Energy Management for Building Climate Comfort in Smart Thermal Grids with Seasonal Storage Systems

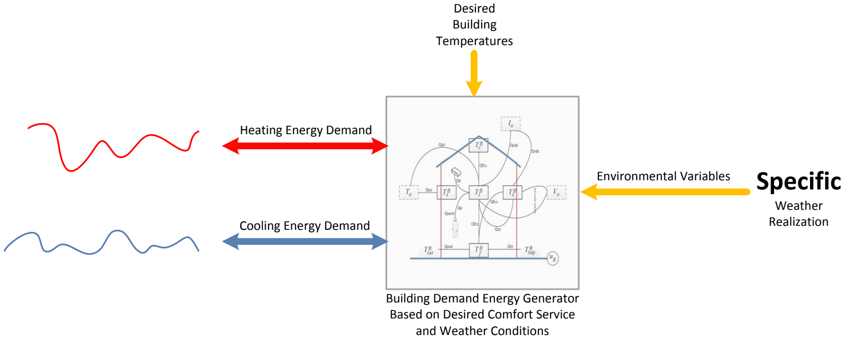
Vahab Rostampour

Delft University of Technology
Delft Center of Systems and Control

Users' Group Meeting

November 10, 2016

Recap: 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

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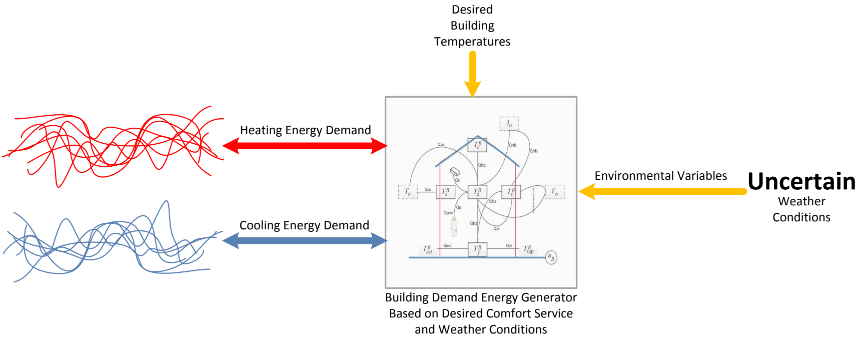
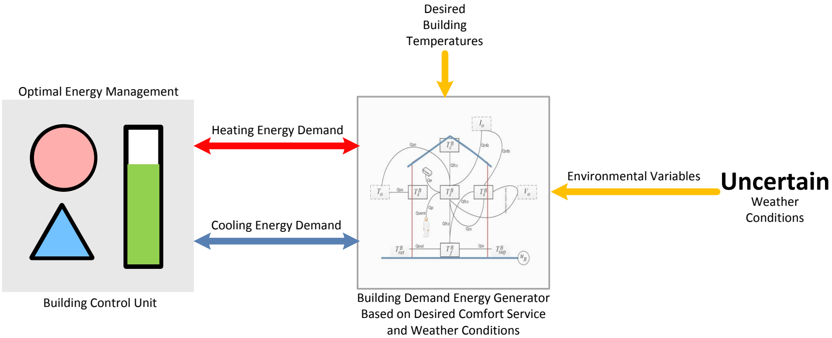


Thermal Energy Demand Generator:

