Buildings-to-Grid Integration Framework

Occupancy Modeling, Frequency Regulation, and Energy Savings

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Code & data: github.com/ahmadtaha1/BtG

Importance of buildings-to-grid (BtG) integration

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BtG Background

- Major initiatives to understand BtG integration
  - DOE's *All-As-One*, PNNL's *B2G*
- Grids and buildings are physically connected to each other ➔
  - Understanding their coupling is natural, needed, not too complex

Key figures

74% *of total electricity produced in the world is consumed by buildings*

40% *of buildings energy consumption is from HVAC, controllable compared to other 60%*

Benefits of BtG Integration

Buildings can enjoy significant energy savings

Grid's resources are efficiently utilized with peak demand

More stable grid with fewer frequency excursions

Jointly optimizing decision variable yields optimal results

DERs at buildings can be more efficiently integrated with grid

BtG integration research: important questions*

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BtG Integration Research Questions

1. What are the needed sensing and control technologies?
2. How can financial incentives and business models be developed?
3. What is the right scale? City, campus, single building?
4. Upgrades to HVAC technologies?
5. Can BtG integration improve grid stability and resiliency?
6. How can DER/DG be integrated with BtG?
7. How does building occupancy impact grid stability, energy consumption?
8. What are efficient demand response schedules for BtG?

*T. Lawrence et al. "Ten questions concerning integrating smart buildings into the smart grid." *Building and Environment* 108 (2016): 273-283.

Brief literature review

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BtG Studies

- Experimental architecture that enables smart buildings (Stamatescu et al., 2016)
- Framework for commercial buildings integrated with a distribution grid (Razmara et al., 2016)
- Price signal exchanges, resulting in regulation service offered by buildings (Bilgin et al., 2016)
- BtG studies show that grid-aware, building HVAC controls can provide frequency regulation (Zhao et al., 2013; Hao et al., 2014; Lin et al. 2017)
- Above methods integrate OPF + DERs with building temperature control

Building Temp. Controls

- 100s of studies on how to regulate indoor temperatures in buildings (commercial, residential)
- Focus on various aspects
    - Uncertainty in load, weather, electricity price, occupants' behavior
    - Methods proposed are variants of model predictive control (MPC)
    - MPC shown to be superior to PID control
    - Stochastic/deterministic
- Prominent examples (Oldewurtel et al., 2010; Ma et al., 2012; Dobbs & Hencey, 2014; Koehler & Borrelli, 2013; Dong & Lam, 2014)

Technical challenges

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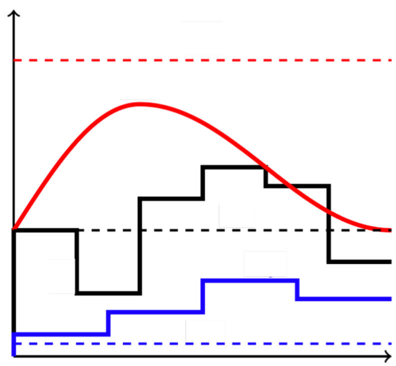
BtG MATHEMATICAL FRAMEWORK

…that explicitly couples the operation of 1000s of buildings and grid controls

We formulate a simple integration model

SIGNIFICANT TIME-SCALES DESCREPANCY

…between grid control decisions (seconds) and buildings HVAC controls (minutes)



We address this issue via simple, tractable routines

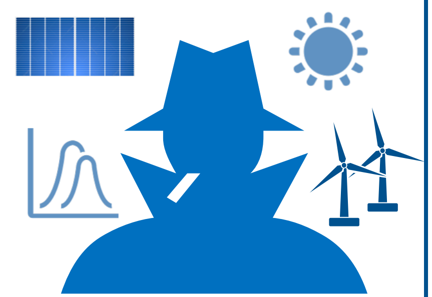
OCCUPANCY MODELING

…that captures people's behavior in relevance to BtG integration, maintaining occupants' comfort

