Platform-based Design Approach to Modeling and Control of Energy Cyber-Physical Systems:

Applications: Smart buildings, Smart Grid, and Aircrafts

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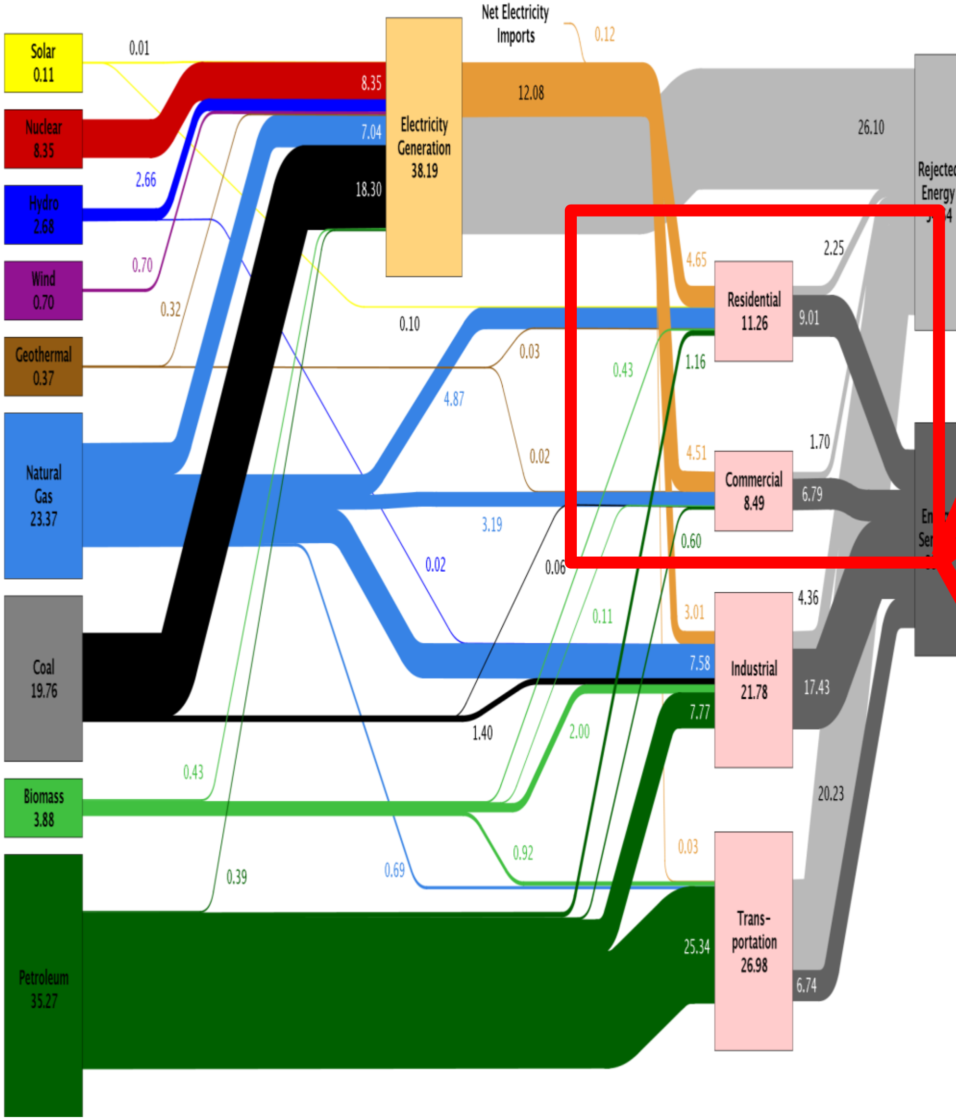
Outline

- Smart/Green Buildings
- Smart Grid and Smart Buildings
- Aircraft Electric Power System

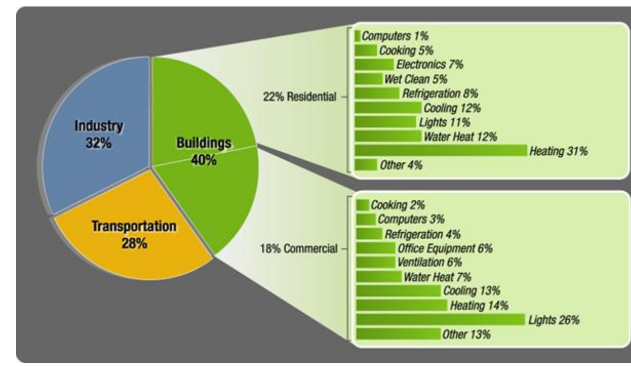
Smart Buildings (SinBerBEST)

