Building Heating and Cooling System with ATES Single Agent Model and Control

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Research Direction

The following concepts are involved:

1. **Constrained Optimal Control Techniques:**
   - Model Predictive Control

2. **Large Scale Complex System:**
   - Aquifer Thermal Energy Storage Smart Grids

3. **Distributed System Solutions:**
   - Cooperative Strategy - Negotiation Approach

4. **Robustness of Solutions w.r.t. Uncertainties**
   - Randomized Approach - Data-Based Robust Optimization

Main research direction:
Stochastic Distributed Optimal Control for Large Scale Complex Systems

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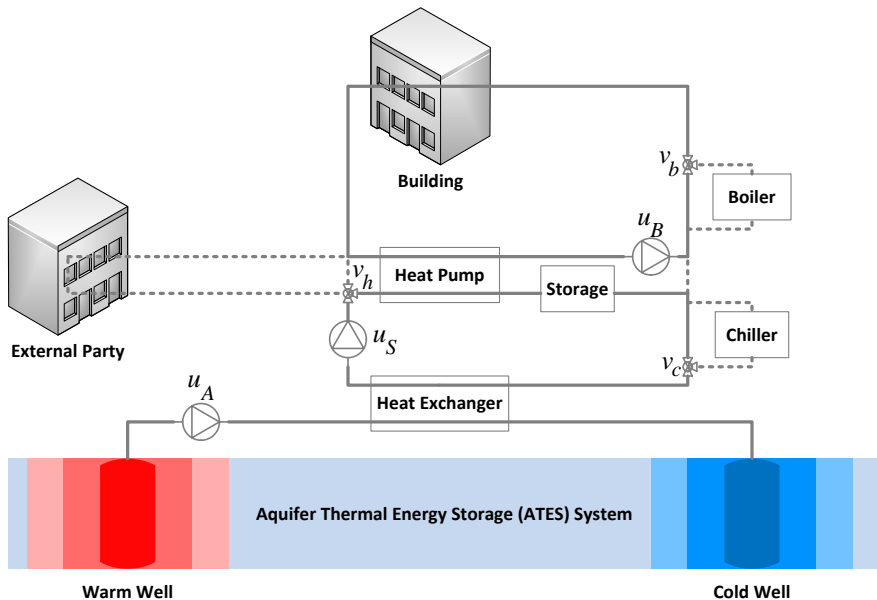   - Randomized Approach - Data-Based Robust Optimization

Main research direction:

Stochastic Distributed Optimal Control for Large Scale Complex Systems

Large Scale Complex Systems

University

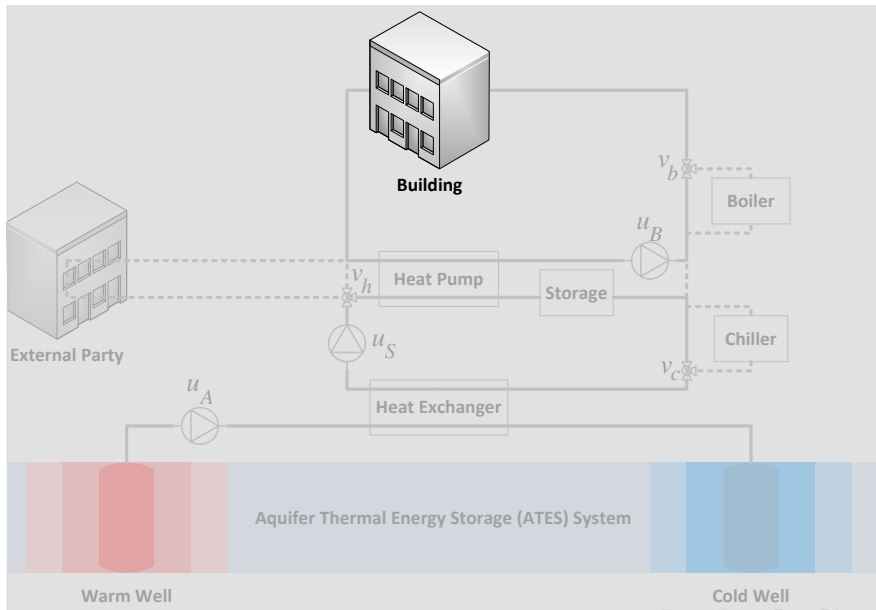Aquifer Thermal Energy Storage (ATES) System

Bank Buildings
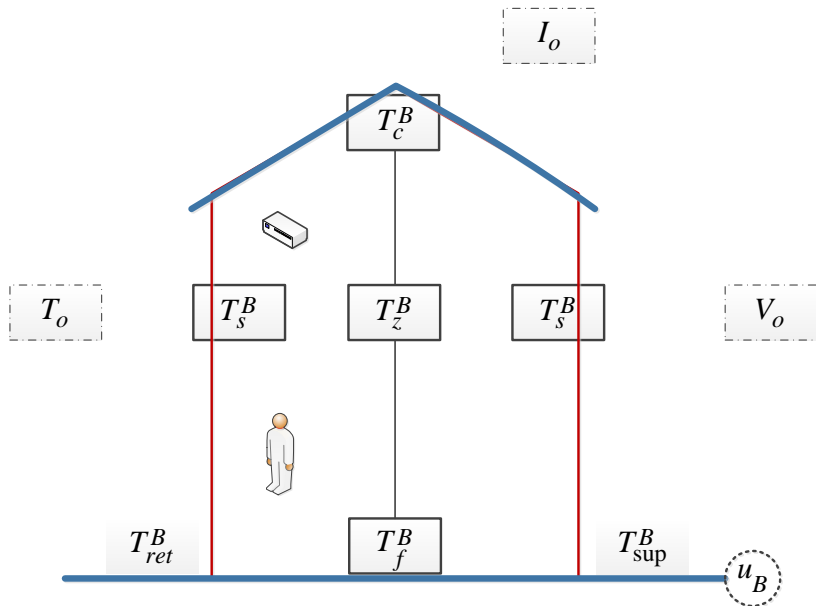
Mega Markets
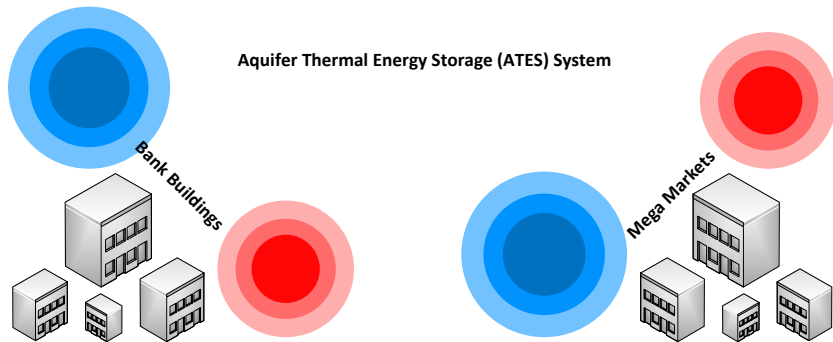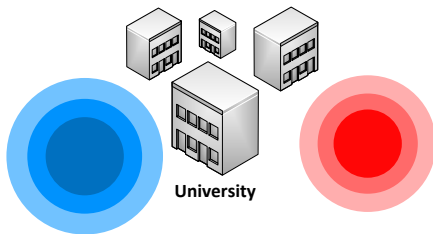
Single Agent System

