Energy Management for Building Climate Comfort in Uncertain STGs with ATES

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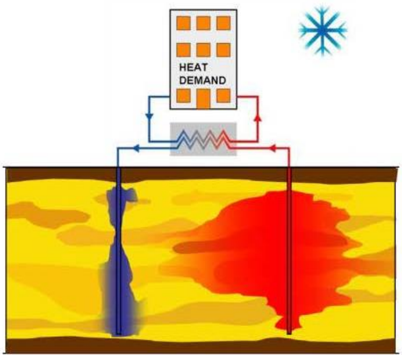
Aquifer Thermal Energy Storage (ATES)

- 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 heating purpose
- Water is injected into cold well and is taken from warm well
- The stored water contains cold thermal energy for next season



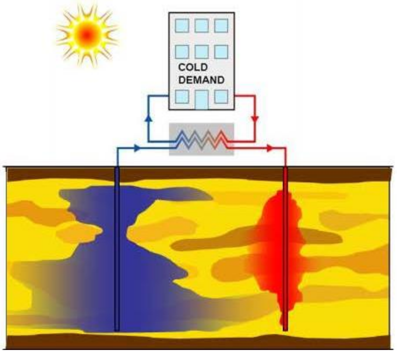
[Rostampour et al., JEP, 2016]

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:

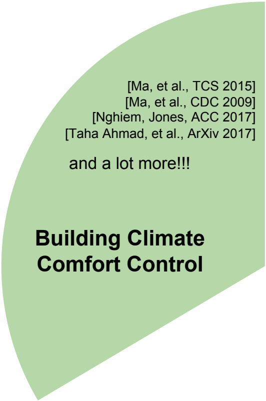
- The building requests thermal energy for cooling purpose
- Water is injected into warm well and is taken from cold well
- The stored water contains warm thermal energy for next season



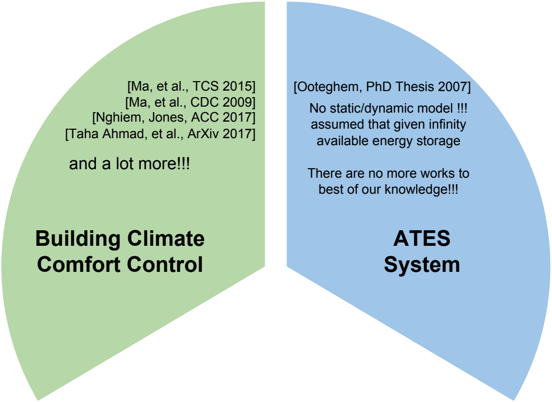
[Rostampour et al., JEP, 2016]

How to Deal with ATES Systems in Smart Thermal Grids?

Challenges and Contributions



Challenges and Contributions



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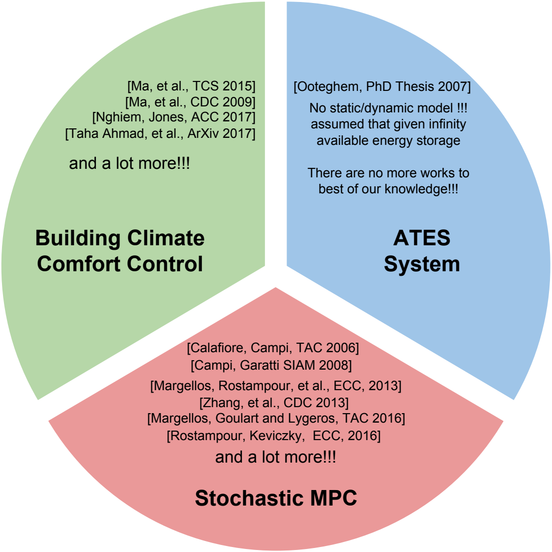
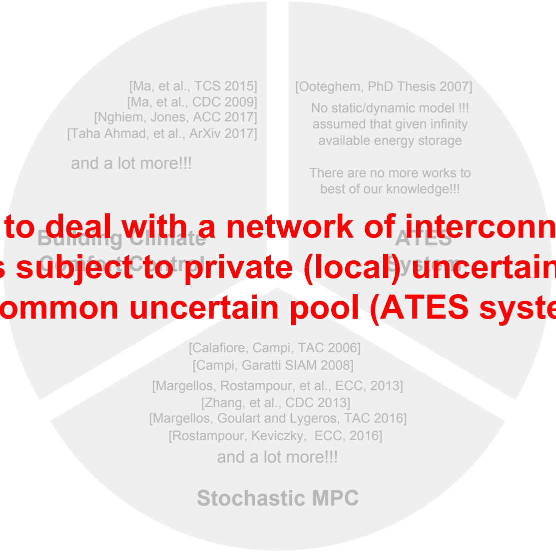


