TerraSwarm

Model Predictive Control Approach to Online Computation of Demand-Side Flexibility of Commercial Buildings HVAC Systems for Supply Following

Theme 1: Smart City, Task: D.1.2 TerraSwarm Applications

http://terraswarm.org/

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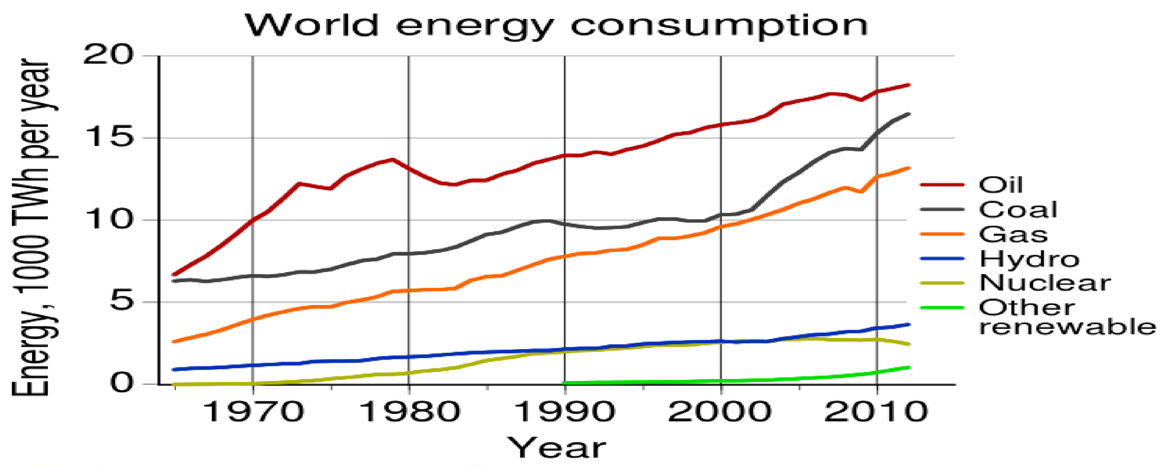
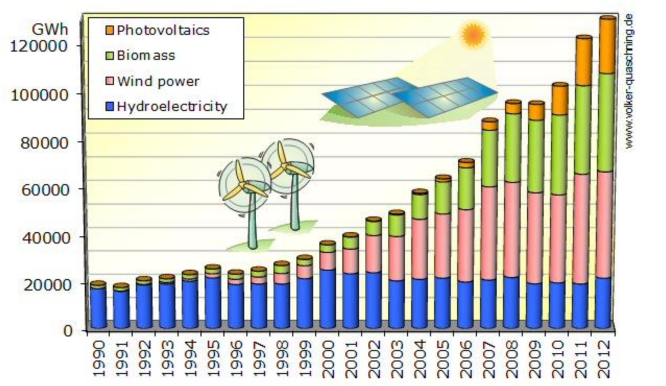
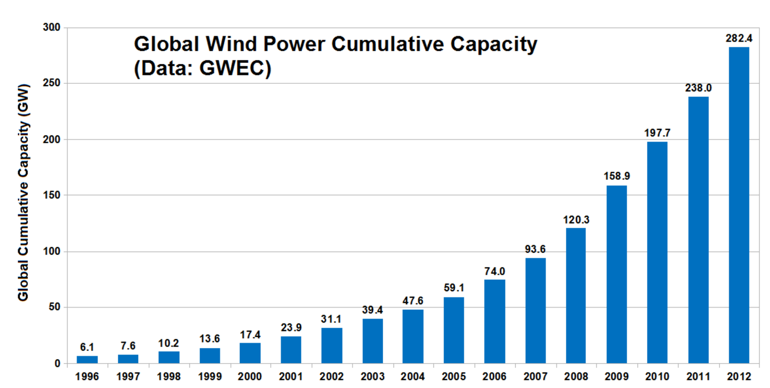
Motivation:

- Total primary energy consumption in the world increased from 400 Quadrillion Btu in 2000 to 510 Quadrillion Btu in 2010.
- Sustainable energy future requires significant penetration of Renewable Energy Sources (RES)
- RES (e.g. wind, solar) inherit variability i.e. volatility, uncertainty, and intermittency. It is a challenge to integrate RES into the power grid at large scale.