Occupancy behavior is integrated within framework

HANDLING UNCERTAINTY

…from prediction errors of loads, weather conditions, DERs, occupancy behavior



Uncertainty can be easily captured through the proposed work

Paper’s approach, comes to you in 4 parts

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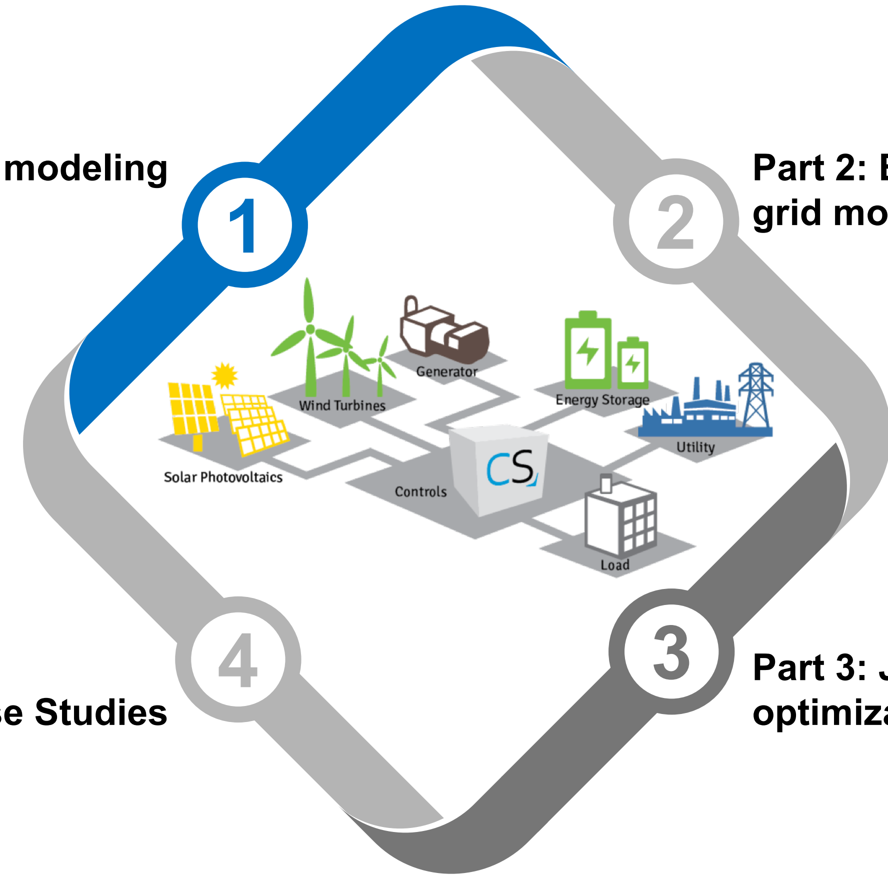
Part 1: Building control modeling

Part 2: Building-integrated grid modeling



Part 3: Joint BtG integration optimization + Occupancy Modeling

Part 4: Case Studies

Part 1: Building temperature control model

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Basics

- Detailed energy models have been developed based on physics/statistics
- **Main focus:** HVAC and building temperature control
- Unrealistic to consider every thermal zone of each bldg. for BtG integration

Modeling assumptions

- **High-level approach:** At BtG integration level, cooling/heating load setpoint required is optimized
- Given the setpoint, other low-level problems can be solved

Building parameters/variables

- **States**: indoor temperature, wall temperature
- **Control inputs**: HVAC cooling load (KW)
- **Disturbances**: ambient temperature, solar radiation, heat gain from heat sources such as desktops and lights
- **Parameters**: size, materials, etc.

Part 1: Bldgs. model details

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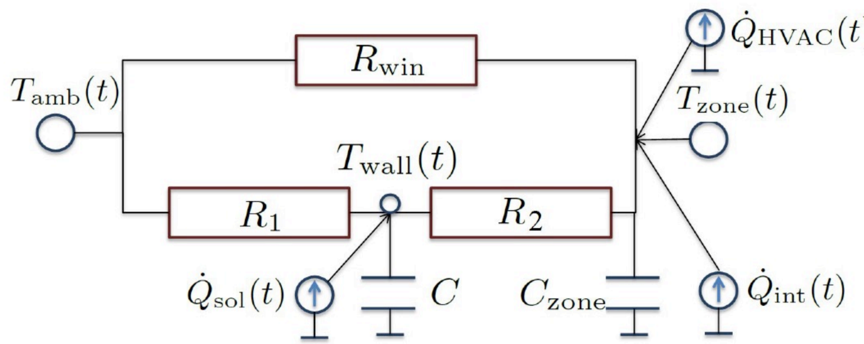
- One-zone, simple model for building l:

$$\dot{T}_{\text{wall}} = \frac{T_{\text{amb}} - T_{\text{wall}}}{CR_2} + \frac{T_{\text{zone}} - T_{\text{wall}}}{CR_1} + \frac{\dot{Q}_{\text{sol}}}{C}$$

$$\dot{T}_{\text{zone}} = \frac{T_{\text{wall}} - T_{\text{zone}}}{C_{\text{zone}}R_1} + \frac{T_{\text{amb}} - T_{\text{zone}}}{C_{\text{zone}}R_{\text{win}}} + \frac{\dot{Q}_{\text{int}} + \dot{Q}_{\text{HVAC}}}{C_{\text{zone}}},$$



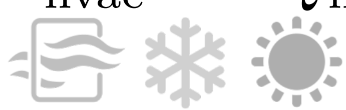
- State-space model for building i: $\dot{\boldsymbol{x}}_b^i = \boldsymbol{A}_b^i \boldsymbol{x}_b^i + \boldsymbol{B}_{u_b} \boldsymbol{u}_b^i + \boldsymbol{B}_{w_b}^i \boldsymbol{w}_b^i$

- State-space model for n_b buildings:

$$\dot{\boldsymbol{x}}_b(t) = \boldsymbol{A}_b \boldsymbol{x}_b(t) + \boldsymbol{B}_{u_b} \boldsymbol{u}_b(t) + \boldsymbol{B}_{w_b} \boldsymbol{w}_b(t)$$