Outline

1 Single Agent Model

2 Control Problem Formulation

3 Simulation Study and Main Results

4 Discussions and Future Works

Single Agent System
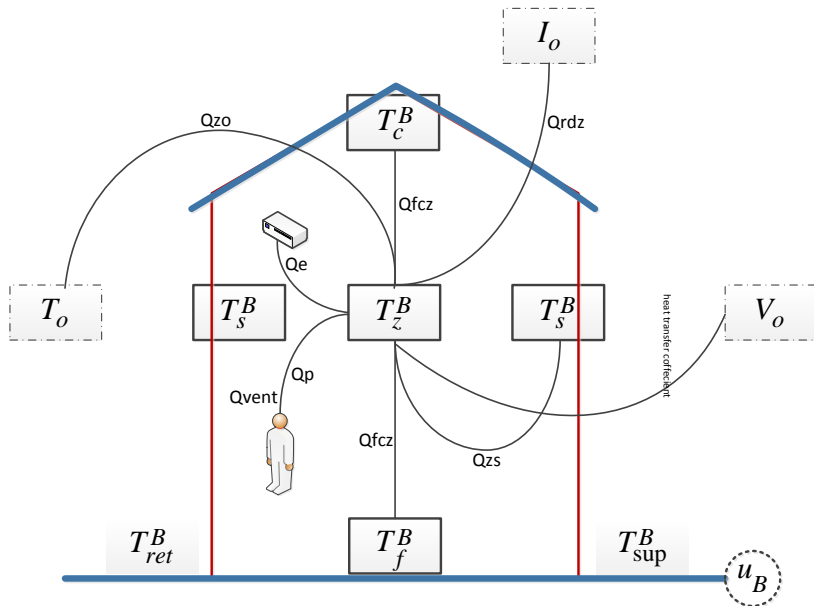
Building Thermal Comfort Relations
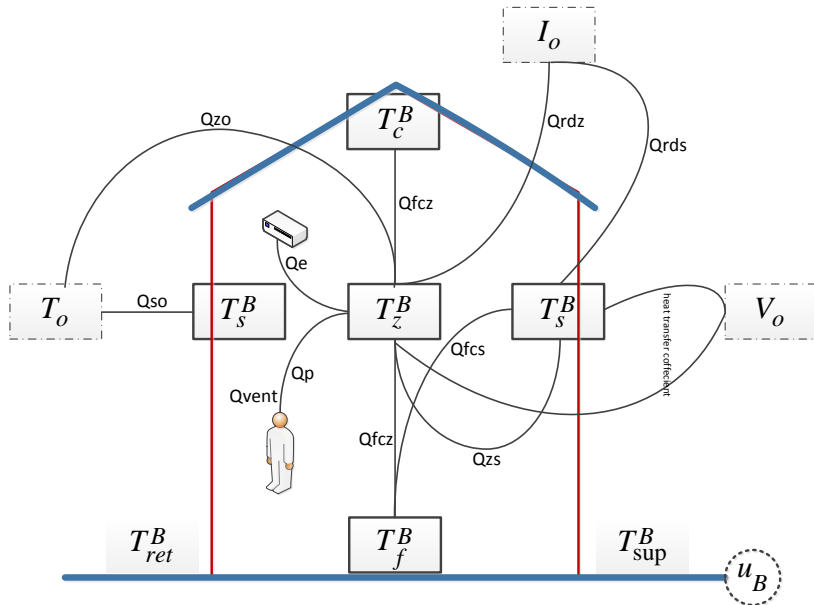
Building Thermal Comfort Relations

Building Thermal Comfort Relations

Building Thermal Comfort Relations

Building Thermal Comfort Model Formulation

We define the following model:

Building Dynamical Model

$$x_{B,k+1} = x_{B,k} + f_B(x_{B,k}, u_{B,k}, \nu_{B,k}, \nu_{Bext,k})\tau$$
$$y_{B,k} = g_B(x_{B,k}, u_{B,k})$$

- Building inside variables (states): $\quad x_{B,k} \in \mathbb{R}^3$
- Building outside variables (uncertain): $\quad \nu_{Bext,k} \in \mathbb{R}^3$
- Pump flow rate variable (control): $\quad u_{B,k}$
- Supplied water temperature: $\quad \nu_{B,k}$
- Returned water temperature: $\quad y_{B,k}$
- Sampling period: $\quad \tau$

Single Agent System
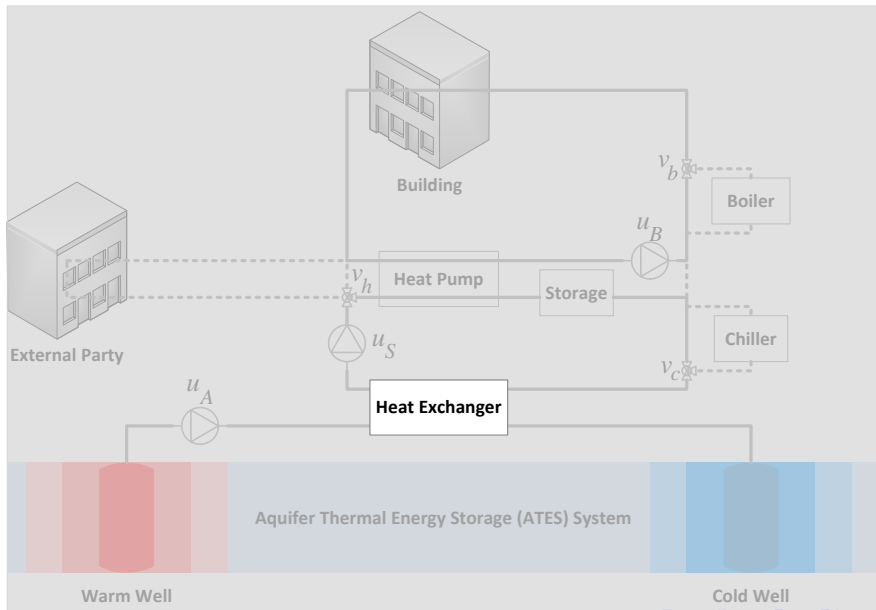
Heat Exchanger Model

A countercurrent heat exchanger is used and it presents via a static model.