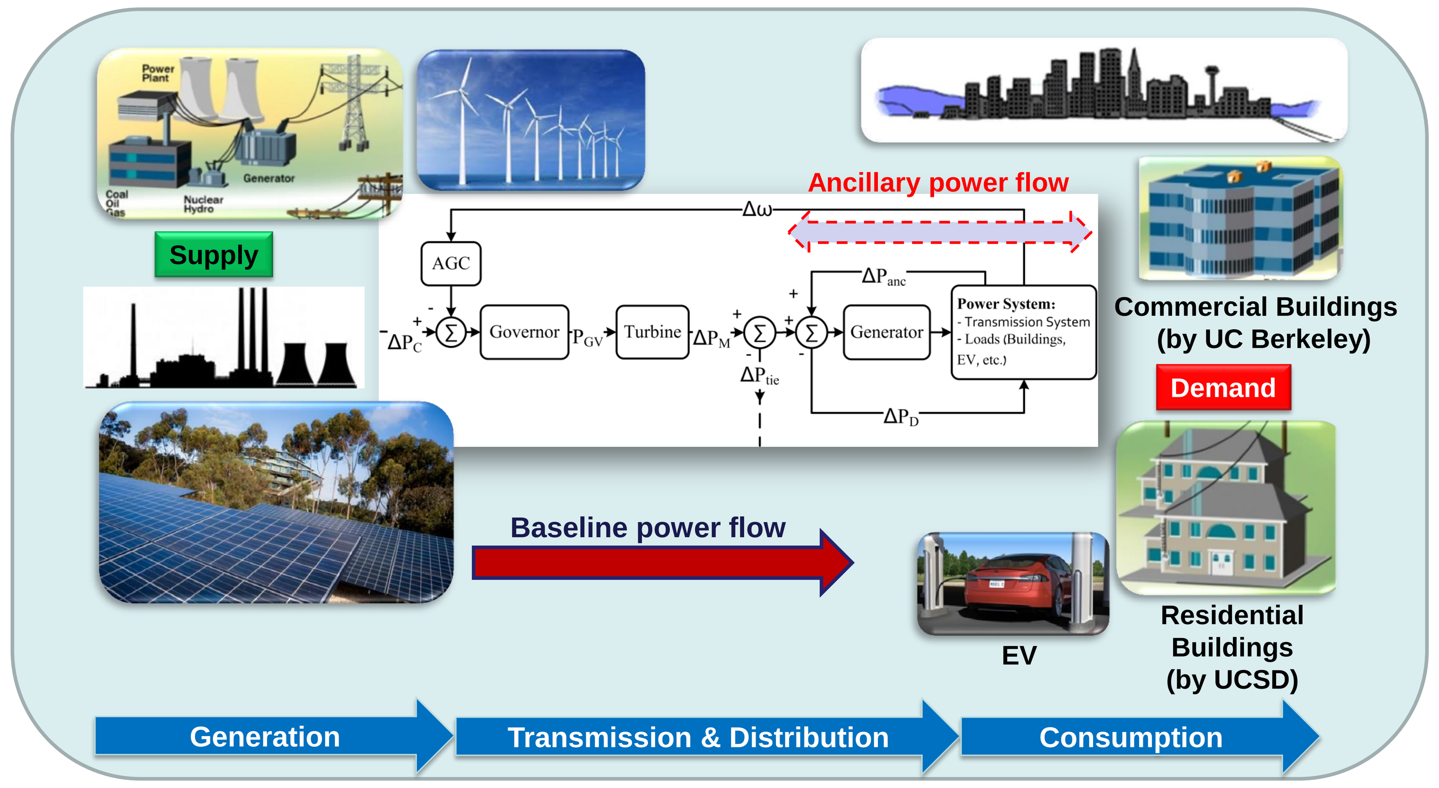
Example: Renewable energy generation capacity in Germany.