$T_{\text{wall}}, T_{\text{zone}}$

$P_{\text{hvac}} = \alpha \dot{Q}_{\text{hvac}}$



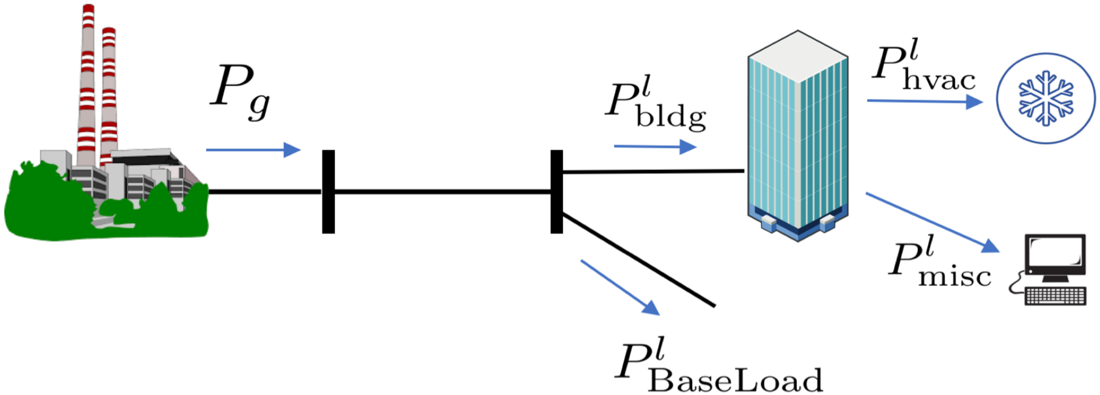
$T_{\text{amb}}, \dot{Q}_{\text{sol}}, \dot{Q}_{\text{int}}$

Part 2: Building-integrated gird model

- Model the transients in a power network, lump distribution/transmission
- Similar to building temperature model, we write the *swing equation* $\left(\sum F = ma\right)$
- ***Swing equation*** models the dynamic transfer of energy in electric networks:

$$M_k \ddot{\delta}_k(t) + D_k \dot{\delta}_k(t) = P_{g_k}(t) - P_{l_k}(t) - \sum_{j \in \mathcal{N}_k} b_{kj} \sin(\delta_k(t) - \delta_j(t))$$

$$P_{l_k}(t) = P_{\mathrm{BaseLoad}_k}(t) + \sum_{l=1}^{n_b} P_{\mathrm{bldg}}^{(l)}(t) = P_{\mathrm{BaseLoad}_k}(t) + \sum_{l=1}^{n_b} P_{\mathrm{hvac}}^{(l)}(t) + P_{\mathrm{misc}}^{(l)}(t)$$



Part 2: Building-integrated gird model

$$\begin{aligned}\dot{\delta}_k(t) &= \omega_k(t)\\ M_k\dot{\omega}_k(t) &= -D_k\omega_k(t) + P_{g_k}(t)\\ &\quad -P_{\mathrm{BaseLoad}_k} - \sum_{l=1}^{n_b}\left(P_{\mathrm{hvac}}^{(l)}(t) + P_{\mathrm{misc}}^{(l)}(t)\right) - \sum_{j\in\mathcal{N}_k} b_{kj}\sin\left(\delta_k(t)-\delta_j(t)\right)\end{aligned}$$

- Vectorize all states, obtain uncertain **differential algebraic equations** (DAE):

$$\boldsymbol{E}_g\dot{\boldsymbol{x}}_g(t) = \boldsymbol{A}_g\boldsymbol{x}_g(t) + \boldsymbol{\Phi}(\boldsymbol{\delta}(t)) + \boldsymbol{A}_{u_b}\boldsymbol{u}_b(t) + \boldsymbol{B}_{u_g}\boldsymbol{u}_g(t) + \boldsymbol{B}_{w_g}\boldsymbol{w}_g(t)$$

Frequencies and angles | Nonlinear power flows | Buildings HVAC **controls** | Generator **controls** | Grid disturbances

- $\boldsymbol{E}_g$ is singular, since some load buses have no generation $(M_k = D_k = 0)$

Buildings & grid dynamics have a common term UTSA

- **Explicit** coupling between
  - Grid dynamics

$$\boldsymbol{E}_g\dot{\boldsymbol{x}}_g(t) = \boldsymbol{A}_g\boldsymbol{x}_g(t) + \boldsymbol{\Phi}(\boldsymbol{\delta}(t)) + \boldsymbol{A}_{u_b}\boldsymbol{u}_b(t) + \boldsymbol{B}_{u_g}\boldsymbol{u}_g(t) + \boldsymbol{B}_{w_g}\boldsymbol{w}_g(t)$$

  - And building dynamics

$$\dot{\boldsymbol{x}}_b(t) = \boldsymbol{A}_b\boldsymbol{x}_b(t) + \boldsymbol{B}_{u_b}\boldsymbol{u}_b(t) + \boldsymbol{B}_{w_b}\boldsymbol{w}_b(t)$$

Grid and buildings disturbances

- The term $\boldsymbol{u}_b(t)$ couples the two dynamic systems, establishes BtG integration
- Smarter building controls can impact grid stability through $\boldsymbol{x}_g(t)$, grid's frequency