Static Model Variables:

- Input water temperatures: $\nu_{\mathsf{he},k} \in \mathbb{R}^2$
- Pump flow rates (control variables): $u_{\mathrm{A},k}, u_{\mathrm{S},k}$
- Output water temperatures: $y_{\mathsf{he},k} \in \mathbb{R}^2$
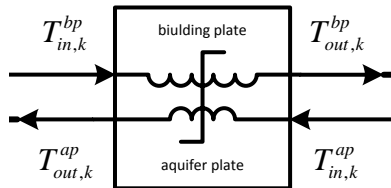
Heat Exchanger

Heat Exchanger Static Model

$$y_{\mathsf{he},k} = \mathrm{H}(\nu_{\mathsf{he},k}, u_{\mathrm{A},k}, u_{\mathrm{S},k})$$

Single Agent System

Heat Pump Model

An electrical water to water heat pump is used with static model.

Static Model Variables:

- Input water temperatures: $\nu_{\text{hp},k} \in \mathbb{R}^2$
- Pump flow rates (control variables): $u_{\text{B},k}$, $u_{\text{S},k}$
- Output water temperatures: $y_{\text{hp},k} \in \mathbb{R}^2$

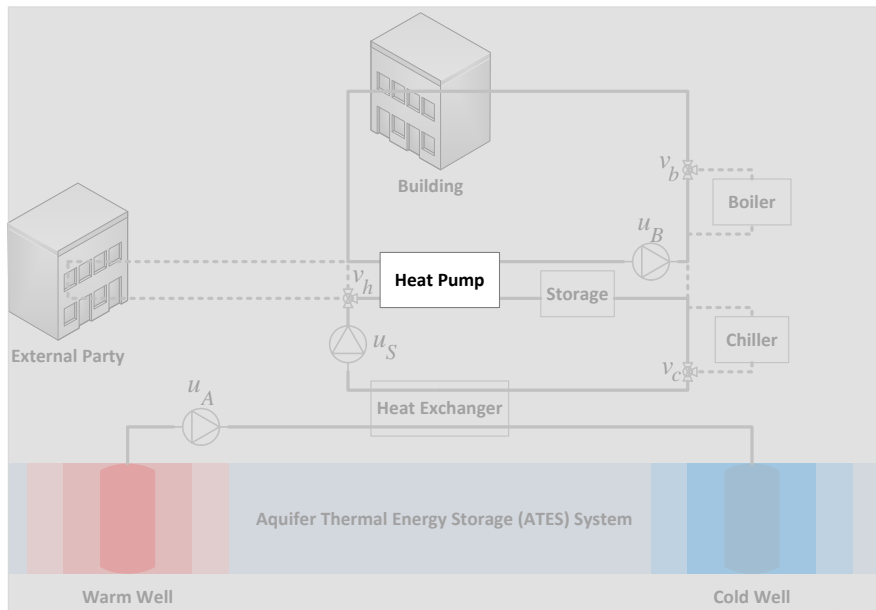

$T_{in,k}^{eva}$ $T_{out,k}^{con}$

evaporator condenser

$T_{out,k}^{eva}$ **Heat Pump** $T_{in,k}^{con}$
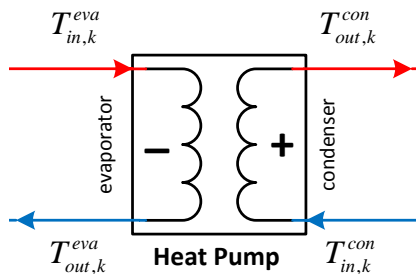
Heat Pump Static Model

$$y_{\text{hp},k} = \mathrm{P}(\nu_{\text{hp},k}, u_{\text{B},k}, u_{\text{S},k})$$

Single Agent System
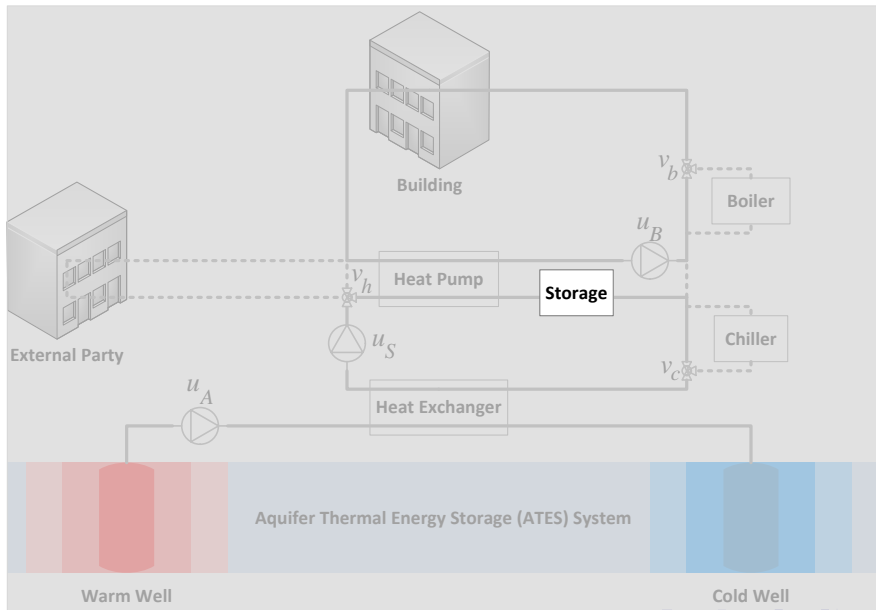
Storage Tank Model

We define an storage tank model with the following first order difference equations:

$$V_{s,k+1} = V_{s,k} + V_{in,k} - V_{out,k}$$

$$T_{s,k+1} = \frac{V_{s,k}}{V_{s,k} + V_{in,k}} T_{s,k} + \frac{V_{in,k}}{V_{s,k} + V_{in,k}} T_{in,k}$$

Storage Dynamical Model

$$x_{S,k+1} = f_S(x_{S,k}, u_{S,k}, \nu_{S,k})$$
$$y_{S,k} = g_S(x_{S,k})$$

- Tank temperature and volume variables (state): $x_{S,k} \in \mathbb{R}^2$
- Pump flow rate variable (control): $u_{S,k}$
- Input water temperature: $\nu_{S,k}$
- Output water temperature: $y_{S,k}$

