A Control-Oriented Model for Combined Building Climate Comfort and ATES System

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Aquifer Thermal Energy Storage (ATES)

- A large-scale natural subsurface storage for thermal energy
- An innovative method for thermal energy balance in smart grids

Cold season:
- The building requests thermal energy for the heating purpose
- Water is injected into cold well and is taken from warm well
- The stored water contains cold thermal energy for next season
Aquifer Thermal Energy Storage (ATES)

- A large-scale natural subsurface storage for thermal energy
- An innovative method for thermal energy balance in smart grids

**Warm season:**

- The building requests thermal energy for the cooling purpose
- Water is injected into warm well and is taken from cold well
- The stored water contains warm thermal energy for next season
Building Climate Comfort with ATES System (Agent)

Aquifer Thermal Energy Storage (ATES) System

Warm Well

Cold Well

Building

External Party

Heat Pump

Storage

Chiller

Boiler

Heat Exchanger

Vahab Rostampour (TUD)
Outline

1. Single Agent Model
2. Control Problem Formulation
3. Simulation Study and Estimation
4. Ongoing Work and Results
Building Thermal Comfort Relations

$T_o$  $T^B_s$  $T^B_z$  $T^B_f$  $T^B_{ret}$  $T^B_{sup}$  $I_o$  $V_o$
Building Thermal Comfort Relations

$T_o$, $T_s$, $T_z$, $T_s^B$, $T_c$, $I_o$, $V_o$, $T_{ret}^B$, $T_f^B$, $T_{sup}^B$, $u_B$, $Q_{zo}$, $Q_e$, $Q_p$, $Q_{vent}$, $Q_{fcz}$, $Q_{rdz}$, $Q_{zs}$, heat transfer coefficient, $Q_{vent}$

Vahab Rostampour (TUD) Building with ATES 19-23 September (EGC 2016)
Building Thermal Comfort Relations

\[ T^B_{\text{ret}} \]

\[ T^B_S \]

\[ T^B_z \]

\[ T^B_{\text{sup}} \]

\[ T^B_f \]

\[ Q_{zo} \]

\[ Q_{so} \]

\[ Q_{e} \]

\[ Q_{p} \]

\[ Q_{\text{vent}} \]

\[ Q_{fcs} \]

\[ Q_{fcz} \]

\[ Q_{rds} \]

\[ Q_{rdz} \]

\[ I_o \]

\[ V_o \]

\[ u_B \]
Building Thermal Comfort Relations

Diagram showing various thermal parameters and their interrelations. The diagram includes symbols for:
- $T_o$: Outside temperature
- $T_s$: Surface temperature
- $T_b$: Indoor temperature
- $T_{sup}$: Supply temperature
- $T_{ret}$: Return temperature
- $Q_{zo}$: Solar gain
- $Q_{e}$: Enthalpy gain
- $Q_{p}$: Heat gain from people
- $Q_{vent}$: Ventilation heat loss
- $Q_{fcs}$: Furnace heat supply
- $Q_{qds}$: Heat gain from domestic loads
- $Q_{qdz}$: Heat gain from electrical loads
- $Q_{in}$: Heat inflow
- $Q_{out}$: Heat outflow
- $u_B$: Building heat transfer coefficient
We define the following model:

**Building Dynamical Model**

\[
\begin{align*}
    x_{B,k+1} &= x_{B,k} + f_B(x_{B,k}, u_{B,k}, \nu_{B,k}, \nu_{Bext,k})\tau \\
    y_{B,k} &= g_B(x_{B,k}, u_{B,k})
\end{align*}
\]

- Building inside variables (states): \( x_{B,k} \in \mathbb{R}^3 \)
- Building outside variables (uncertain): \( \nu_{Bext,k} \in \mathbb{R}^3 \)
- Pump flow rate variable (control): \( u_{B,k} \)
- Supplied water temperature: \( \nu_{B,k} \)
- Returned water temperature: \( y_{B,k} \)
- Sampling period: \( \tau \)
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:** \( \nu_{he,k} \in \mathbb{R}^2 \)
- **Pump flow rates** (control variables): \( u_A,k, u_S,k \)
- **Output water temperatures:** \( y_{he,k} \in \mathbb{R}^2 \)