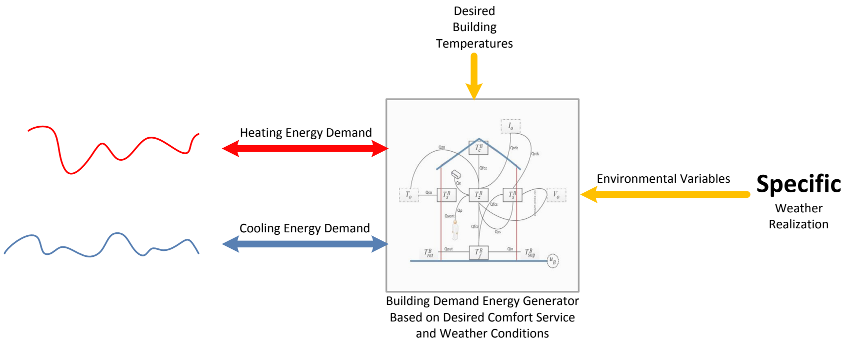
Challenges and Contributions



How to deal with a network of interconnected buildings subject to private (local) uncertainty source and common uncertain pool (ATES systems) !!!

Outline

Single Building Thermal Energy Demand

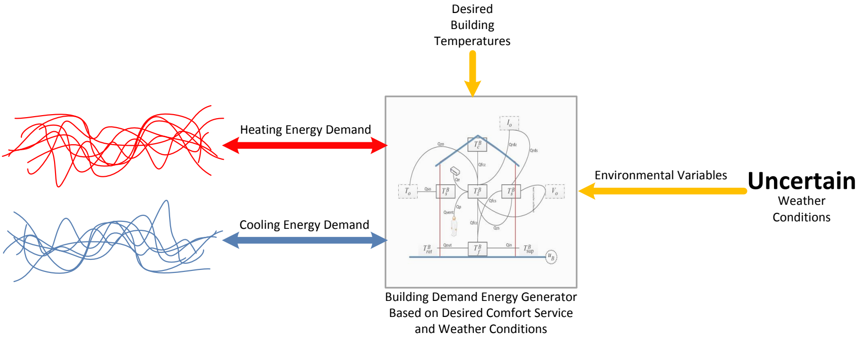


Thermal Energy Demand Profile:

- Complete and detailed building dynamical model
- Desired building temperatures (local controller unit)
- In specific weather realization, certain demand profiles are generated

[Rostampour & Keviczky, ECC, 2016]

Single Building Thermal Energy Demand

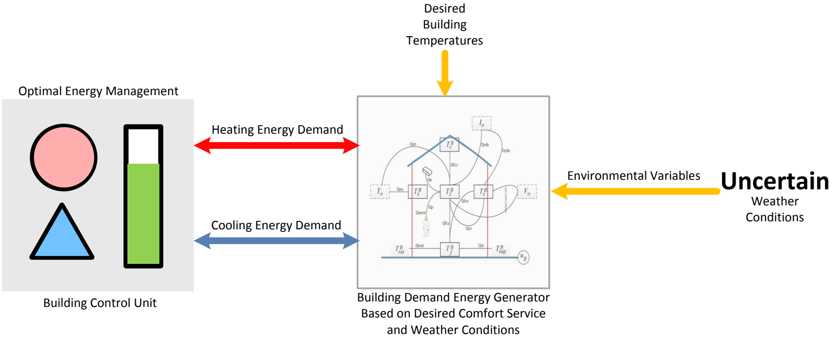


Thermal Energy Demand Profile:

- Complete and detailed building dynamical model
- Desired building temperatures (local controller unit)
- In uncertain conditions, uncertain demand profiles are generated

[Rostampour & Keviczky, ECC, 2016]

Single Building Climate Comfort System

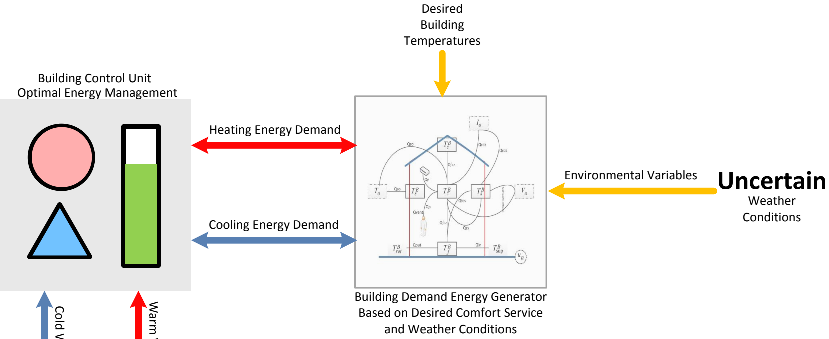


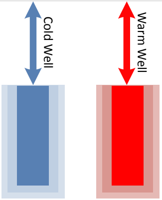
Building Control Unit:

- Main components: Boiler, HP, HE, micro-CHP, Storage Tank
- **ON/OFF status** together with **production schedule** as decisions
- **Control Objective:** thermal **energy balance** for the overall systems

[Rostampour & Keviczky, ECC, 2016]

Building Climate Comfort and ATES Systems

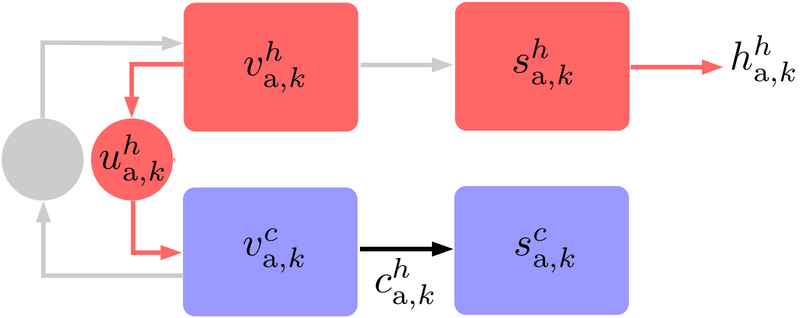




- **Incorporate ATES System**
- **Interaction between components**
- **Different prediction horizon lengths**
- **Additional degrees of freedom**

ATES System Dynamics: Control Block Diagram

An important operational limitation of ATES system is that the sum of injected and extracted thermal energy over a period of time has to be zero.



$$\sum_{t=k}^{T} (c^h_{a,t} - h^h_{a,t}) = 0 \quad \text{(Heating Mode)}$$

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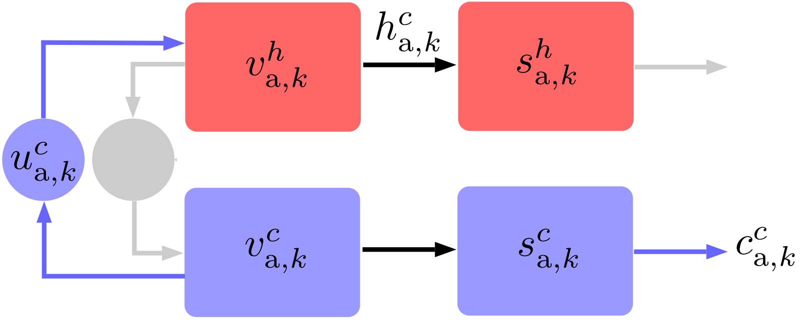