Single Agent System
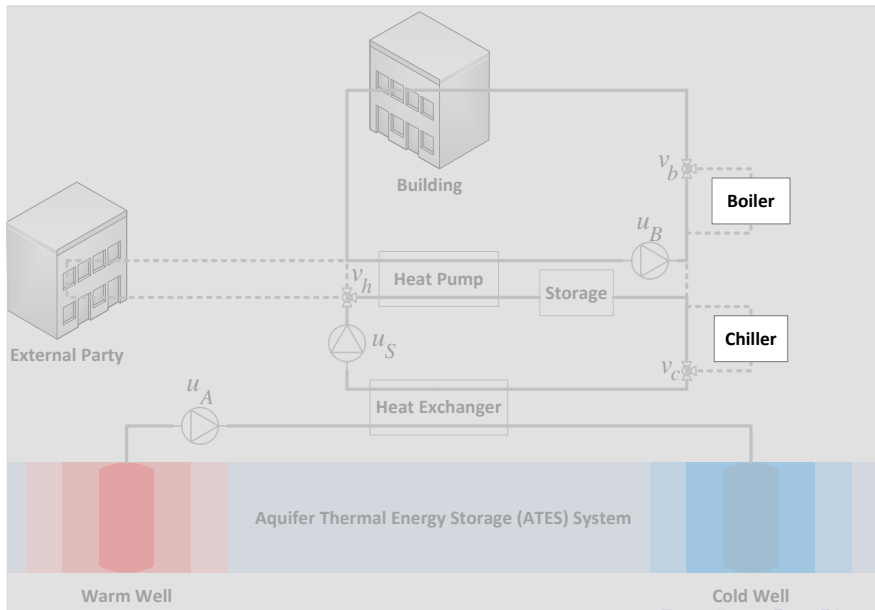
Boiler and Chiller Model

We define the boiler and chiller water temperatures with the following relations:

Boiler:
$$\begin{cases} \mathsf{T}^{\mathrm{boi}}_{\boldsymbol{out},k} = \mathbf{90}^{\circ}\mathrm{C} \\ \mathsf{T}^{\mathrm{boi}}_{\boldsymbol{in},k} = \mathsf{T}_{\mathrm{bypass},\boldsymbol{k}} \\ \boldsymbol{u_{b,k}} = \boldsymbol{v_{b,k}} \boldsymbol{u_{\mathrm{B},k}} \end{cases}$$
Chiller:
$$\begin{cases} \mathsf{T}^{\mathrm{chi}}_{\boldsymbol{out},k} = \mathbf{5}^{\circ}\mathrm{C} \\ \mathsf{T}^{\mathrm{chi}}_{\boldsymbol{in},k} = \mathsf{T}_{\mathrm{bypass},\boldsymbol{k}} \\ \boldsymbol{u_{c,k}} = \boldsymbol{v_{c,k}} \boldsymbol{u_{\mathrm{S},k}} \end{cases}$$

- Boiler valve position (control): $\boldsymbol{v_{b,k}} \in [\mathbf{0}, \mathbf{1}]$
- Chiller valve position (control): $\boldsymbol{v_{c,k}} \in [\mathbf{0}, \mathbf{1}]$

Single Agent System

Aquifer Thermal Energy Storage System Principle

Similar modeling as the storage model by introducing different modes:

- Water is taken from one of the wells and is injected into the counterpart well.
- Taken water has constant temperature until the aquifer water temperature dominates.
- Injected water has gained thermal energy and it is stored for the next upcoming season.
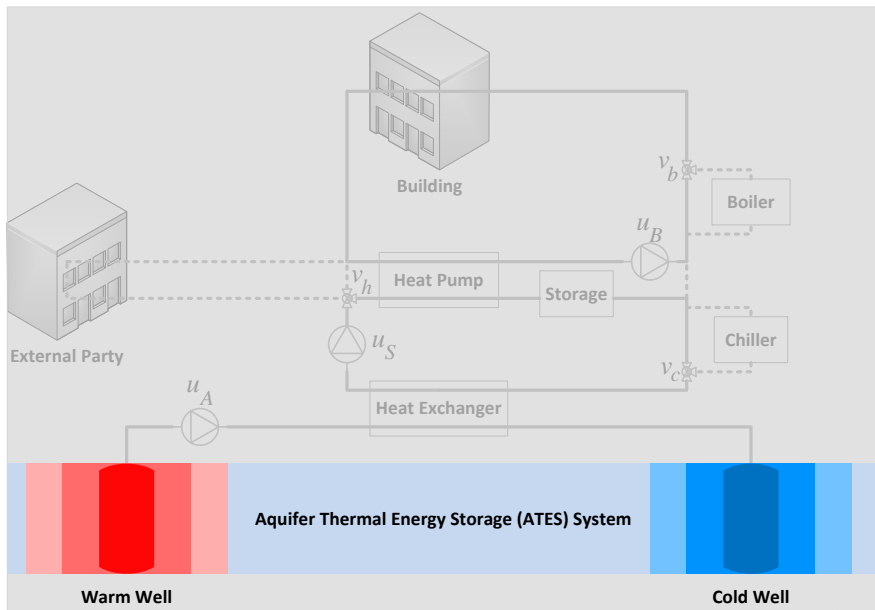
Aquifer Thermal Energy Storage System Model

We define the following Model:

ATES system Dynamical Model

$$x_{A,k+1} = f_A(x_{A,k}, u_{A,k}, \nu_{A,k}, s_{w,k}, s_{c,k})$$
$$y_{A,k} = g_A(x_{A,k}, s_{w,k}, s_{c,k})$$

- Wells temperature and volume variables (state): $x_{A,k} \in \mathbb{R}^4$

- Pump flow rate variable (control): $u_{A,k}$

- Output water temperature: $y_{A,k}$

- Input water temperature: $\nu_{A,k}$

Interconnections Between Each Subsystem
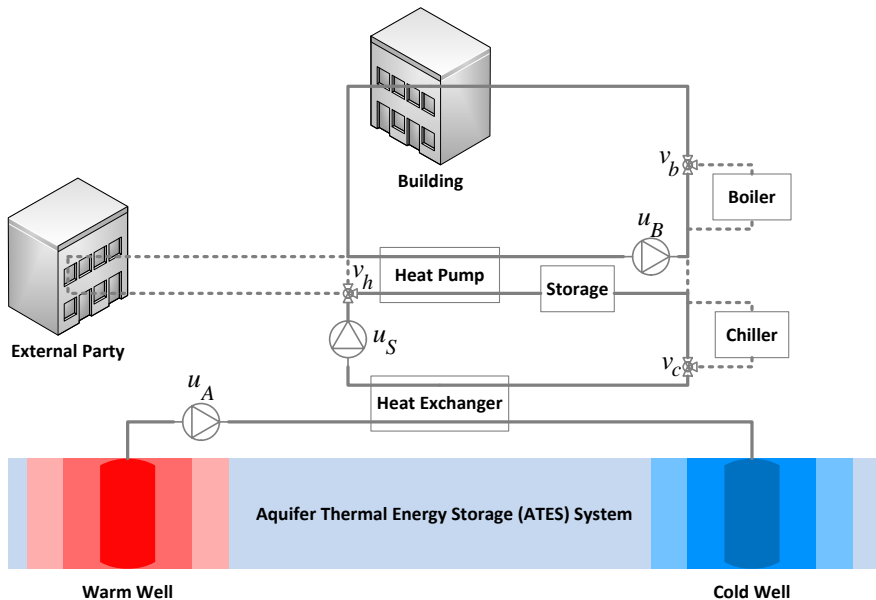
Interconnections Between Each Subsystem

