The model domain is assumed to be saturated and a hydraulic gradient of 0.002 is placed across the model with temperature boundary conditions set to allow 10°C ambient inlet flow. The FEFLOW mesh is set up as shown in Figure 6.

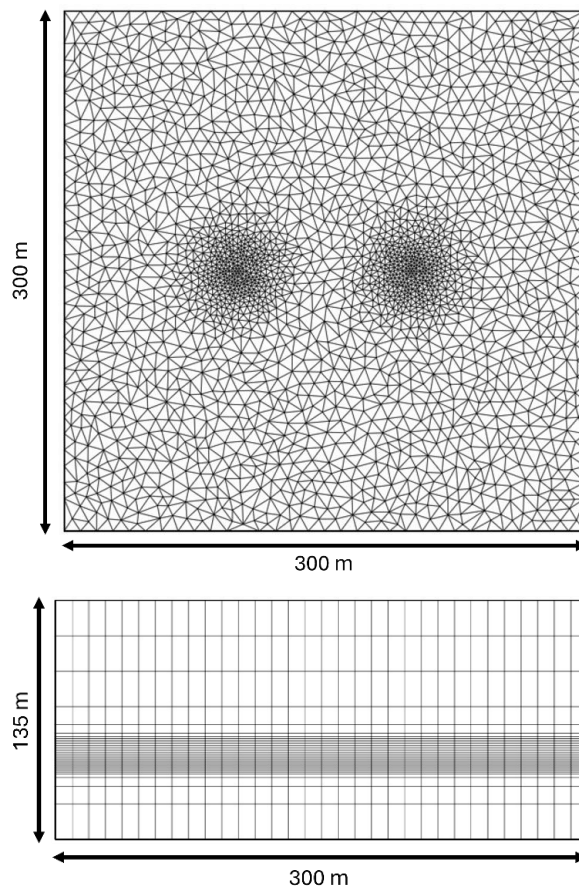


Figure 6: Model set-up for the aquifer thermal energy storage doublet in FEFLOW.

The results for the model set-up described above are shown in Figure 7. The primary input to the model (outdoor air temperature) varies from 2 to 15 °C during the modelled week, creating a combination of heating and cooling demands from the ATES and energy system. This variation in demands through the day creates varying injection temperatures and flow rates to the ATES, within the pre-defined constraints from regulation and system productivity, respectively. The decision of component operational status is taken with respect to the forecasted electricity price which replicates the trends of the true day-ahead prices. The costs of running the system are subsequently calculated using the true day-ahead prices. The hydraulic and thermal plumes can be estimated analytically from the tracked stored volumes or taken directly from a cross-section of nodes in the FEFLOW model.