$$\sum_{t=k}^{T} (h^h_{a,t} - h^c_{a,t}) = 0 \quad \text{(Cooling Mode)}$$

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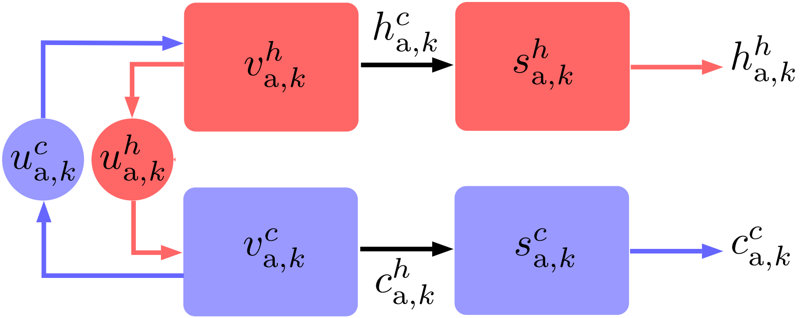


$$\sum_{t=k}^{T} (c^h_{a,t} - h^h_{a,t}) = 0 \quad , \quad \sum_{t=k}^{T} (h^h_{a,t} - h^c_{a,t}) = 0$$

Energy Balance between Wells of ATES

Proposed Constraint Reformulation

Given $\bar{s}_{\mathsf{a}}$ the initial amount of stored thermal energy in ATES system, then the following reformulation is exact.

$$\text{(I)} \quad \left.\begin{aligned} \textstyle\sum_{t=k}^{T} (c^h_{\mathsf{a},t} - h^h_{\mathsf{a},t}) &= 0 \\ \textstyle\sum_{t=k}^{T} (h^h_{\mathsf{a},t} - h^c_{\mathsf{a},t}) &= 0 \end{aligned}\right\} \quad \Leftrightarrow \quad s^h_{\mathsf{a},T} + s^c_{\mathsf{a},T} = \bar{s}_{\mathsf{a}} \quad \text{(II)}$$

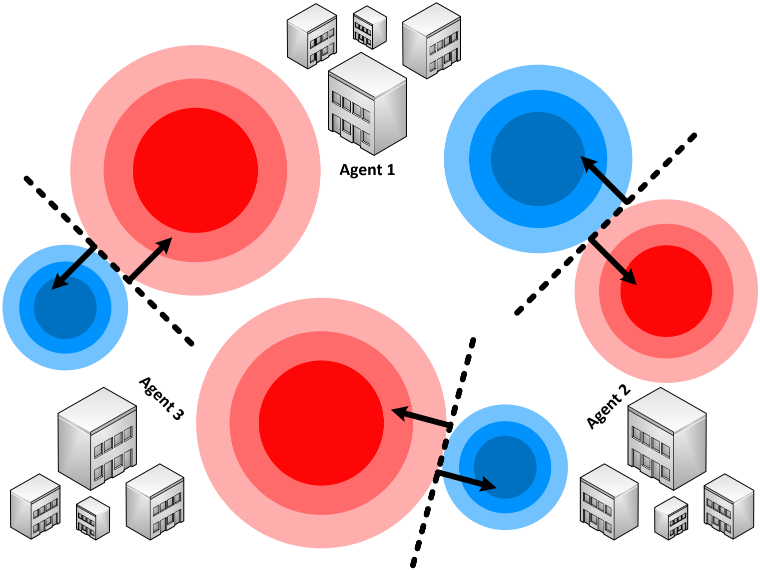
Note that the constraint (II) should be imposed as a terminal constraint.