1. **ATES system:** $\nu_{\text{A},k} := \mathsf{T}^{\text{aq}}_{in,k}, \quad y_{\text{A},k} := \mathsf{T}^{\text{aq}}_{out,k}$
   - $\mathsf{T}^{\text{aq}}_{in,k} = \mathsf{T}^{\text{ap}}_{out,k}$

2. **Heat exchanger:** $\nu_{\text{he},k} := [\mathsf{T}^{\text{ap}}_{in,k}, \mathsf{T}^{\text{bp}}_{in,k}], \quad y_{\text{he},k} := [\mathsf{T}^{\text{ap}}_{out,k}, \mathsf{T}^{\text{bp}}_{out,k}]$
   - $\mathsf{T}^{\text{ap}}_{in,k} = \mathsf{T}^{\text{aq}}_{out,k} \quad \text{and} \quad \mathsf{T}^{\text{bp}}_{in,k} = (1 - v_{c,k})\mathsf{T}_{s,k} + v_{c,k}\mathsf{T}^{\text{chi}}_{out,k}$

3. **Heat pump:** $\nu_{\text{hp},k} := [\mathsf{T}^{\text{con}}_{in,k}, \mathsf{T}^{\text{eva}}_{in,k}], \quad y_{\text{hp},k} := [\mathsf{T}^{\text{con}}_{out,k}, \mathsf{T}^{\text{eva}}_{out,k}]$
   - $\mathsf{T}^{\text{con}}_{in,k} = s_{n,k}(s_{w,k}\mathsf{T}^{\text{bp}}_{out,k} + s_{c,k}\mathsf{T}^{\text{B}}_{ret,k}) + (1-s_{n,k})(s_{w,k}\mathsf{T}^{\text{ext}}_{out,k} + s_{c,k}\mathsf{T}^{\text{B}}_{ret,k})$
   - $\mathsf{T}^{\text{eva}}_{in,k} = s_{n,k}(s_{c,k}\mathsf{T}^{\text{bp}}_{out,k} + s_{w,k}\mathsf{T}^{\text{B}}_{ret,k}) + (1-s_{n,k})(s_{w,k}\mathsf{T}^{\text{ext}}_{out,k} + s_{c,k}\mathsf{T}^{\text{B}}_{ret,k})$

4. **Storage model:** $\nu_{\text{S},k} := \mathsf{T}_{in,k}, \quad y_{\text{S},k} := \mathsf{T}^{s}_{out,k}$
   - $\mathsf{T}^{s}_{in,k} = v_{h,k}(s_{w,k}\mathsf{T}^{\text{con}}_{out,k} + s_{c,k}\mathsf{T}^{\text{eva}}_{out,k}) + (1 - v_{h,k})\mathsf{T}^{\text{B}}_{ret,k}$

5. **Building model:** $\nu_{\text{B},k} := \mathsf{T}^{\text{B}}_{\text{sup},k}, \quad y_{\text{B},k} := \mathsf{T}^{\text{B}}_{\text{ret},k}$

$$\mathsf{T}^{\text{B}}_{\text{sup},k} = v_{h,k}(s_{w,k}\mathsf{T}^{\text{eva}}_{out,k} + s_{c,k}((1-v_{b,k})\mathsf{T}^{\text{con}}_{out,k} + v_{b,k}\mathsf{T}^{\text{boi}}_{out,k})) + (1-v_{h,k})\mathsf{T}^{\text{bp}}_{out,k}$$

Single Agent Representation

Consider compact formulation of dynamical agent system:

Single Agent Model

$$x_{k+1} = f(x_k, u_k, v_k, s_k, w_k)$$

- State variables: $x_k := [x_{B,k}, x_{S,k}, x_{A,k}] \in \mathbb{R}^9$
- Pump flow rate variables: $u_k := [u_{B,k}, u_{S,k}, u_{A,k}] \in \mathbb{R}^3$
- Valve position variables: $v_k := [v_{b,k}, v_{c,k}, v_{h,k}] \in [0,1]^3$
- Operating mode variables: $s_k := [s_{w,k}, s_{c,k}, s_{n,k}] \in \{0,1\}^3$
- Uncertain variables: $w_k := [\mathsf{T}_{o,k}, \mathsf{I}_{o,k}, \mathsf{V}_{o,k}] \subseteq \mathbf{\Delta} \in \mathbb{R}^3$
- State variables are available at each sampling time k.

Outline

Control Problem Formulation

We formulate an optimization problem as follows:

$$\min_{\{u_k, v_k\}_{k=1}^{N}}$$ Objective Function: Reference Tracking

subject to: Nonlinear System Dynamics

State and Control Bounds

Valves, Modes and Uncertainty Sets

Heat Exchanger Capacity Constraints

Heat Pump Capacity Constraints

Proposed Formulation

Stochastic Mixed-Integer Nonlinear Optimization Problem

Control Problem Formulation

We formulate an optimization problem as follows:

$$\min_{\{u_k, v_k\}_{k=1}^{N}} \quad \mathbb{E}\left[\sum_{k=1}^{N} \gamma (\mathsf{T}^{\mathsf{B}}_{z,k} - \mathsf{T}_{\mathsf{set}})^2 \right]$$

subject to: Nonlinear System Dynamics

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subject to:
$$x_{k+1} = f(x_k, u_k, v_k, s_k, w_k)$$

$$x_{\min} \leq x_k \leq x_{\max} \ , \ u_{\min} \leq u_k \leq u_{\max}$$

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$$x_{\min} \leq x_k \leq x_{\max} \ , \ u_{\min} \leq u_k \leq u_{\max}$$
$$0 \leq v_k \leq 1 \ , \ s_k \in \{0, 1\} \ , \ w_k \in \mathbf{\Delta}$$

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$$0 \leq v_k \leq 1 \ , \ s_k \in \{0, 1\} \ , \ w_k \in \Delta$$
$$\nu_{\mathsf{he}}^{\min} \leq \nu_{\mathsf{he},k} \leq \nu_{\mathsf{he}}^{\max} \ , \ y_{\mathsf{he}}^{\min} \leq y_{\mathsf{he},k} \leq y_{\mathsf{he}}^{\max}$$