**Heat Exchanger Static Model**

\[
y_{he,k} = H(\nu_{he,k}, u_A,k, u_S,k)
\]
Single Agent System

Building with ATES System

Aquifer Thermal Energy Storage (ATES) System

Warm Well

Cold Well

External Party

Boiler

Chiller

Heat Pump

Heat Exchanger

Storage
Heat Pump Model

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

**Static Model Variables:**

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

Heat Pump Static Model

\[
y_{hp,k} = P(\nu_{hp,k}, u_{B,k}, u_{S,k})
\]
Single Agent System

- External Party
- Building
- Heat Pump
- Heat Exchanger
- Aquifer Thermal Energy Storage (ATES) System
- Warm Well
- Cold Well
- Boiler
- Chiller
- Storage

Aquifer Thermal Energy Storage (ATES) System

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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: \( y_{S,k} \)
Aquifer Thermal Energy Storage (ATES) System

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Aquifer Thermal Energy Storage (ATES) System

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Building with ATES

19-23 September (EGC 2016)
Boiler and Chiller Model

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

**Boiler:**
\[
\begin{align*}
T_{\text{boi}}^{\text{out},k} &= 90^\circ \text{C} \\
T_{\text{boi}}^{\text{in},k} &= T_{\text{bypass},k} \\
u_{b,k} &= v_{b,k} u_{B,k}
\end{align*}
\]

**Chiller:**
\[
\begin{align*}
T_{\text{chi}}^{\text{out},k} &= 5^\circ \text{C} \\
T_{\text{chi}}^{\text{in},k} &= T_{\text{bypass},k} \\
u_{c,k} &= v_{c,k} u_{S,k}
\end{align*}
\]

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

\[
\begin{align*}
\mathbf{x}_{A,k+1} &= f_A(\mathbf{x}_{A,k}, \mathbf{u}_{A,k}, \nu_{A,k}, s_{w,k}, s_{c,k}) \\
\mathbf{y}_{A,k} &= g_A(\mathbf{x}_{A,k}, s_{w,k}, s_{c,k})
\end{align*}
\]

- Wells temperature and volume variables (state): \( \mathbf{x}_{A,k} \in \mathbb{R}^4 \)
- Pump flow rate variable (control): \( \mathbf{u}_{A,k} \)
- Output water temperature: \( \mathbf{y}_{A,k} \)
- Input water temperature: \( \nu_{A,k} \)
Interconnections Between Each Subsystem

Aquifer Thermal Energy Storage (ATES) System

- Warm Well
- Cold Well
- Building
- Heat Exchanger
- Heat Pump
- Storage
- Boiler
- Chiller
- External Party
Interconnections Between Each Subsystem

1. **ATES system:** $\nu_{A,k} := T_{in,k}^{aq}$, $y_{A,k} := T_{out,k}^{aq}$
   - $T_{in,k}^{aq} = T_{out,k}^{ap}$

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

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

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

5. **Building model:** $\nu_{B,k} := T_{sup,k}^{B}$, $y_{B,k} := T_{ret,k}^{B}$
   - $T_{sup,k}^{B} = \nu_{h,k}(s_{w,k}T_{out,k}^{eva} + s_{c,k}(T_{out,k}^{con} + \nu_{b,k}T_{out,k}^{boi})) + (1 - \nu_{h,k})T_{out,k}^{bp}$
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: \( w_k := [T_{o,k}, l_{o,k}, V_{o,k}] \subseteq \Delta \in \mathbb{R}^3 \)
- State variables are available at each sampling time \( k \).
Outline

1 Single Agent Model
2 Control Problem Formulation
3 Simulation Study and Estimation
4 Ongoing Work and Results
Control Problem Formulation

We formulate an optimization problem as follows:

\[
\min_{\{u_k,v_k\}_{k=1}^N} \quad \text{Objective Function: Reference Tracking}
\]
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:

$$\min \left\{ u_k, v_k \right\}_{k=1}^N$$

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:

\[ \min \{u_k, v_k\}_{k=1}^N \]

subject to:

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

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:

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

subject to:

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

\[
x_{\text{min}} \leq x_k \leq x_{\text{max}}, \quad u_{\text{min}} \leq u_k \leq u_{\text{max}}
\]

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:

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

subject to:

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

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

$$0 \leq v_k \leq 1, \quad s_k \in \{0, 1\}, \quad w_k \in \Delta$$

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:

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

subject to:

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

\[
x_{\text{min}} \leq x_k \leq x_{\text{max}}, \quad u_{\text{min}} \leq u_k \leq u_{\text{max}}
\]

\[
0 \leq v_k \leq 1, \quad s_k \in \{0, 1\}, \quad w_k \in \Delta
\]

\[
u_{he,\text{min}} \leq \nu_{he,k} \leq \nu_{he,\text{max}}, \quad y_{he,\text{min}} \leq y_{he,k} \leq y_{he,\text{max}}
\]

Heat Pump Capacity Constraints

Proposed Formulation

Stochastic Mixed-Integer Nonlinear Optimization Problem
Control Problem Formulation

We formulate an optimization problem as follows:

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

subject to:

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

\[
x_{\text{min}} \leq x_k \leq x_{\text{max}}, \quad u_{\text{min}} \leq u_k \leq u_{\text{max}}
\]

\[
0 \leq v_k \leq 1, \quad s_k \in \{0, 1\}, \quad w_k \in \Delta
\]

\[
u_{\text{he,min}} \leq v_{\text{he,k}} \leq v_{\text{he,max}}, \quad y_{\text{he,min}} \leq y_{\text{he,k}} \leq y_{\text{he,max}}
\]

\[
u_{\text{hp,min}} \leq v_{\text{hp,k}} \leq v_{\text{hp,max}}, \quad y_{\text{hp,min}} \leq y_{\text{hp,k}} \leq y_{\text{hp,max}}
\]
Control Problem Formulation

We formulate an optimization problem as follows:

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

subject to:

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

\[
x_{\min} \leq x_k \leq x_{\max}, \quad u_{\min} \leq u_k \leq u_{\max}
\]

\[
0 \leq v_k \leq 1, \quad s_k \in \{0, 1\}, \quad w_k \in \Delta
\]

\[
\nu_{\min}^{\text{he}} \leq \nu_{\text{he},k} \leq \nu_{\max}^\text{he}, \quad y_{\min}^\text{he} \leq y_{\text{he},k} \leq y_{\max}^\text{he}
\]

\[
\nu_{\min}^\text{hp} \leq \nu_{\text{hp},k} \leq \nu_{\max}^\text{hp}, \quad y_{\min}^\text{hp} \leq y_{\text{hp},k} \leq y_{\max}^\text{hp}
\]
Outline

1. Single Agent Model
2. Control Problem Formulation
3. Simulation Study and Estimation
4. Ongoing Work and Results
A single agent model control problem formulation:

- Sampling period: 1h

- Prediction horizon: 24h

- No integer variables (fixed)

- No stochastic terms (deterministic controller)

- Linear approximation of HP & HE complex subsystems

- Remove complex constraints of HP & HE:

\[
\nu_{he}^{min} \leq \nu_{he,k} \leq \nu_{he}^{max}, \quad y_{he}^{min} \leq y_{he,k} \leq y_{he}^{max}
\]

\[
\nu_{hp}^{min} \leq \nu_{hp,k} \leq \nu_{hp}^{max}, \quad y_{hp}^{min} \leq y_{hp,k} \leq y_{hp}^{max}
\]
Simulation Results
Simulation Results

![Simulation Results Graph](image-url)
Parameter Estimation (loss-term)

Temperature of wells

Energy in storage

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Outline

1 Single Agent Model
2 Control Problem Formulation
3 Simulation Study and Estimation
4 Ongoing Work and Results
Large Scale Complex Systems: ATES Smart Grids
Ongoing Developments: Interactions Model

Aquifer Thermal Energy Storage (ATES) System

University

Bank Buildings

Mega Markets

Vahab Rostampour (TUD)
Ongoing Developments: Optimal Operation

Aquifer Thermal Energy Storage (ATES) System
Ongoing Developments: Effective Operation

Aquifer Thermal Energy Storage (ATES) System

University

Bank Buildings

Mega Markets
Ongoing Developments: Cooperative Approach

Aquifer Thermal Energy Storage (ATES) System

University

Bank Buildings

Mega Markets

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Results: Centralized vs. Decoupled