Problem Statement:

Increasing penetration of renewable energy sources, poses management, economic and technical challenges to utility companies and is jeopardizing the stability of the grid.

Idea: Demand-side flexibility of commercial building HVAC systems for supply-following.

Abstract: We first propose a means to define and quantify the flexibility of a commercial building. We then propose a contractual framework that can be used by the building operator and the utility to declare flexibility on one side and reward structure on the other side. We then design a control mechanism for the building to decide its flexibility for the next contractual period to maximize the reward, given the contractual framework. Finally, we perform at-scale experiments to demonstrate the feasibility of the proposed algorithm.



Why Commercial Buildings?

1) Commercial buildings account for more than 35% of electricity consumption in the US.
2) ~ 30% of commercial buildings have Building Energy Management System (BEMS) technology which facilitate communication with the grid for providing flexibility.
3) Majority of these buildings are equipped with variable frequency drives, which in coordination with BEMS, can modulate the HVAC system power consumption frequently (in the order of seconds).

Baseline MPC for Buildings:

Objective: minimize total energy cost
Constraints: System dynamics, state and input constraints
Given: Predictive cost of energy, predictive disturbance information

$$\min_{\vec{u}_t} \sum_{k=0}^{H^m-1} C_{\text{hvac}}(u_{t+k}, \pi^e_{t+k}, \pi^{ne,c}, \pi^{ne,h}, T^{\text{out}}_{t+k})$$
$$\text{s.t.} \quad x_{t+k+1} = f(x_{t+k}, u_{t+k}, d_{t+k}), \quad k = 0, ..., H^m-1$$
$$x_{t+k} \in \mathcal{X}_{t+k}, \quad k = 1, ..., H^m$$
$$u_{t+k} \in \mathcal{U}_{t+k}, \quad k = 0, ..., H^m-1$$

Flexibility-Aware MPC for Buildings:

Control mechanism for the building to decide its flexibility on the fly
while:
- Maximizing economic benefit of the building.
- Guaranteeing thermal comfort of the building.

Min-max Problem

$$\min_{\vec{u}_t, \vec{\Phi}_{t+1}} \max_{\vec{w}_t} \sum_{k=0}^{H^m-1} C_{\text{hvac}}(u_{t+k}, \pi_{t+k}) - R(\Phi_{t+k+1}, \mathcal{B}_{t+k+1}) \quad (18a)$$

subject to:
$$x_{t+k+1} = f(x_{t+k}, u_{t+k} + w_{t+k}, d_k)$$
$$\forall \quad k = 0, ..., H^m-1 \quad (18b)$$
$$\forall\, w_t \text{ s.t. : } \underline{\varphi}_t \le w_t \le \overline{\varphi}_t \quad (18c)$$
$$\forall\, w_{t+k} \text{ s.t. : } \underline{\varphi}_{t+k} \le w_{t+k} \le \overline{\varphi}_{t+k}$$
$$\forall k = 1, ..., H^m-1 \quad (18d)$$
$$\overline{\varphi}_{t+k} \ge 0, \quad \forall\, k = 1, ...H^m-1 \quad (18e)$$
$$\underline{\varphi}_{t+k} \le 0, \quad \forall\, k = 1, ...H^m-1 \quad (18f)$$
$$x_{t+k} \in \mathcal{X}_{t+k} \;\forall\, k = 1, ..., H^m \quad (18g)$$
$$u_{t+k} + w_{t+k} \in \mathcal{U}_{t+k} \;\forall\, k = 0, ..., H^m-1 \quad (18h)$$

Theorem: Let C be a closed convex set and let $f: C \to \mathbb{R}$ be a convex function. Then if f attains a maximum over C, it attains a maximum at some extreme point of C.