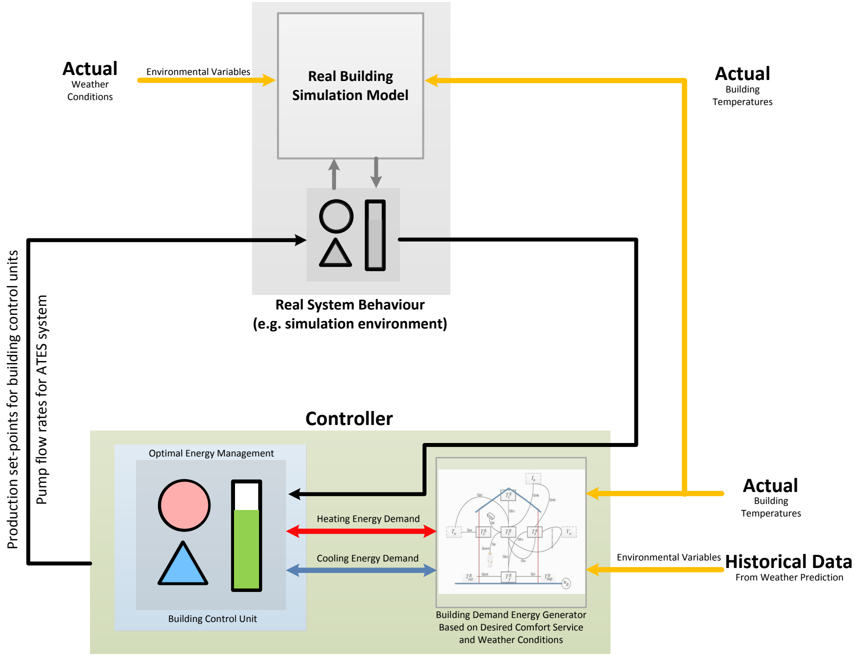
- Complete and detailed building dynamical model
- Desired building temperature (local controller unit)
- In uncertain weather conditions, uncertain demand profiles are generated

Recap: Building Climate Comfort System

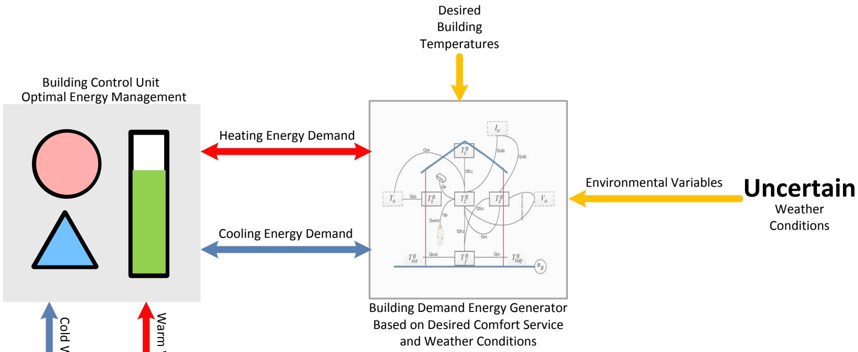


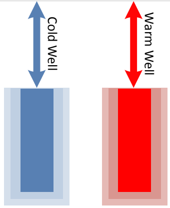
Building Control Unit:

- 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


Actual
Weather
Conditions
Environmental Variables
Real Building
Simulation Model
Actual
Building
Temperatures
Real System Behaviour
(e.g. simulation environment)
Production set-points for building control units
Pump flow rates for ATES system
Controller
Optimal Energy Management
Building Control Unit
Heating Energy Demand
Cooling Energy Demand
Building Demand Energy Generator
Based on Desired Comfort Service
and Weather Conditions
Actual
Building
Temperatures
Environmental Variables
Historical Data
From Weather Prediction

Building Climate Comfort and ATES Systems [1]

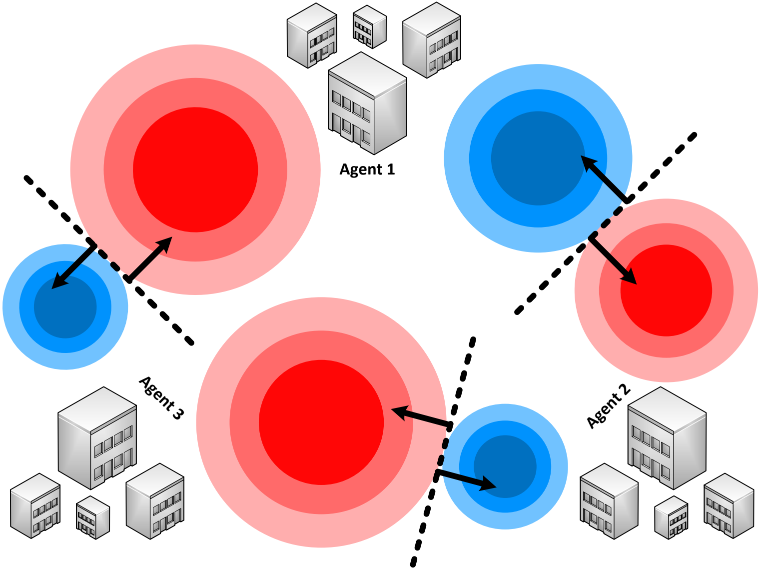




- **Incorporate ATES System**
- **Interaction between components**
- **Different prediction horizon lengths**
- **Additional degrees of freedom**