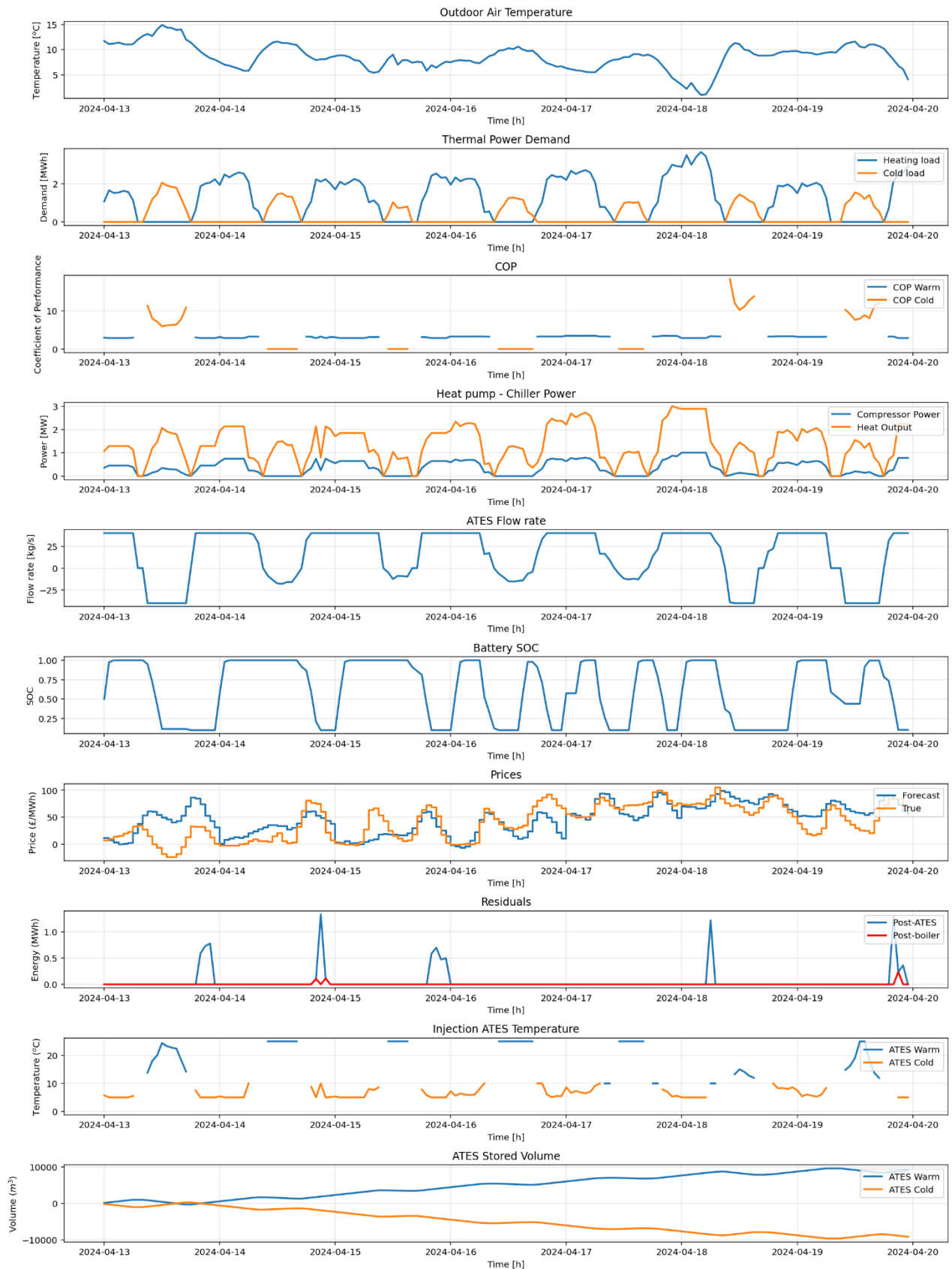


Figure 7: Example outputs for the energy system modelling framework, showing the fluctuation in injection temperatures and flow rates for the aquifer thermal energy storage system.

4 DISCUSSIONS AND CONCLUSIONS

The wider system benefits of UTES have not been sufficiently explored. The use of ESMFs with integrated or interfaced models of subsurface heat and fluid transport fulfils an important role in these investigations. The work presented herein shows one approach to sector-coupling with ATES and wider energy systems, focussing on the importance of operational dependencies of the central TES and P2H (heat pump and chiller) technologies and demand-side response to price signals. The rules-based approach to control, supported by the forecasts of day-ahead electricity prices, provides a techno-market ESMF which complies with these important component constraints and non-linear dynamics. The uncertainty in this forecasting an important factor in energy system scheduling. The results in Figure 7 show the disparity in electricity price forecast that can arise from a range of exogenous factors upon which prices are conditional. The use of EnbPI prediction intervals in future iterations of the work will highlight the degree of confidence in the demand side response control decisions.

Future work in this area extends to the scheduling optimisation of energy systems. Initial work is underway by the authors to use linear and mixed-integer programming for day-ahead scheduling. While the optimisation process demands a simplification of the component dynamics, it offers the possibility of reducing total energy system costs. Leveraging the advantages of both the OS-ESMF and rules-based physical system modelling framework in a two-step process presents a direction for further development. The model framework should also aim to integrate regulatory constraints to maintain a contextual awareness in the control the ATES. This can be realised by placing boundary limits on the thermal plume propagation and the storage temperatures which support confidence in permitting compliance. The use of FEFLOW in the ESMF opens the potential for plume monitoring and context-aware ATES modelling.

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