Minimization Problem

$$\min_{\vec{u}_t, \vec{\Phi}_{t+1}} \sum_{k=0}^{H^m-1} C_{\text{hvac}}(u_{t+k}, \pi_{t+k}) - R(\Phi_{t+k+1}, \mathcal{B}_{t+k+1}) \quad (22a)$$

s. t.:
$$\underline{x}_{t+k+1} = f(x_{t+k}, u_{t+k} + \underline{\varphi}_{t+k}, d_{t+k}) \quad (22b)$$
$$\forall k = 0, ..., H^m-1$$
$$\overline{x}_{t+k+1} = f(x_{t+k}, u_{t+k} + \overline{\varphi}_{t+k}, d_{t+k}) \quad (22c)$$
$$\forall k = 0, ..., H^m-1$$
$$\overline{\varphi}_{t+k} \ge 0, \quad \forall\, k = 1, ...H^m-1 \quad (22d)$$
$$\underline{\varphi}_{t+k} \le 0, \quad \forall\, k = 1, ...H^m-1 \quad (22e)$$
$$\underline{x}_{t+k} \in \mathcal{X}_{t+k} \quad \forall \quad k = 1, ..., H^m \quad (22f)$$
$$\overline{x}_{t+k} \in \mathcal{X}_{t+k} \quad \forall \quad k = 1, ..., H^m \quad (22g)$$
$$u_{t+k} + \underline{\varphi}_{t+k} \in \mathcal{U}_{t+k} \quad \forall\, k = 0, ..., H^m-1 \quad (22h)$$
$$u_{t+k} + \overline{\varphi}_{t+k} \in \mathcal{U}_{t+k} \quad \forall\, k = 0, ..., H^m-1 \quad (22i)$$

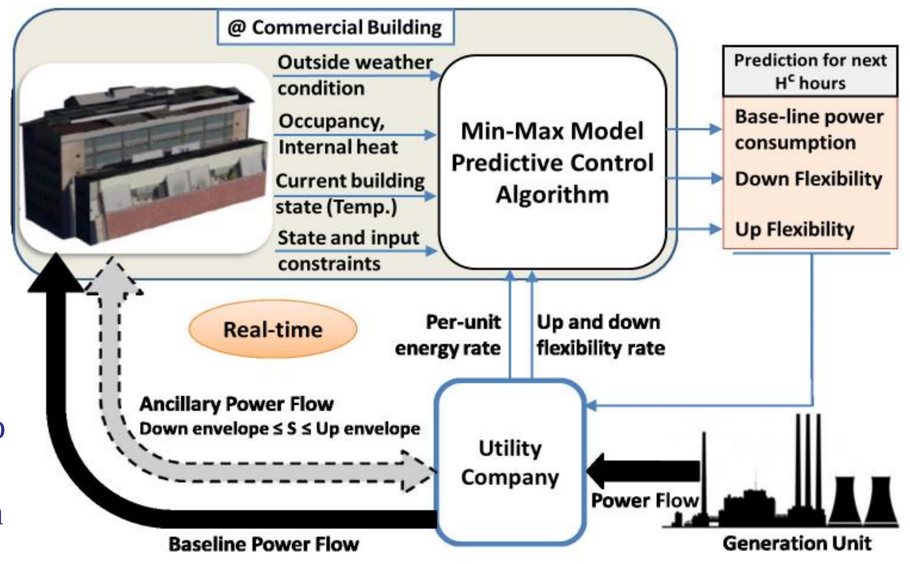
Nonlinear Optimization Problem

Solved by: IPOpt.

Proposed Architecture:

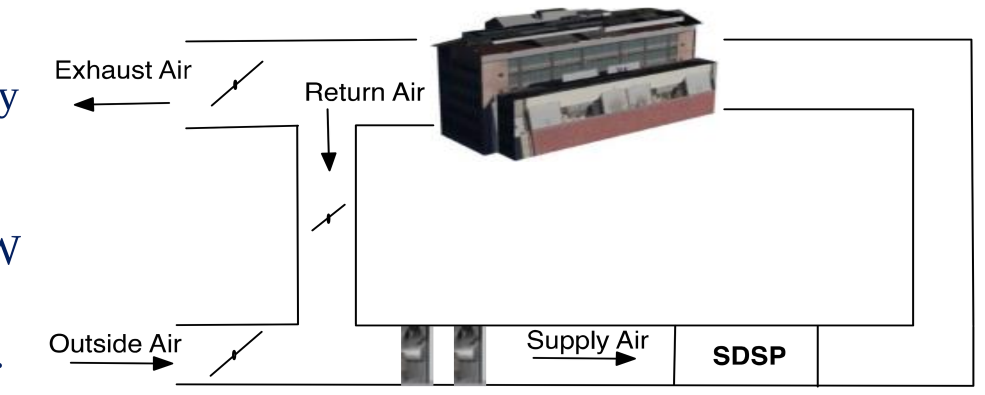
- Define and quantify flexibility of commercial building power consumption.
- Contractual framework for the building and the utility to declare:
1) flexibility 2) reward structure