Heat Pump Capacity Constraints

Proposed Formulation

Stochastic Mixed-Integer Nonlinear Optimization Problem

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$$
\min_{\{u_k, v_k\}_{k=1}^{N}} \quad \mathbb{E}\left[\sum_{k=1}^{N} \gamma(T_{z,k}^{B} - T_{set})^2\right]
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$$\nu_{he}^{min} \leq \nu_{he,k} \leq \nu_{he}^{max} \,, \; y_{he}^{min} \leq y_{he,k} \leq y_{he}^{max}$$

$$\nu_{hp}^{min} \leq \nu_{hp,k} \leq \nu_{hp}^{max} \,, \; y_{hp}^{min} \leq y_{hp,k} \leq y_{hp}^{max}$$

Proposed Formulation

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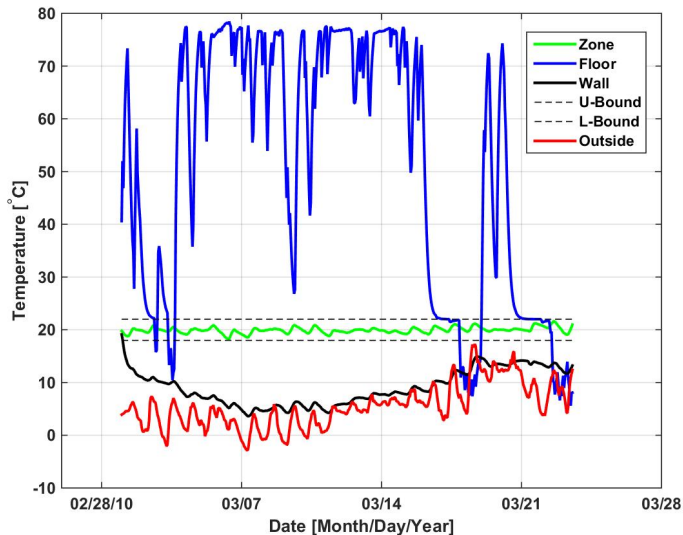
Outline

Simulation Study

A single agent model control problem formulation:

- Sampling period: **1**h

- Prediction horizon: **24**h

- No integer variables (fixed)

- No stochastic terms (deterministic controller)

- Linear approximation of HP & HE complex subsystems

- Remove complex constraints of HP & HE:

$$\nu_{\text{he}}^{\text{min}} \leq \nu_{\text{he},k} \leq \nu_{\text{he}}^{\text{max}} \; , \; y_{\text{he}}^{\text{min}} \leq y_{\text{he},k} \leq y_{\text{he}}^{\text{max}}$$
$$\nu_{\text{hp}}^{\text{min}} \leq \nu_{\text{hp},k} \leq \nu_{\text{hp}}^{\text{max}} \; , \; y_{\text{hp}}^{\text{min}} \leq y_{\text{hp},k} \leq y_{\text{hp}}^{\text{max}}$$

Simulation Results

Simulation Results

Main Results

1. Single Agent Model Derivation:
   - Detailed mathematical representations of each subsystem (components) that are involved in building heating and cooling system with ATES.

2. Single Agent Control problem Formulation:
   - Deterministic nonlinear program for each sampling time k
   - Determination of feasible operating bounds

3. Simulation Results:
   - Building model simulation with a real building case study properties
   - Illustrate a performance of controller for the case study building model
   - Obtain a feasible control solution for the case study building model

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Research Results

- **Published:**

  1. IFAC Conference on Nonlinear Model Predictive Control, Seville, Spain September 17-20, 2015. (conference paper)

  2. 34th Benelux Meeting on Systems and Control, Lommel, Belgium March 24-26, 2015. (abstract paper)

  3. 6th European Geothermal PhD Day, Delft, Netherlands February 25-27, 2015. (abstract paper)

- **Next Plans:**

  1. European Control Conference 2016 by October 20, 2015.

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Discussions: Open Issues

1. **Computational Tractability:**
   complexity of single nonlinear optimization problem:
   - Dimension of decision space: $(3 + 3) \times 24$
   - Dimension of constraint function:
     - nonlinear equality: 9×24
     - inequality: $2 \times (9 + 3 + 3) \times 24$
   - Computational time: construction: $\leq 0.1s$ & solver: $\leq 2\,\text{min}$
   - Simulation time for one year: ≤ 2 weeks

2. **Computational** time is growing w.r.t. **Complexity**:
   - Adding integer variables
   - Considering number of uncertain scenarios: ≥ 1000
   - Interactions modeling between multiple agents
   - Iterations of negotiation approach between agents

3. **Simulation** time is growing w.r.t. **Computational** time:
   - Simulation for at least **two years** to capture agents interactions?

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- Adding integer variables
- Considering number of uncertain scenarios: $\geq \mathbf{1000}$
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Discussions: Some Ideas

1. **Hierarchical** settings:
   - Weekly-based control approach for ATES system
     - Simulate time for more than **two years**
   - Hourly-based control approach for Building system
     - Simulate time for about **one week**

2. **Alternative** aspects:
   - An agent consists of an ATES system with building:
     - Building model represents via an uncertain energy demand profile
     - Thermal energy balance has to be satisfied
   - A more simple agent model:
     - An ATES system with the stored water volume as a state variable and the fixed water temperatures
     - A building thermal comfort model with the building zone temperature as a state variable and the supplied/returned water temperatures