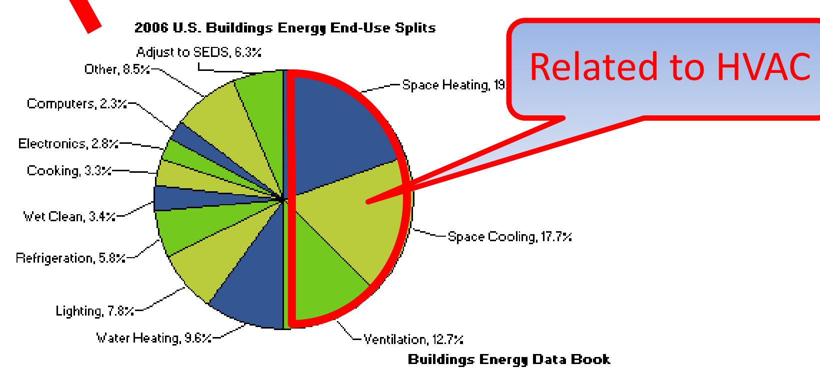
Source: www.agefotostock.com

US Energy System and important sub-systems



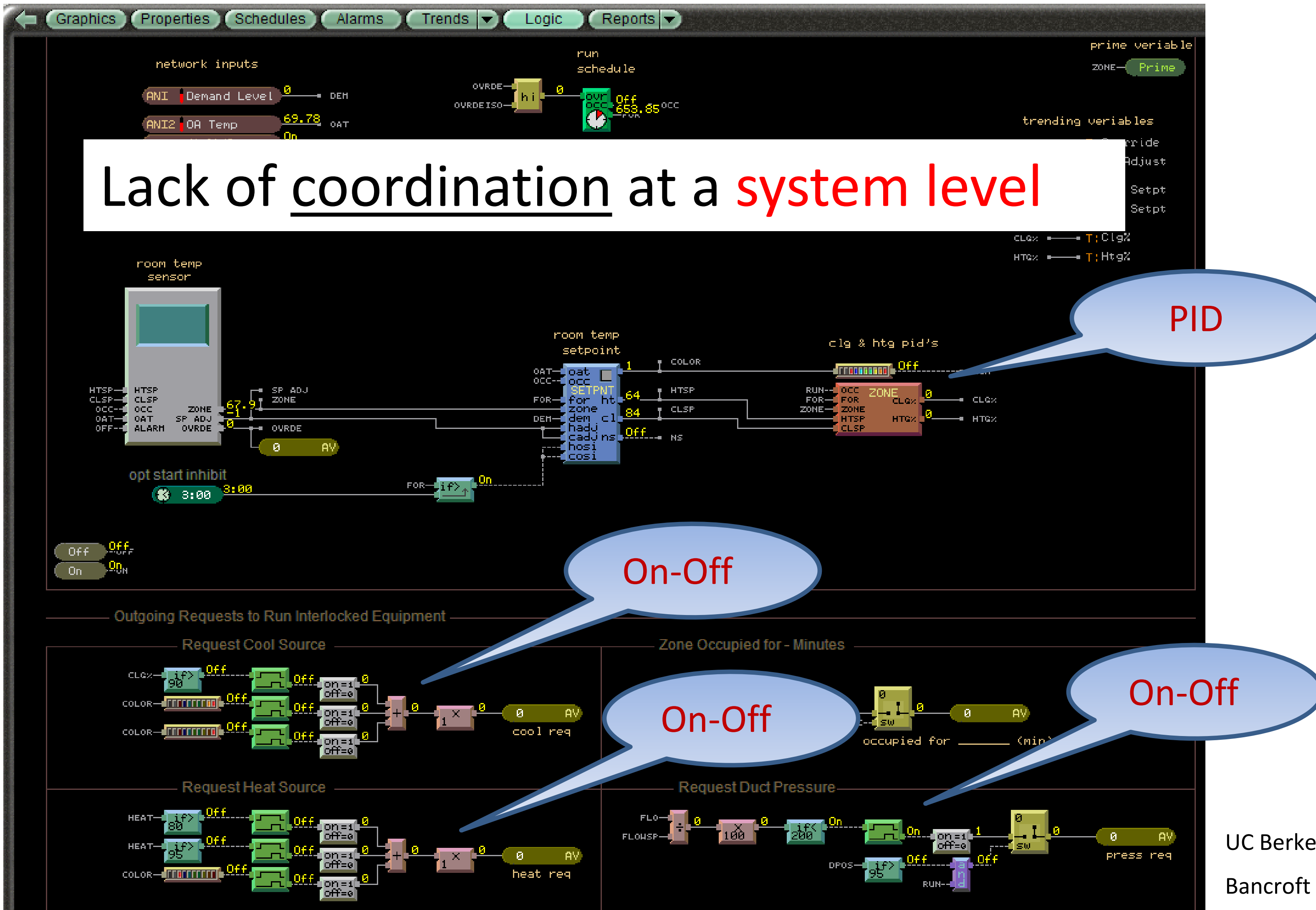
Grid ⇔ Building ⇔ Occupant ⇔ Design





Courtesy LLNL

Current HVAC control systems

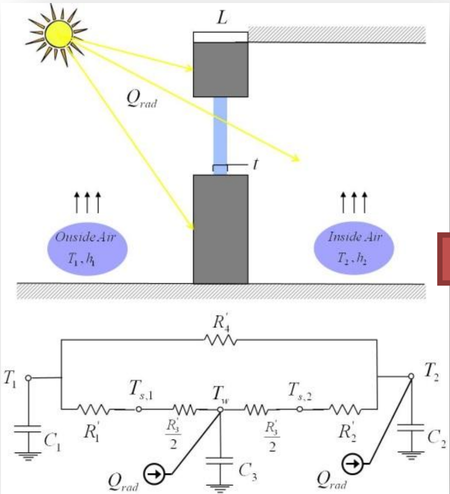


UC Berkeley,