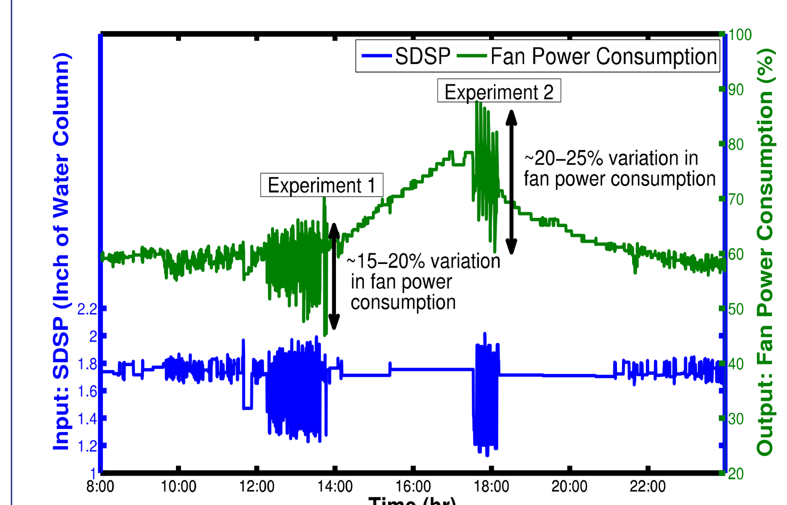
The solid line power flow arrows correspond to the baseline system and contract. The ancillary power flow via the flexibility contract is shown with dashed line arrow.



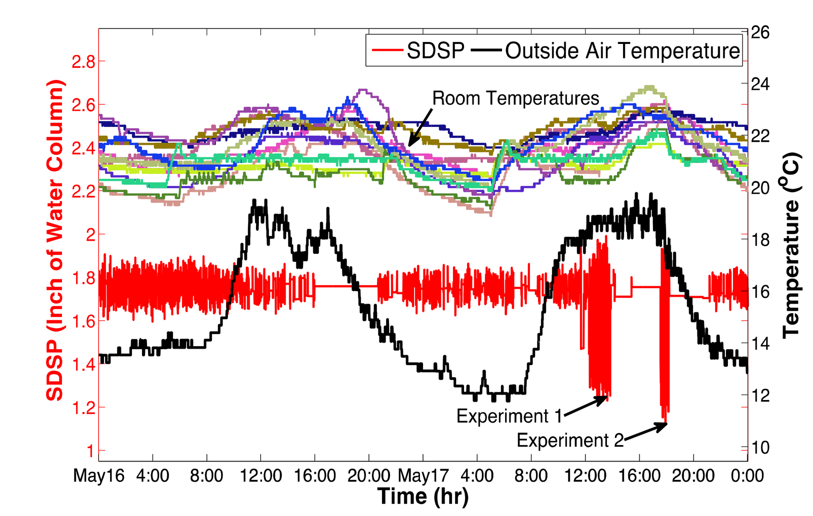
Experimental Results:

Sutardja Dai Hall on UC Berkeley campus variable speed fans, with power consumption with the maximum rated power of 134 KW or about 14% of the maximum power consumed in that building.