[1] [Rostampour, Keviczky, Submitted to IFAC World Congress, 2017]

ATES Systems in Smart Thermal Grids [1]



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Control Frameworks and Solutions

1. Control formulations:
   - Decoupled Solution (DS): each agent problem w/o common constraint
   - Centralized Solution (CS): a complete problem with coupling constraint
   - Move-Blocking Centralized Solution (MCS): CS + multi-rate actions
   - Deterministic DS: we fixed the uncertain elements ($\boldsymbol{w}_i$)
2. Simulation Setup:
   - Actual registered weather data; realistic buildings parameters
   - Three-agent example in city center of Utrecht, the Netherlands
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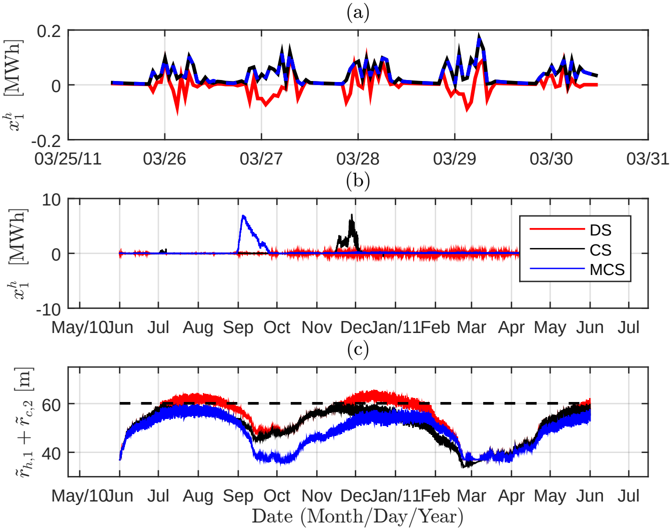
     - weekly-based within the first month, and monthly-based in the rest of season

Simulations Results: A-Posteriori Feasibility Validation



Conclusions and Future Works

- Remarks:
  1. ATES System Modeling + Energy Balance Problem
  2. Integrated ATES System into Building Climate Comfort System
  3. ATES in STGs + Preventing Unwanted Mutual Interactions
  4. DS, CS, and MCS Control Problem Formulations
  5. Simulation Results Showed Expected Results

- Next Steps:
  1. Refinement of the ATES System Model
  2. Develop/Formulate A Hierarchical Framework to Predict longer horizon

Scientific Output

- Building Climate Energy Management in Smart Thermal Grids via Aquifer Thermal Energy Storage Systems
  Journal of Energy Procedia, Elsevier. (2016, to appear)
- A Model Predictive Framework of GSHP coupled with ATES System in Heating and Cooling Networks of a Building
  Accepted for the IEA Conference on Heat Pump, Rotterdam, The Netherlands. (2017, May)
- Chance Constrained Model Predictive Controller Synthesis for Stochastic Max-Plus Linear Systems
  IEEE International Conference on Systems, Man, and Cybernetics, Budapest, Hungary. (2016, October)
- A Control-Oriented Model for Combined Building Climate Comfort and Aquifer Thermal Energy Storage System
  European Geothermal Congress, Strasbourg, France. (2016, September)
- Robust Randomized Model Predictive Control for Energy Balance in Smart Thermal Grids
  European Control Conference, Aalborg, Denmark. (2016, June)
- Distributed Energy Management in Smart Thermal Grids with Uncertain Demands
  MSc thesis (Ananduta, W.W.), DCSC, TU Delft. (2016, August)
- A Set Based Probabilistic Approach to Threshold Design for Optimal Fault Detection
  Submitted to American Control Conference 2017
- Probabilistic Energy Management for Building Climate Comfort in Smart Thermal Grids with Seasonal Storage Systems
  Submitted to IFAC World Congress 2017