Part 3: Joint BtG integration optimization

Formulate a joint optimal control problem

Frequency deviations & generation cost curve

Electricity (HVAC) price & thermal comfort of occupants

$$\text{minimize} \quad J_{\text{grid}}(\boldsymbol{u}_g, \boldsymbol{x}_g) + J_{\text{bldgs}}(\boldsymbol{u}_b, \boldsymbol{x}_b)$$

$$\text{subject to} \quad \text{BldgDynamics, GridDynamics}$$ Discretized

$\boldsymbol{x}_g \in \mathcal{X}_g$ Frequency deviation bounds

$\boldsymbol{u}_g \in \mathcal{U}_g$ Generation constraints

$\boldsymbol{x}_b \in \mathcal{U}_b$ Bldg. temperature bounds

$\boldsymbol{u}_b \in \mathcal{U}_b$ HVAC capacity

$\boldsymbol{u}_g = \boldsymbol{u}_g^{\text{OPF}} + \Delta \boldsymbol{u}_g \in \mathcal{U}_{\text{OPF}}$ Optimal power flow constraints

Solve using MPC!

Part 3: Handling occupancy-based modeling

- Without occupancy modeling, building temperature constraints are fixed

$$21^\circ C = \mathbf{x}_b^{\min} \leq \mathbf{x}_b(t) \leq \mathbf{x}_b^{\max} = 23^\circ C$$

- To incorporate occupancy modeling, alter the upper/lower bounds to reflect the occupants' behavior

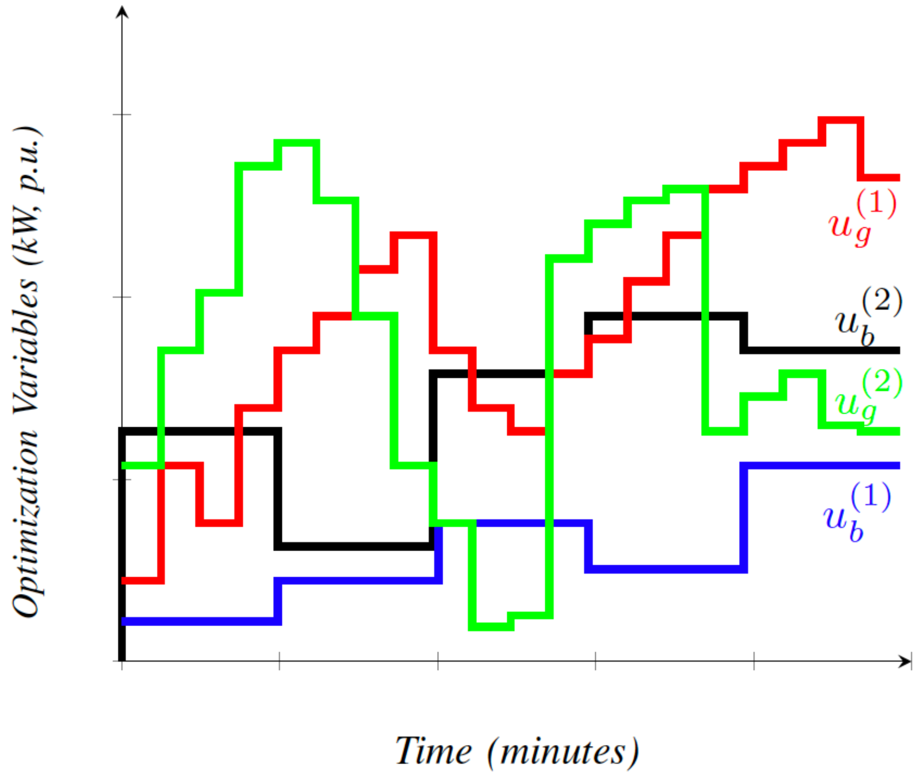
- With occupancy modeling, updated building constraints as

$$\mathbf{x}_b^{\min} \leq \mathbf{x}_b(t) \leq \mathbf{x}_b^{\max} + \mathcal{E}(\mathbf{O}_t)$$

where $\mathcal{E}(\boldsymbol{O}_t)$ is a quantity that depends on the occupancy state $\boldsymbol{O}_t$, which evolves depending on the occupancy behavior in the buildings

Challenges to Part 3

- **Challenge 1:** BtG optimization is nonlinear due to power flows
  - Linearize power flow ➔ results in a scalable quadratic program
- **Challenge 2:** Algebraic equations in grid dynamics
  - User special discretization method, Gear's method, to take care of that
- **Challenge 3:** Two time-scales
  - Bldg. controls vary every 5-15 minutes
  - Grid controls vary in seconds
  - **Solution**: Restrict the change in bldgs. controls; see figure



Don't like applying grid controls? No need!