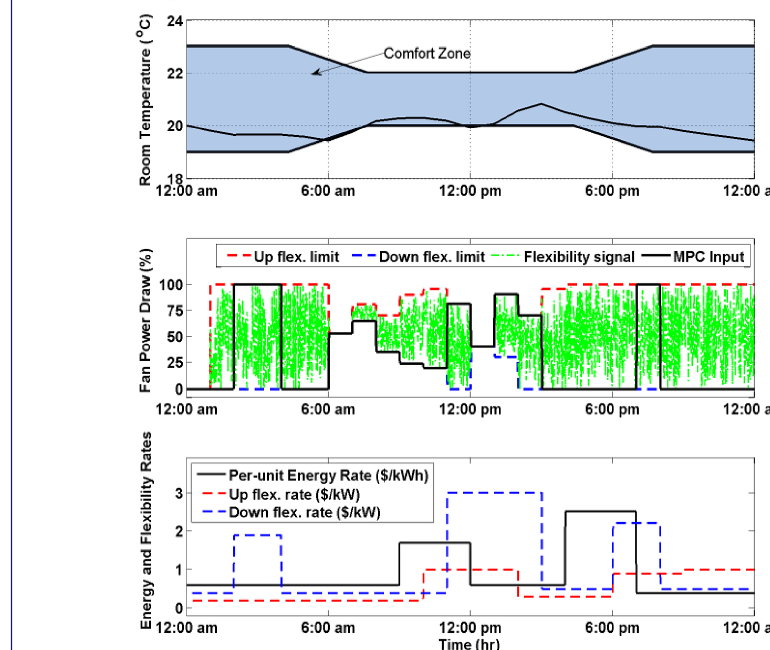


Fan power consumption can vary as quickly as in a few seconds by up to 25% by changing the SDSP setpoint.

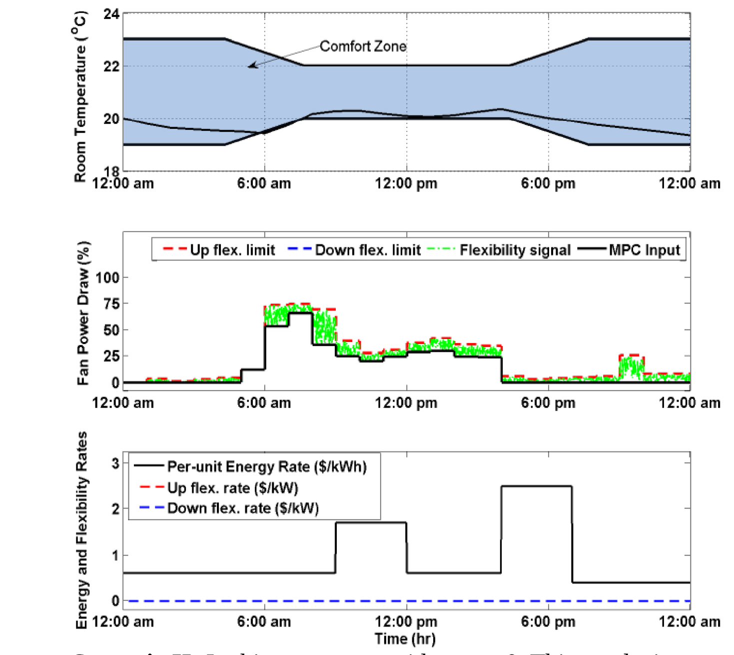


SDSP setpoint, outside air temperature, and temperature of 15 randomly selected rooms are shown for one day before (May 16, 2013) and the day of the experiment (May 17, 2013).

Simulation Results:



Scenario I: The Per-unit energy rate, and upward and downward flexibility reward are shown in the lowest figure. The middle figure shows the resulting flexibility at each time, and the top figure shows the resulting room temperature.



Scenario II: In this case we consider = = 0. This results into a performance similar to the one of the nominal MPC

There are **4.9 million** commercial buildings in the US with a total area of about 72 billion sq. ft. We estimate that at least 11.4 GW of fast ancillary service is readily available at almost no cost, based on the 2003 data. Commercial building floor space is expected to reach 103 billion sq. ft. in 2035. With the same assumption of the above calculations, about 16.3 GW of regulation reserve will be available in 2035.

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