Bancroft Library

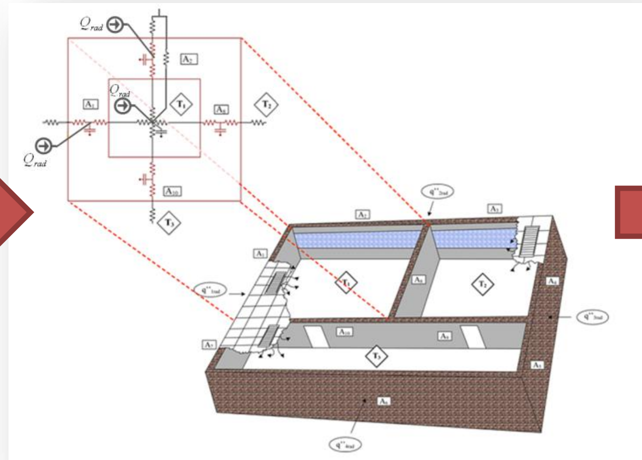
Energy in Smart Tropical Buildings

Mathematical Model



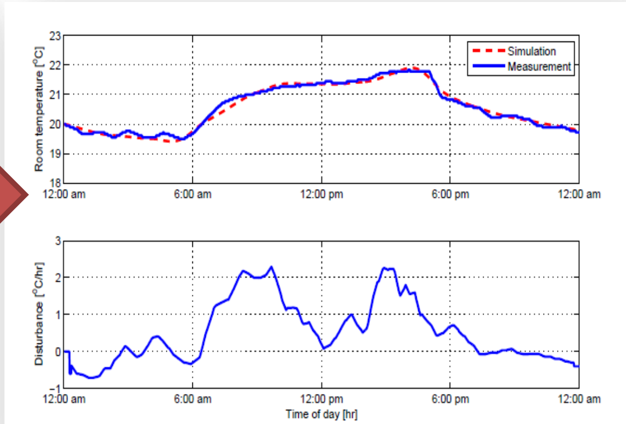
$$\frac{dT_{w_i}}{dt} = \frac{1}{C_{w_i}} \left[\sum_{j \in \mathcal{N}_{w_i}} \frac{T_j - T_{w_i}}{R'_{ij}} + r_i \alpha_i A_i q''_{rad_i} \right]$$