Part 4: Case studies

Code & data:
github.com/ahmadtaha1/BtG

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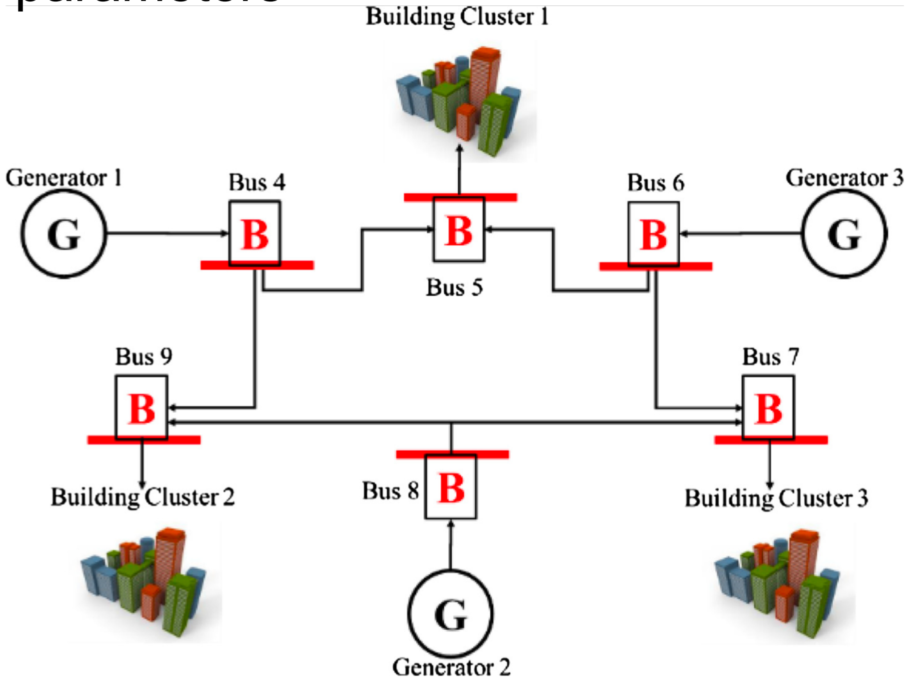
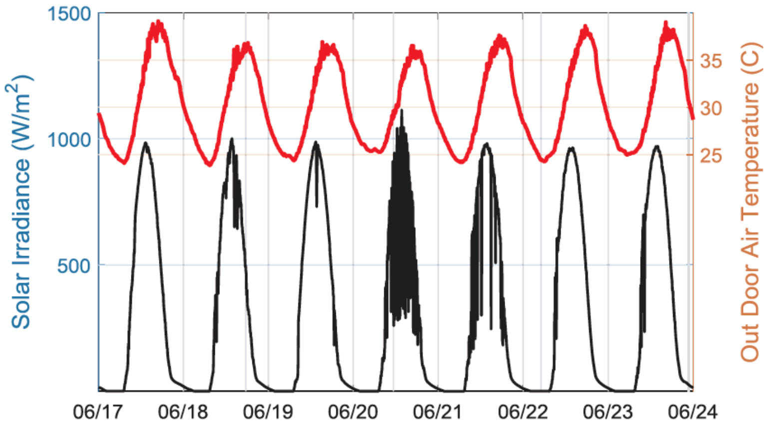
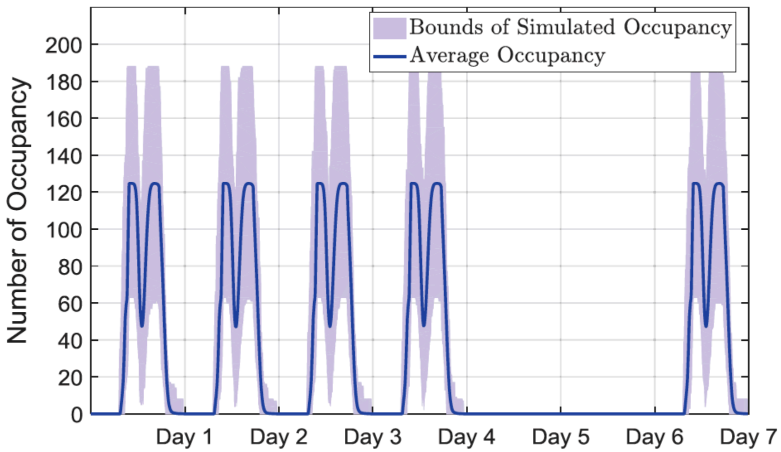
- Classical 3-machine, 9-bus power network
- 1000s of buildings connected to transmission network
- Industry-grade commercial building parameters



- Weather pattern, solar irrradiance from San Antonio, occupancy pattern from LBNL simulator