Simulated building energy demand profiles

- Building 1
- Building 2
- Building 3

GJ/wk vs. Weeks
Results: Centralized vs. Decoupled

Impact of control scheme on average thermal efficiency

- Centralized control
- Decoupled control
Results: Centralized vs. Decoupled

![Graph showing impact of control scheme on cold well flow and extraction temperature (Building 2).]
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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: $Q_{\text{vent}}$
- Endogenous source of energy: $E_{\text{gain}} = Q_{\text{radz}} + Q_{\text{rads}} + Q_p + Q_e$
- Radiation absorption by building zone and solid: $Q_{\text{radz}}, Q_{\text{rads}}$
- Occupancy and heat gain due to the electrical devices: $Q_p, Q_e$
Heat Exchanger Model

Having the following relations:

- Aquifer plate thermal energy: \( Q_{he,k} = \rho_w c_{p,w} u_{A,k} (T_{out,k}^{ap} - T_{in,k}^{ap}) \)
- Building plate thermal energy: \( Q_{he,k} = \rho_w c_{p,w} u_{S,k} (T_{in,k}^{bp} - T_{out,k}^{bp}) \)
- Using the internal thermal energy conditions: \( Q_{he,k} = k_{he} A_{he} \Delta T_{he,m} \)
- \( \Delta T_{he,m} \) 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:
  \[ Q_{h,k} = \rho \omega c_p \omega u_B,k (T_{\text{con, out, } k} - T_{\text{con, in, } k}) \]
  \[ Q_{c,k} = \rho \omega c_p \omega u_S,k (T_{\text{eva, in, } k} - T_{\text{eva, out, } k}) \]

- Using the internal thermal energies conditions:
  \[ Q_{h,k} = k_{hp} A_{hp} \Delta T_{m,h} \] and \[ Q_{c,k} = k_{hp} A_{hp} \Delta T_{m,c} \]

- The coefficient of performance: \( \text{COP} = \frac{Q_{h,k}}{Q_{c,k}} - 1 \)

- Using Carnot cycle: \( \text{COP} = \eta_{hp} T_{hs} (T_{hs} - T_{cs})^{-1} \)

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:

\[
\begin{align*}
V_{aq,w,k+1} &= V_{aq,w,k} + (s_{w,k} - s_{c,k})V_{in,k}^aq \\
V_{aq,c,k+1} &= V_{aq,c,k} + (s_{c,k} - s_{w,k})V_{in,k}^aq
\end{align*}
\]

\[
\begin{align*}
T_{aq,w,k+1} &= \frac{V_{aq,w,k}^aq}{V_{aq,w,k}^aq + s_{w,k}V_{in,k}^aq}T_{w,k}^aq + \frac{s_{w,k}V_{in,k}^aq}{V_{aq,w,k}^aq + s_{w,k}V_{in,k}^aq}T_{in,k}^aq - \frac{\alpha(T_{aq,w,k}^aq - T_{aq,amb,k}^aq)}{V_{aq,w,k}^aq + s_{w,k}V_{in,k}^aq} \\
T_{aq,c,k+1} &= \frac{V_{aq,c,k}^aq}{V_{aq,c,k}^aq + s_{c,k}V_{in,k}^aq}T_{c,k}^aq + \frac{s_{c,k}V_{in,k}^aq}{V_{aq,c,k}^aq + s_{c,k}V_{in,k}^aq}T_{in,k}^aq - \frac{\alpha(T_{aq,c,k}^aq - T_{aq,amb,k}^aq)}{V_{aq,c,k}^aq + s_{c,k}V_{in,k}^aq}
\end{align*}
\]

- 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

1. **ATES system:** \( \nu_{A,k} := T_{in,k}^{aq}, \quad y_{A,k} := T_{out,k}^{aq} \)
   - \( T_{in,k}^{aq} = T_{out,k}^{ap} \)

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

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

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

5. **Building model:** \( \nu_{B,k} := T_{sup,k}^{B}, \quad y_{B,k} := T_{ret,k}^{B} \)
   - \( T_{sup,k}^{B} = \nu_{h,k}(s_{w,k}T_{out,k}^{eva} + s_{c,k}((1 - \nu_{b,k})T_{out,k}^{con} + \nu_{b,k}T_{out,k}^{boi})) + (1 - \nu_{h,k})T_{out,k}^{bp} \)
Simulation Results

![Graph showing pump flow rate over time with three lines representing different scenarios: Building, Storage, and ATES. The x-axis represents the date in the format Month/Day/Year, and the y-axis represents the pump flow rate in $m^3$ s$^{-1}$. The graph shows fluctuations in flow rate with peaks and troughs, indicating varying levels of activity or demand.]