Scale-up to Building Level

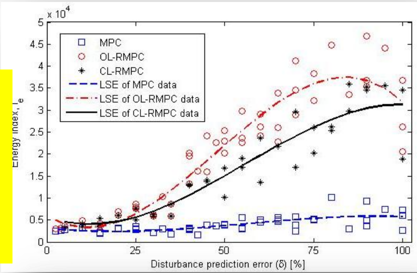


$$\dot{x}(t) = Ax(t) + Bu(t) + d(t)$$
$$y(t) = Cx(t)$$

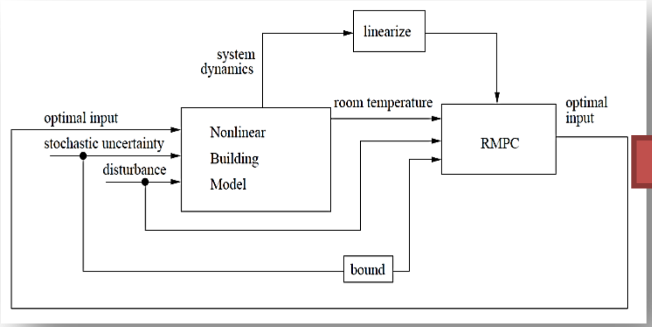
Data-Driven Predictive Model



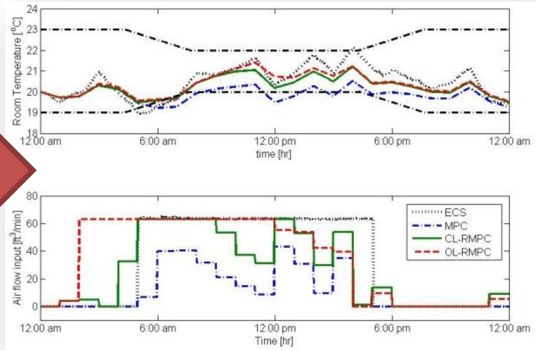
Energy Saving > 50%

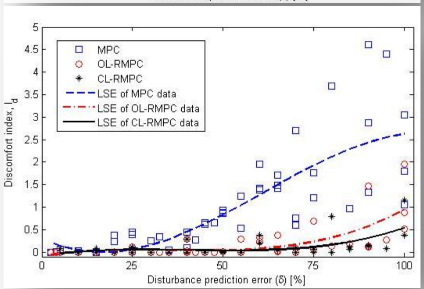


Control Architecture



Optimal Performance





Model predictive control

$$\min_{U_t,\bar{\epsilon},\underline{\epsilon}} \quad \{|U_t|_1 + \kappa |U_t|_\infty + \rho(|\bar{\epsilon}_t|_1 + |\underline{\epsilon}_t|_1)\} =$$

$$\min_{U_t,\bar{\varepsilon},\underline{\varepsilon}} \quad \{\sum_{k=0}^{N-1} |u_{t+k|t}| + \kappa \max(|u_{t|t}|, \cdots, |u_{t+N-1|t}|) + \rho \sum_{k=1}^{N} (|\bar{\varepsilon}_{t+k|t}| + |\underline{\varepsilon}_{t+k|t}|)\}$$

s.t.

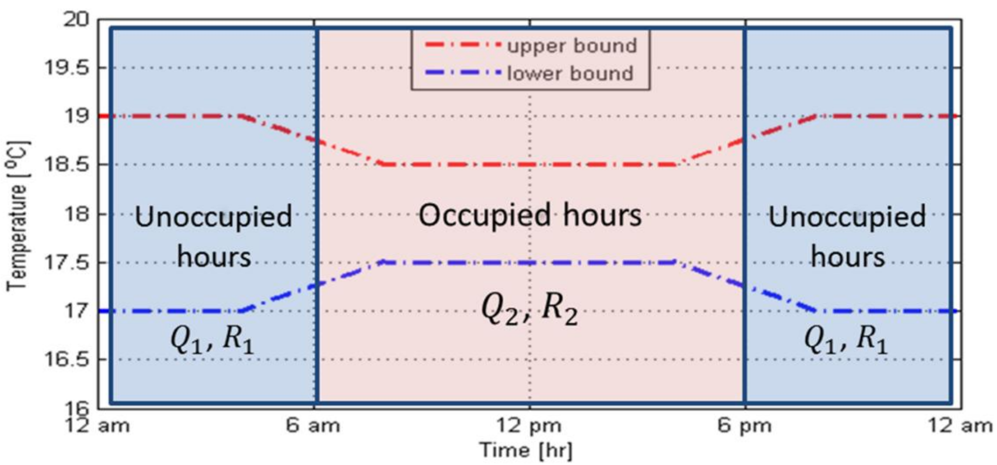
$$x_{t+k+1|t} = Ax_{t+k|t} + Bu_{t+k|t} + Ed_{t+k|t}, \qquad k = 0, \ldots, N-1$$