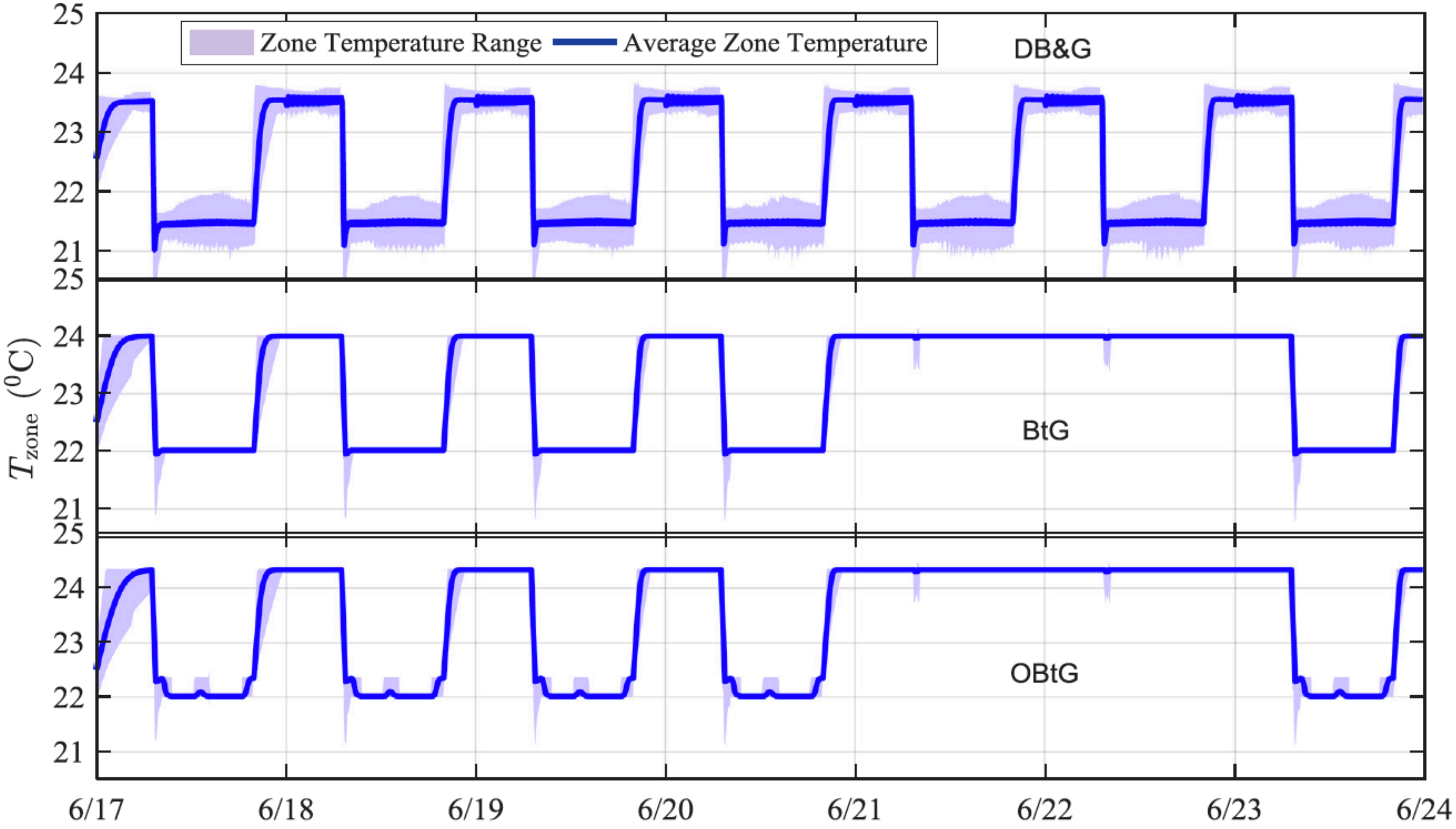


Comparison with other approaches

- **Approach 1:** Decoupled Building and Control (**DB&G**)
  - Building HVAC controls and grid controls determined separately
  - On/Off buildings control + MPC for the grid
- **Approach 2:** Buildings-to-Grid (**BtG)**
  - Centralized computation of buildings + grid control variables
- **Approach 3**: Occupancy-based BtG (**OBtG)**
  - Centralized computation of buildings + grid control variables considering occupancy modeling

Results

Impact on zone temperature of buildings



DB&G

BtG

OBtG

Results

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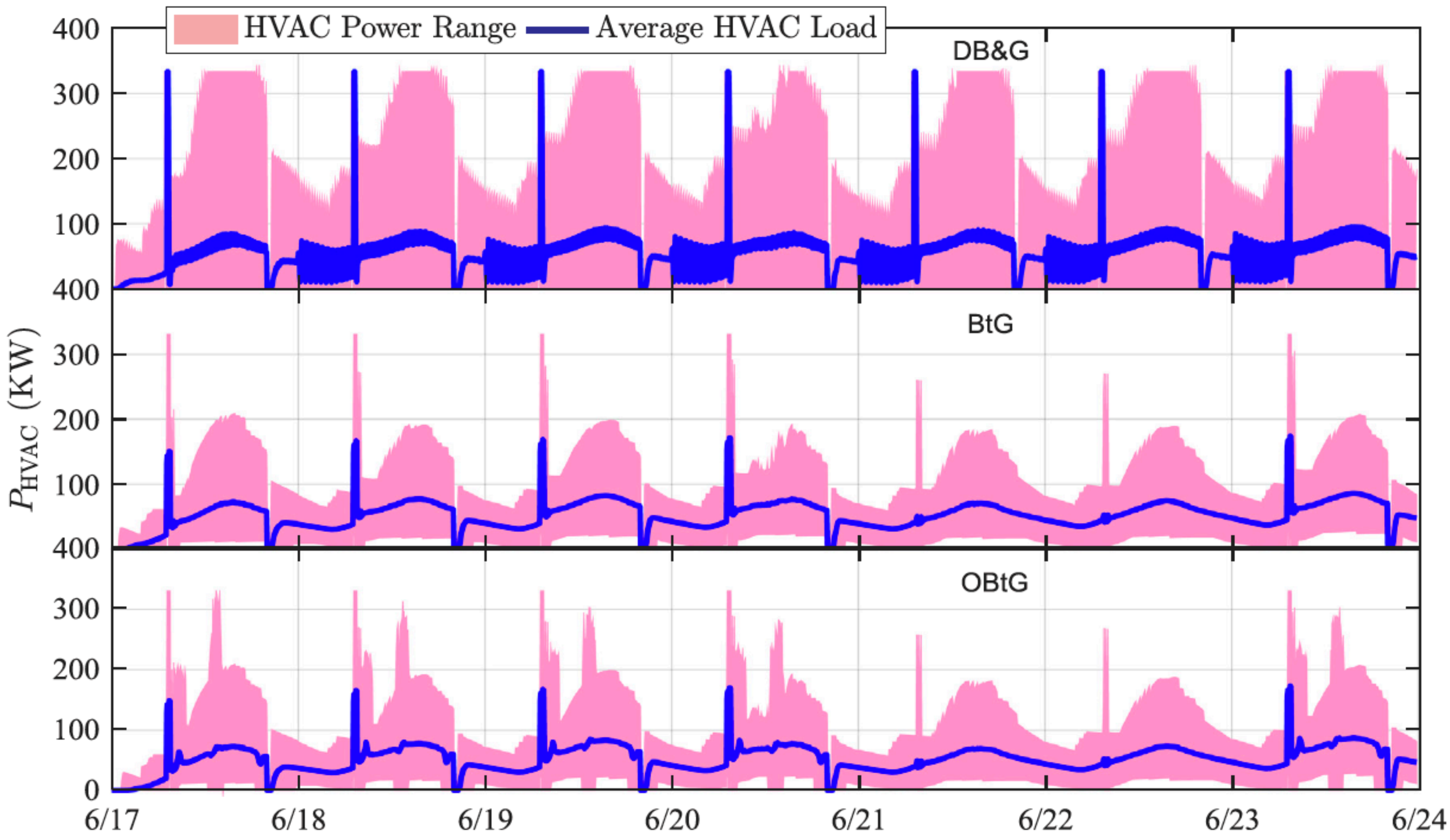
Impact on HVAC power consumption (control variable)