- Proposed constraint is softened using $e_{i,t}$ as an auxiliary variable:

$$s^h_{\mathsf{a},T} + s^c_{\mathsf{a},T} \leq \bar{s}_{\mathsf{a}} + e_{i,T} \quad , \quad s^h_{\mathsf{a},T} + s^c_{\mathsf{a},T} \geq \bar{s}_{\mathsf{a}} - e_{i,T}$$

Outline

ATES Systems in STGs



How to Avoid Interactions Between Neighboring Wells?

Problem: Nonconvex constraint formulation!

One can now restrict the thermal radius between the neighboring agents:

$$(r^h_{\mathsf{a},t})_i + (r^c_{\mathsf{a},t})_j \le d_{ij}$$

where d_{ij} is a given distance between the neighboring agents i, j.

Proposed convex constraint reformulation

Given $\delta_{ij,t} = 2c_{aq}\pi\ell\,(\bar{r}^h_{\mathsf{a},t})_i\,(\bar{r}^c_{\mathsf{a},t})_j/c_{pw}$ as a common uncertainty source between the neighboring agents i, j, then we propose the following linear (convex) constraint:

$$(v^h_{\mathsf{a},t})_i + (v^c_{\mathsf{a},t})_j \le \bar{v}_{ij} - \delta_{ij,t}$$

where $\bar{v}_{ij} = \frac{c_{aq}}{c_{pw}}\pi\ell\, d^2_{ij}$ is an upper-bound on the capacity of common resource pool.

Outline

Probabilistic Energy Management Problem

Optimization Problem

$\min_*$ thermal energy imbalance error + cost of equipment operation

s.t.
1) equipment limits
2) imbalance error dynamics
3) ATES system dynamics + local thermal energy balance
4) coupling constraint on the thermal radius between agents

*set-points for control units of buildings and pump flow rate for ATES systems

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(Constraints 1)–3) → $\mathcal{Y}_i(\boldsymbol{w}_i)$ Local Uncertain Feasible Set)

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$\mathcal{Y}_i(\boldsymbol{w}_i)$ Local Uncertain Feasible Set

$\breve{\mathcal{Y}}_{ij}(\boldsymbol{\delta}_{ij})$ Common Uncertain Feasible Set

*set-points for control units of buildings and pump flow rate for ATES systems

Probabilistic Energy Management Problem

Compact Uncertain Program: decision variables $\boldsymbol{y} = (\boldsymbol{y}_1, \cdots, \boldsymbol{y}_i, \cdots)$

$$\begin{aligned} \min_{\boldsymbol{y}} \quad & \sum_i f_i(\boldsymbol{y}_i) \\ \text{s.t.} \quad & \boldsymbol{y} \in \prod_i \mathcal{Y}_i(\boldsymbol{w}_i) \ , \\ & \boldsymbol{y} \in \prod_i \bigcap_j \breve{\mathcal{Y}}_{ij}(\boldsymbol{\delta}_{ij}) \end{aligned}$$

Probabilistic Energy Management Problem

Stochastic Optimization Problem

$$\min_{\boldsymbol{y}} \quad \sum_i f_i(\boldsymbol{y}_i)$$

$$\text{s.t.} \quad \mathbb{P}_{\boldsymbol{w}}\Big[\boldsymbol{y} \in \prod_i \mathcal{Y}_i(\boldsymbol{w}_i)\Big] \geq 1 - \varepsilon \;, \forall \boldsymbol{w} \in \mathcal{W}$$

$$\mathbb{P}_{\boldsymbol{\delta}}\Big[\boldsymbol{y} \in \prod_i \bigcap_j \breve{\mathcal{Y}}_{ij}(\boldsymbol{\delta}_{ij})\Big] \geq 1 - \bar{\varepsilon} \;, \forall \boldsymbol{\delta} \in \Delta$$

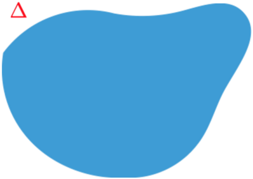
Stochastic Setting:

- $\mathcal{W}, \Delta$: Possibly unknown distribution and unbounded set
- Multiple chance constraints mixed-integer optimization
- Semi-infinite optimization problem