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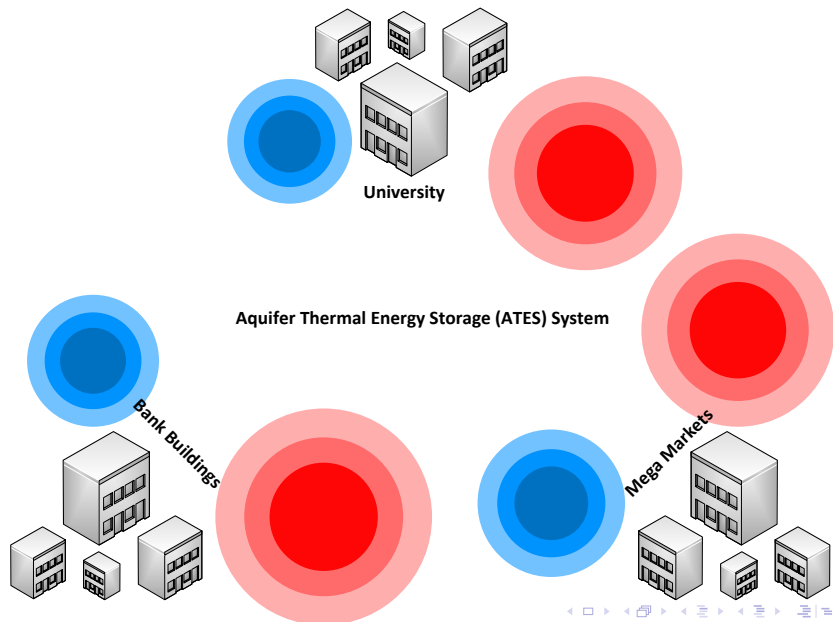
Future Works: Interactions Model
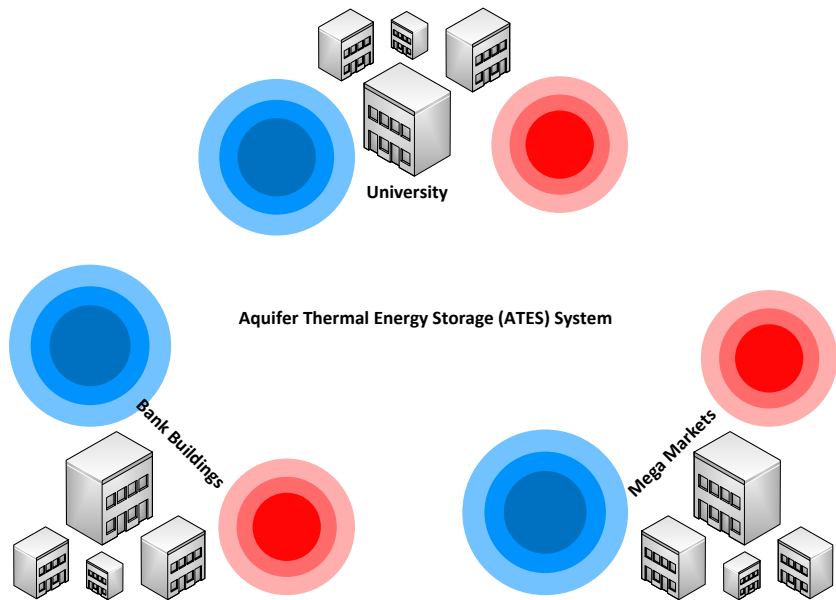
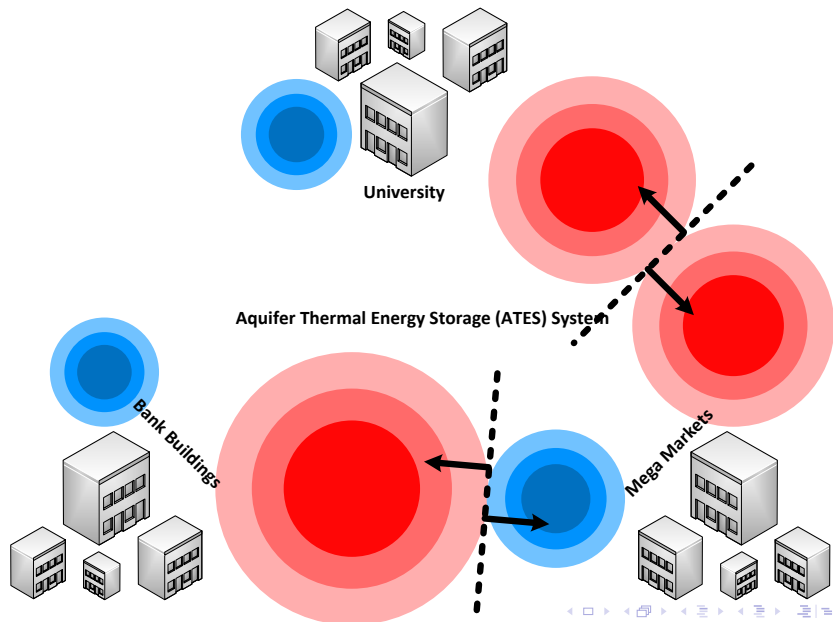# Future Works: Optimal Operation
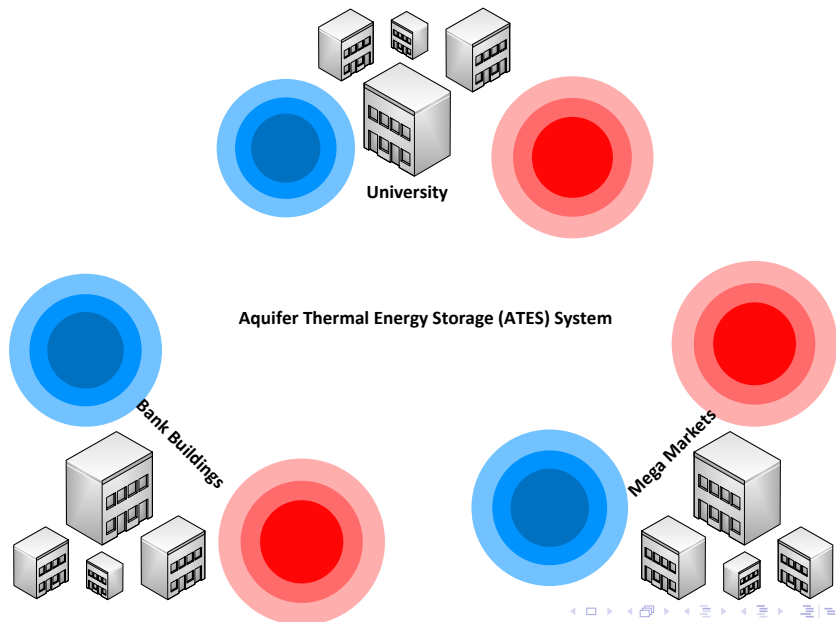
Future Works: Effective Operation

Future Works: Negotiation Approach

Thanks!
Questions?

Building Thermal Comfort Energy Demand

Main goal is to keep **building zone temperature at the desired level**.

- Building energy demand level is: $E_d = E_{\text{gain}} - E_{\text{loss}}$

- Endogenous source of losses: $E_{\text{loss}} = Q_{zo} + Q_{so} + Q_{\text{vent}}$

- Convection heat transfer from zone and solid to outside air: Q_{zo}, Q_{so}

- Ventilation thermal energy lost: Q_{vent}

- Endogenous source of energy: $E_{\text{gain}} = Q_{\text{rad}z} + Q_{\text{rad}s} + Q_p + Q_e$

- Radiation absorption by building zone and solid: $Q_{\text{rad}z}, Q_{\text{rad}s}$

- Occupancy and heat gain due to the electrical devices: Q_p, Q_e

Heat Exchanger Model

Having the following relations:

- Aquifer plate thermal energy: $Q_{he,k} = \rho_w c_{p,w} u_{A,k}(T^{ap}_{out,k} - T^{ap}_{in,k})$

- Building plate thermal energy: $Q_{he,k} = \rho_w c_{p,w} u_{S,k}(T^{bp}_{in,k} - T^{bp}_{out,k})$

- Using the internal thermal energy conditions: $Q_{he,k} = k_{he} A_{he} \Delta T^{he}_m$

- ΔT^{he}_m is the mean temperature difference for the heat transfer.