DB&G

BtG

OBtG

Results

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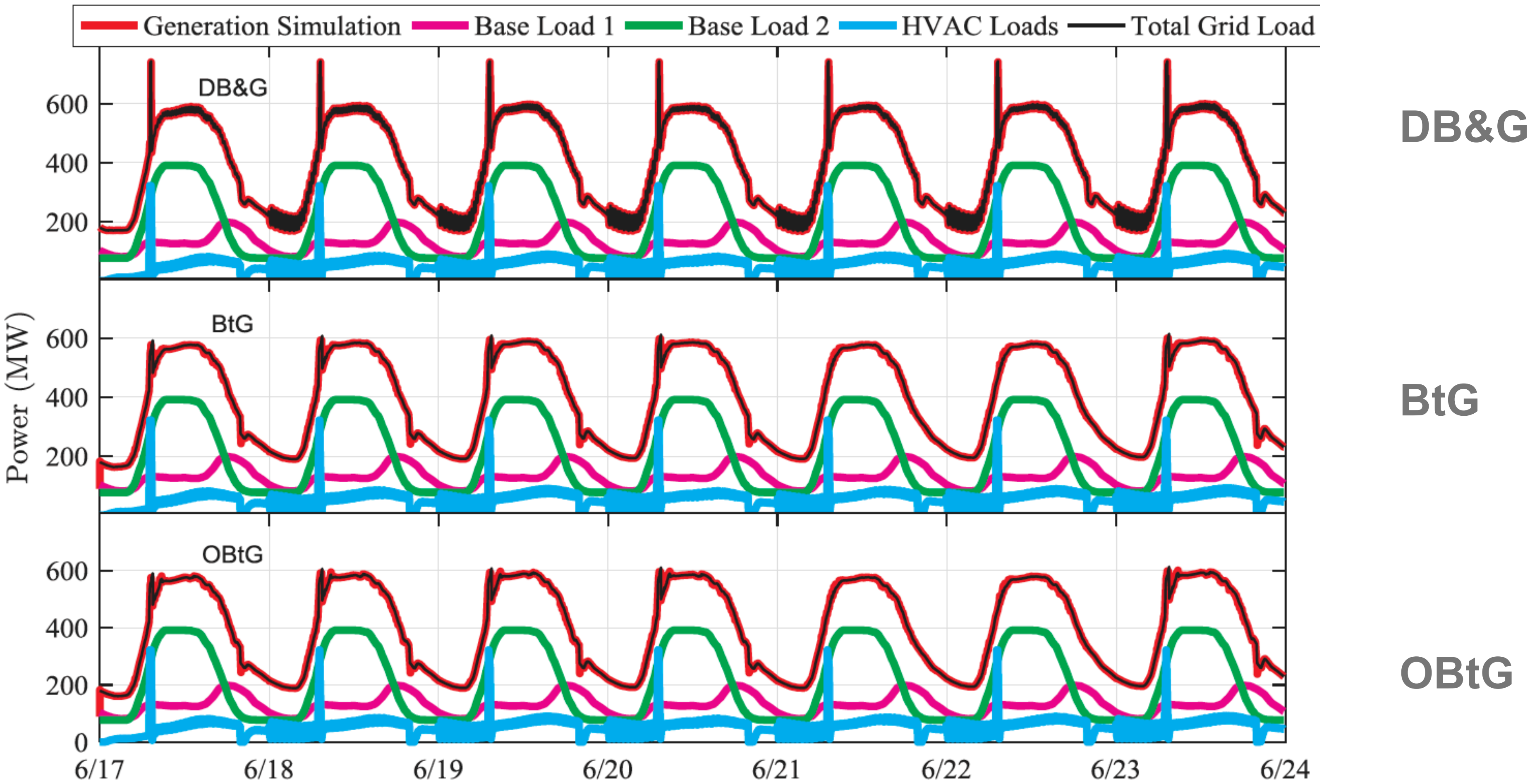
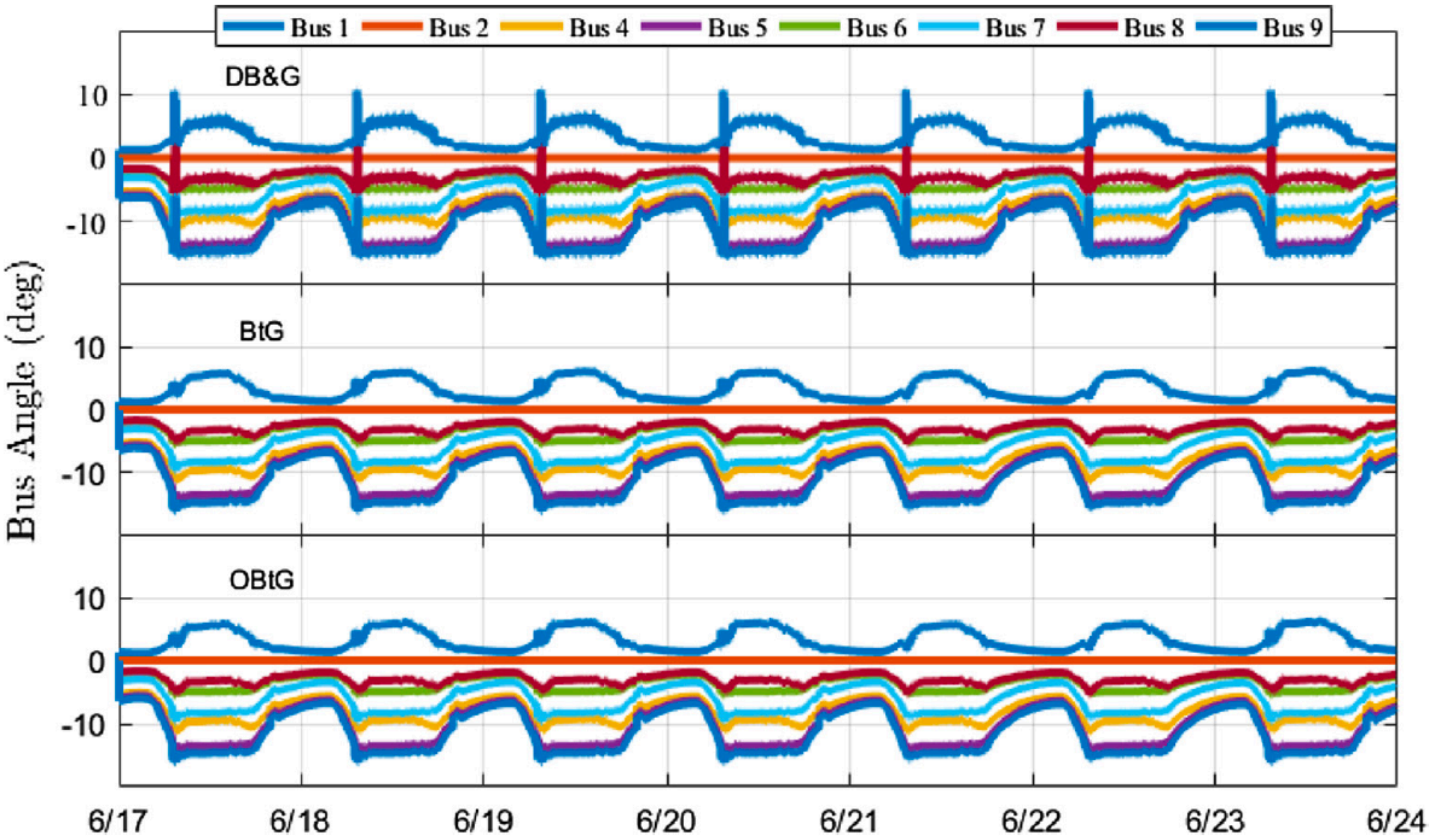
Impact on output power from generators



~50%—61% Overall cost reduction for the BtG/OBtG from DB&G

Results

Impact on bus angles



DB&G

BtG

OBtG

Summary and future work

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- Future work
  - Explicit modeling of uncertainty
  - Distributed optimization and control

NSF

CBET #1637249

- Please check out our two papers on this topic

1. Dong, Li, Taha, Gatsis, "Occupancy-based buildings-to-grid integration framework for smart and connected communities." *Applied Energy, 2018.*
2. Taha, Gatsis, Dong, Pipri, Li. "Buildings-to-grid integration framework." *IEEE Transactions on Smart Grid, 2018.*

Thank You!

Code & data:
github.com/ahmadtaha1/BtG