Current Research Status

Under Progress:

- Stochastic Distributed MPC for Chance Constrained Linear Systems
- Computationally Distributed Algorithm for Chance Constrained Optimization
- On the Road Between Convex and Nonconvex Scenario Program for Chance Constrained Optimization Problems
- Privacy Preserving Scheme in Distributed Constrained Optimization

Master Students' Thesis:

- Distributed Stochastic Production Scheduling in Smart Grids
  Ole ter Haar (Expected Graduation February 2017)

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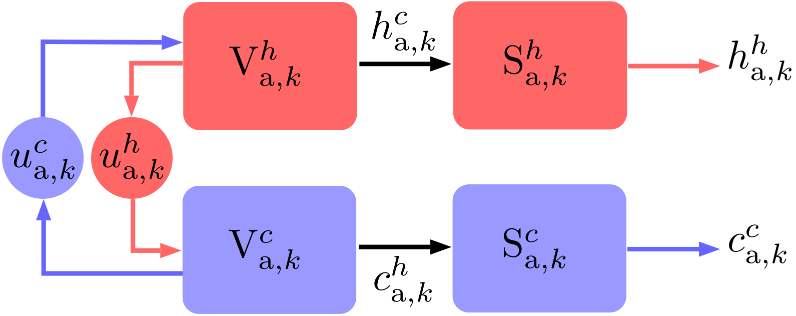
Outline

ATES System: Conceptual Block Diagram



ATES System: Model Dynamics — Heating Mode

$$\mathsf{V}^h_{\mathsf{a},k+1} = \mathsf{V}^h_{\mathsf{a},k} - (u^h_{\mathsf{a},k} - u^c_{\mathsf{a},k})$$

$$\mathsf{V}^c_{\mathsf{a},k+1} = \mathsf{V}^c_{\mathsf{a},k} + (u^h_{\mathsf{a},k} - u^c_{\mathsf{a},k})$$

$$\mathsf{S}^h_{\mathsf{a},k+1} = \eta_{\mathsf{a}}\,\mathsf{S}^h_{\mathsf{a},k} - (h^h_{\mathsf{a},k} - h^c_{\mathsf{a},k})$$

$$\mathsf{S}^c_{\mathsf{a},k+1} = \eta_{\mathsf{a}}\,\mathsf{S}^c_{\mathsf{a},k} + (c^h_{\mathsf{a},k} - c^c_{\mathsf{a},k})$$

$$h_{a,k} = \alpha\, u^h_{a,k} \quad , \quad h^h_{a,k} = \alpha_h\, u^h_{a,k} \quad , \quad c^h_{a,k} = \alpha_c\, u^h_{a,k}$$

$$\alpha = \alpha_h + \alpha_c \, , \begin{cases} \alpha_h & = \rho_w\, c_{pw}\, (\mathsf{T}^h_{\mathsf{a},k} - \mathsf{T}^{\mathsf{amb}}_{\mathsf{a},k}) \\ \alpha_c & = \rho_w\, c_{pw}\, (\mathsf{T}^{\mathsf{amb}}_{\mathsf{a},k} - \mathsf{T}^c_{\mathsf{a},k}) \end{cases},$$

ATES System: Model Dynamics — Cooling Mode

$$\mathsf{V}^h_{\mathsf{a},k+1} = \mathsf{V}^h_{\mathsf{a},k} - (u^h_{\mathsf{a},k} - u^c_{\mathsf{a},k})$$

$$\mathsf{V}^c_{\mathsf{a},k+1} = \mathsf{V}^c_{\mathsf{a},k} + (u^h_{\mathsf{a},k} - u^c_{\mathsf{a},k})$$

$$\mathsf{S}^h_{\mathsf{a},k+1} = \eta_{\mathsf{a}}\, \mathsf{S}^h_{\mathsf{a},k} - (h^h_{\mathsf{a},k} - h^c_{\mathsf{a},k})$$

$$\mathsf{S}^c_{\mathsf{a},k+1} = \eta_{\mathsf{a}}\, \mathsf{S}^c_{\mathsf{a},k} + (c^h_{\mathsf{a},k} - c^c_{\mathsf{a},k})$$

$$c_{a,k} = \alpha\, u^c_{a,k} \quad , \quad c^c_{a,k} = \alpha_c\, u^c_{a,k} \quad , \quad h^c_{a,k} = \alpha_h\, u^c_{a,k}$$