Probabilistic Energy Management Problem

Using two-step (robust-randomized) approach[1]:

- Determining a bounded set that contains $1 - \bar{\varepsilon}$ portion of Δ
- Solving the robust counterpart of problem w.r.t. the bounded set $\mathcal{S}^*$



[1] [Margellos, Rostampour, et al., ECC, 2013], [Rostampour & Keviczky, ECC, 2016]

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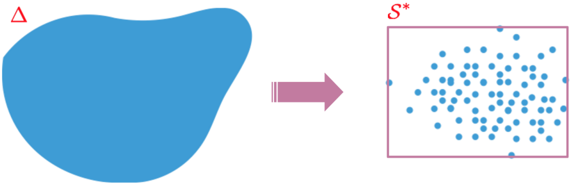

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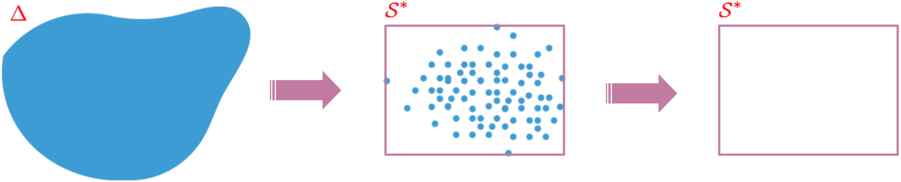

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Probabilistic Energy Management Problem

Multi-Robust-Randomized Optimization Problem

$$\begin{aligned} \min_{\boldsymbol{y}} \quad & \sum_i f_i(\boldsymbol{y}_i) \\ \text{s.t.} \quad & \boldsymbol{y} \in \bigcap_{\boldsymbol{w} \in \{\mathcal{S}^* \cap \mathcal{W}\}} \prod_i \mathcal{Y}_i(\boldsymbol{w}_i) \ , \\ & \boldsymbol{y} \in \bigcap_{\boldsymbol{\delta} \in \{\bar{\mathcal{S}}^* \cap \Delta\}} \prod_i \bigcap_j \breve{\mathcal{Y}}_{ij}(\boldsymbol{\delta}_{ij}) \end{aligned}$$

Probabilistic Energy Management Problem

Multi-Robust-Randomized Optimization Problem

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Requirements

$$\mathcal{W} = \prod_i \mathcal{W}_i \quad \Delta = \prod_i \Delta_i \quad \Delta_i = \prod_j \Delta_{ij}$$

$$\mathcal{S}^* = \prod_i \mathcal{S}_i^* \quad \bar{\mathcal{S}}^* = \prod_i \bar{\mathcal{S}}_i^* \quad \bar{\mathcal{S}}_i^* = \prod_j \bar{\mathcal{S}}_{ij}^*$$

Probabilistically Feasible Solutions

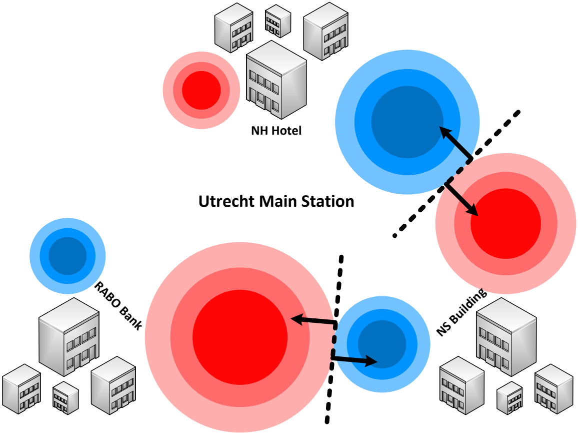
The obtained solution via our proposed scheme is a feasible solution for each chance constraint with their desired level of violations and confidence.