Heat Exchanger Static Model

$$\Pi_{he} := \begin{cases} y_{he,k} = H(\nu_{he,k}, u_{A,k}, u_{S,k}) \\ \forall k \in \{0, 1, 2, \cdots\} \end{cases}$$

Heat Pump Model

Having the following relations:

- The thermal energy of condenser $Q_{h,k}$ and evaporator $Q_{c,k}$ sides:
  $Q_{h,k} = \rho_w c_{p,w} u_{B,k} (T_{out,k}^{con} - T_{in,k}^{con})$
  $Q_{c,k} = \rho_w c_{p,w} u_{S,k} (T_{in,k}^{eva} - T_{out,k}^{eva})$
- Using the internal thermal energies conditions:
  $Q_{h,k} = k_{hp} A_{hp} \Delta T_{m,h}^{hp}$ and $Q_{c,k} = k_{hp} A_{hp} \Delta T_{m,c}^{hp}$
- The coefficient of performance: $COP = Q_{h,k} (Q_{h,k} - Q_{c,k})^{-1}$
- Using Carnot cycle: $COP = \eta_{hp} T_{hs} (T_{hs} - T_{cs})^{-1}$

Heat Pump Static Model

$$\Pi_{hp} := \begin{cases} y_{hp,k} = P(\nu_{hp,k}, u_{B,k}, u_{S,k}) \\ \forall k \in \{0, 1, 2, \cdots\} \end{cases}$$

Aquifer Thermal Energy Storage System Model

Consider the following mixed-integer first-order difference equations:

$$V_{w,k+1}^{aq} = V_{w,k}^{aq} + (s_{w,k} - s_{c,k}) V_{in,k}^{aq}$$

$$V_{c,k+1}^{aq} = V_{c,k}^{aq} + (s_{c,k} - s_{w,k}) V_{in,k}^{aq}$$

$$T_{w,k+1}^{aq} = \frac{V_{w,k}^{aq}}{V_{w,k}^{aq} + s_{w,k} V_{in,k}^{aq}} T_{w,k}^{aq} + \frac{s_{w,k} V_{in,k}^{aq}}{V_{w,k}^{aq} + s_{w,k} V_{in,k}^{aq}} T_{in,k}^{aq} - \frac{\alpha(T_{w,k}^{aq} - T_{amb,k}^{aq})}{V_{w,k}^{aq} + s_{w,k} V_{in,k}}$$

$$T_{c,k+1}^{aq} = \frac{V_{c,k}^{aq}}{V_{c,k}^{aq} + s_{c,k} V_{in,k}^{aq}} T_{c,k}^{aq} + \frac{s_{c,k} V_{in,k}^{aq}}{V_{c,k}^{aq} + s_{c,k} V_{in,k}^{aq}} T_{in,k}^{aq} - \frac{\alpha(T_{c,k}^{aq} - T_{amb,k}^{aq})}{V_{c,k}^{aq} + s_{c,k} V_{in,k}}$$

- Integer variables of warm and cold season: $s_{w,k}, s_{c,k} \in \{0,1\}$
- Output water temperature is: $T_{out,k}^{aq} = s_{c,k} T_{w,k}^{aq} + s_{w,k} T_{c,k}^{aq}$

Interconnections Between Each Subsystem

❶ ATES system: $\nu_{A,k} := \mathsf{T}^{aq}_{in,k}, \quad y_{A,k} := \mathsf{T}^{aq}_{out,k}$

- $\mathsf{T}^{aq}_{in,k} = \mathsf{T}^{ap}_{out,k}$

❷ Heat exchanger: $\nu_{he,k} := [\mathsf{T}^{ap}_{in,k}, \mathsf{T}^{bp}_{in,k}], \quad y_{he,k} := [\mathsf{T}^{ap}_{out,k}, \mathsf{T}^{bp}_{out,k}]$

- $\mathsf{T}^{ap}_{in,k} = \mathsf{T}^{aq}_{out,k} \quad$ and $\quad \mathsf{T}^{bp}_{in,k} = (1 - v_{c,k})\mathsf{T}_{s,k} + v_{c,k}\mathsf{T}^{chi}_{out,k}$

❸ Heat pump: $\nu_{hp,k} := [\mathsf{T}^{con}_{in,k}, \mathsf{T}^{eva}_{in,k}], \quad y_{hp,k} := [\mathsf{T}^{con}_{out,k}, \mathsf{T}^{eva}_{out,k}]$

- $\mathsf{T}^{con}_{in,k} = s_{n,k}(s_{w,k}\mathsf{T}^{bp}_{out,k} + s_{c,k}\mathsf{T}^{B}_{ret,k}) + (1 - s_{n,k})(s_{w,k}\mathsf{T}^{ext}_{out,k} + s_{c,k}\mathsf{T}^{B}_{ret,k})$
- $\mathsf{T}^{eva}_{in,k} = s_{n,k}(s_{c,k}\mathsf{T}^{bp}_{out,k} + s_{w,k}\mathsf{T}^{B}_{ret,k}) + (1 - s_{n,k})(s_{w,k}\mathsf{T}^{ext}_{out,k} + s_{c,k}\mathsf{T}^{B}_{ret,k})$

❹ Storage model: $\nu_{S,k} := \mathsf{T}_{in,k}, \quad y_{S,k} := \mathsf{T}^{s}_{out,k}$

- $\mathsf{T}^{s}_{in,k} = v_{h,k}(s_{w,k}\mathsf{T}^{con}_{out,k} + s_{c,k}\mathsf{T}^{eva}_{out,k}) + (1 - v_{h,k})\mathsf{T}^{B}_{ret,k}$

❺ Building model: $\nu_{B,k} := \mathsf{T}^{B}_{sup,k}, \quad y_{B,k} := \mathsf{T}^{B}_{ret,k}$

$$\mathsf{T}^{B}_{sup,k} = v_{h,k}(s_{w,k}\mathsf{T}^{eva}_{out,k} + s_{c,k}((1 - v_{b,k})\mathsf{T}^{con}_{out,k} + v_{b,k}\mathsf{T}^{boi}_{out,k})) + (1 - v_{h,k})\mathsf{T}^{bp}_{out,k}$$

Simulation Results