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ATES System: Energy Balance between Wells

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:

$$\left.\begin{aligned} \sum_{t=k}^{N_y} \left(h_{\mathsf{a},t}^h - h_{\mathsf{a},t}^c\right) &= 0 \\ \sum_{t=k}^{N_y} \left(c_{\mathsf{a},t}^c - c_{\mathsf{a},t}^h\right) &= 0 \end{aligned}\right\} \longrightarrow \quad \mathsf{S}_{\mathsf{a},t}^h + \mathsf{S}_{\mathsf{a},t}^c = \bar{\mathsf{S}}_{\mathsf{a}}$$

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$$\mathsf{S}^h_{\mathsf{a},t} + \mathsf{S}^c_{\mathsf{a},t} \leq \bar{\mathsf{S}}_{\mathsf{a}} + e_{i,t}$$

$$\mathsf{S}^h_{\mathsf{a},t} + \mathsf{S}^c_{\mathsf{a},t} \geq \bar{\mathsf{S}}_{\mathsf{a}} - e_{i,t}$$

$e_{i,t}$ is an auxiliary control variable to soften the formulated constraint

Energy Management in Single Agent System

At each sampling time, a finite-horizon chance-constrained mixed-integer quadratic optimization problem is formulated for each agent i:

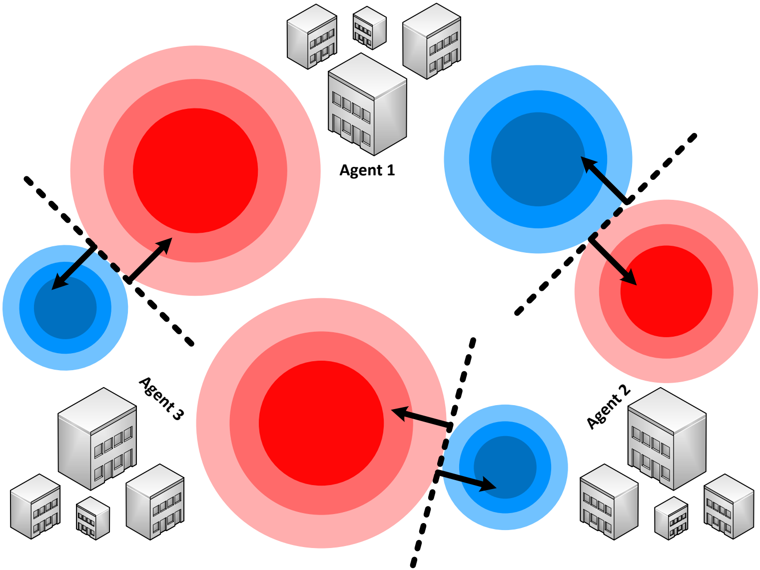
$$\begin{aligned} \underset{\boldsymbol{u}_i,\boldsymbol{v}_i}{\text{minimize}} \quad & \mathcal{V}_i(\boldsymbol{x}_i,\boldsymbol{u}_i) = \mathbb{E}_{\boldsymbol{w}_i}\left[\mathcal{J}_i(\boldsymbol{x}_i,\boldsymbol{u}_i)\right] \\ \text{subject to} \quad & E_i\boldsymbol{u}_i + F_i\boldsymbol{v}_i + P_i \leq 0, \\ & \mathbb{P}_{\boldsymbol{w}_i}\left[A_i x_{i,k} + B_i\boldsymbol{u}_i + C_i\boldsymbol{w}_i \geq 0\right] \geq 1-\varepsilon_i \\ & \quad \boldsymbol{w}_i \in \mathcal{W}_i \end{aligned}$$