Steps of proof:

1. Based on the scenario approach in [Calafiore & Campi, TAC 2006]
2. Following the similar steps in [Margellos, Goulart & Lygeros, TAC 2016]
3. Extending to the multiple chance constraints

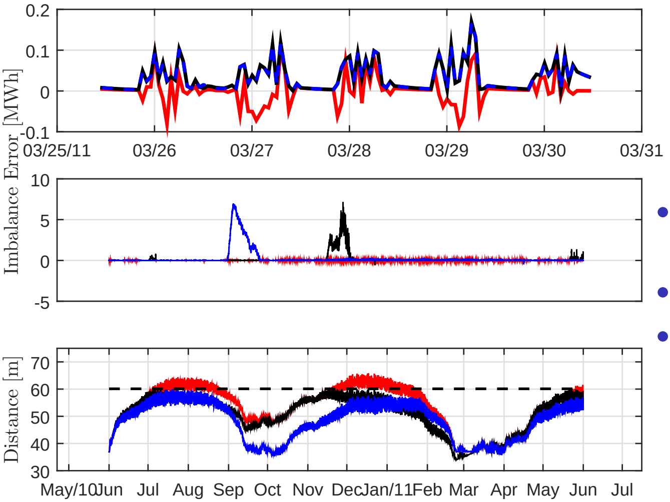
Outline

STGs with ATES Systems: Utrecht City Case Study



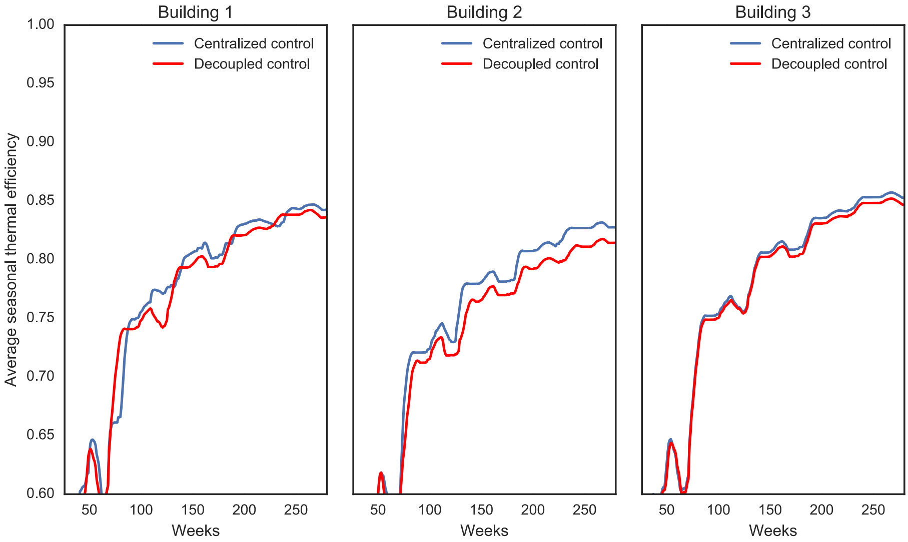
- Three buildings in Utrecht city with real parameters
- Real weather condition data from 2010 to 2012

Simulations Results: A-Posteriori Feasibility Validation



- Deterministic Decoupled MPC
- Centralized SMPC
- Move-Blocking Centralized SMPC

Geohydrological Simulation Environment (MODFLOW)



Geohydrological Simulation Environment (MODFLOW)

Outline

Concluding Remarks

- A **practical predictive dynamical model** of ATES system
  $\Rightarrow$ local energy balance constraint $\Rightarrow$ mutual interaction avoidance

  Pros we can use such a model to predict behavior of the new installed/completely depleted ATES system

  Cons such a model is a stochastic hybrid system (nonconvex program) and this leads sub-optimal performance

- Simulation results showed **expected behavior**

Ongoing and Future Work

What comes next?

1. Distributed Stochastic Hierarchical MPC
   - higher layer to manage ATES systems in STGs
   - lower layer to provide desired comfort level for building control systems
2. Distributed Stochastic MPC in a Plug-and-Play Framework
   - **Rostampour, Keviczky, Submitted.**

Thank you for your attention!
Questions?

Contact at:
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v.rostampour@tudelft.nl

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