The index of $\mathbb{E}_{\boldsymbol{w}_i}, \mathbb{P}_{\boldsymbol{w}_i}$ denotes the dependency of the state trajectory on the string of random scenarios $\boldsymbol{w}_i$

Outline

1. Single Agent System
2. Multi-Agent Network: ATES-SGs
3. Frameworks and Simulation Results

ATES Systems in STGs



ATES Systems in STGs: Mutual Interactions

Thermal radius can be determined using the water volume in each well:

$$r^l_{\mathsf{a},t} = \sqrt{\frac{c_{pw}\,\mathsf{V}^l_{\mathsf{a},t}}{c_{aq}\,\pi\ell}} \quad , \quad l \in \{h, c\}$$

where $c_{aq} = (1 - n_p)c_{\mathsf{sand}} + n_p c_{pw}$, and $c_{\mathsf{sand}}, c_{pw}, n_p$, are parameters.

We restrict the thermal radius between the neighboring agents:

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

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

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where $c_{aq} = (1 - n_p)c_{\mathsf{sand}} + n_p c_{pw}$, and $c_{\mathsf{sand}}, c_{pw}, n_p$, are parameters.

We restrict the stored volume of water between the neighboring agents:

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

where V_{ij} is an upper-bound on the capacity of common resource pool and $\delta_{ij,t} = 2c_{aq}\pi\ell\,(\bar{r}^h_{\mathsf{a},t})_i\,(\bar{r}^c_{\mathsf{a},t})_j / c_{pw}$ is a common uncertainty source.

Energy Management in ATES-SGs

At each sampling time, the energy management problem for ATES systems in STGs is as follows:

$$
\begin{aligned}
\underset{\{\boldsymbol{u}_i,\boldsymbol{v}_i\}_{i=1}^{N}}{\text{minimize}} \quad & \sum_{i=1}^{N} \mathcal{V}_i(\boldsymbol{x}_i, \boldsymbol{u}_i) \\
\text{subject to} \quad & E_i \boldsymbol{u}_i + F_i \boldsymbol{v}_i + P_i \leq 0 \\
& \mathbb{P}_{\boldsymbol{w}_i}\Big[A_i x_{i,k} + B_i \boldsymbol{u}_i + C_i \boldsymbol{w}_i \geq 0\Big] \geq 1 - \varepsilon_i \\
& \mathbb{P}_{\boldsymbol{\delta}_{ij}}\Big[H_i \boldsymbol{x}_i + H_j \boldsymbol{x}_j \leq \bar{V}_{ij} - \boldsymbol{\delta}_{ij}\Big] \geq 1 - \bar{\varepsilon}_{ij} \\
& \boldsymbol{w}_i \in \mathcal{W}_i \ , \ \boldsymbol{\delta}_{ij} \in \Delta_{ij} \ , \ \forall j \in N_i \\
& \forall i \in \{1, 2, \cdots, N\}
\end{aligned}
$$

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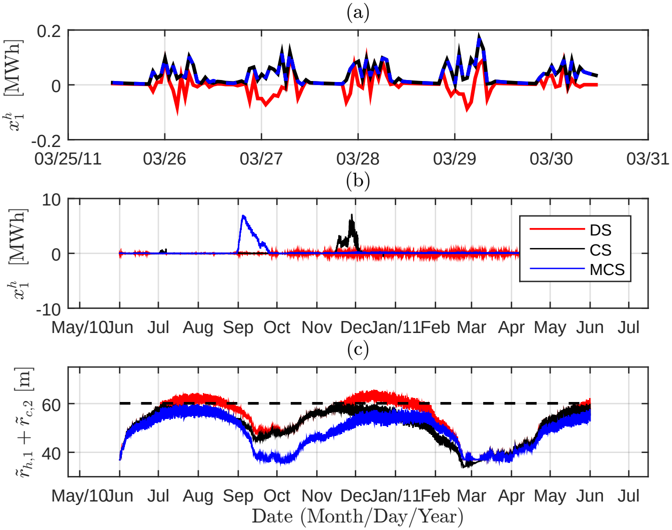

MODFLOW Results: Average Thermal Efficiency