$$y_{t+k|t} = Cx_{t+k|t}, \qquad k = 1, \ldots, N$$

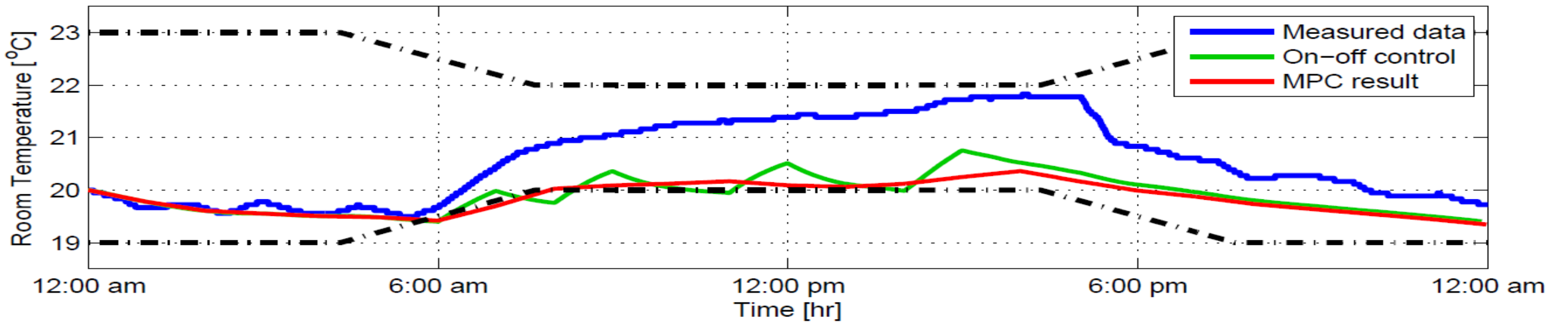
$$0 \le u_{t+k|t} \le \overline{\mathcal{U}}, \qquad k = 0, \ldots, N-1$$

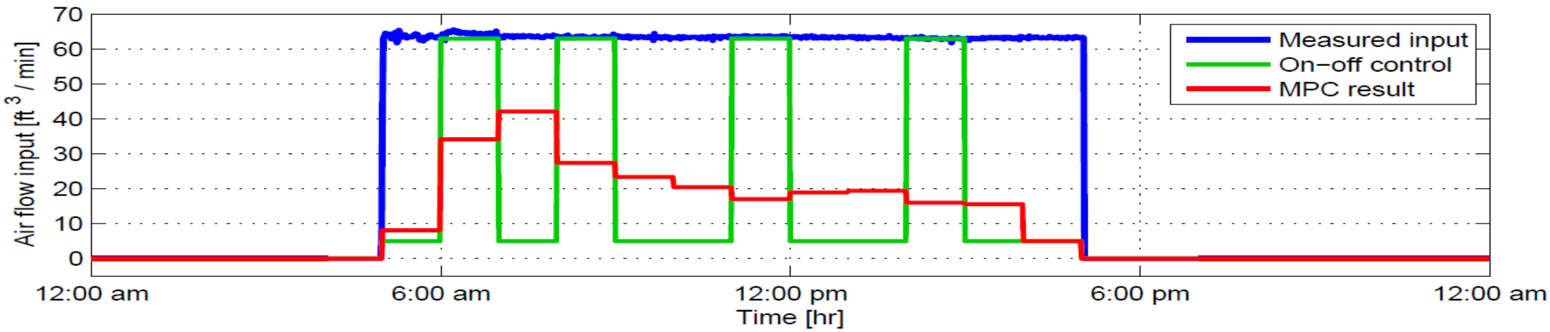
$$\underline{T}_{t+k|t} - \underline{\varepsilon}_{t+k|t} \le y_{t+k|t} \le \overline{T}_{t+k|t} + \bar{\varepsilon}_{t+k|t}, \qquad k = 1, \ldots, N$$

$$\underline{\varepsilon}_{t+k|t}, \bar{\varepsilon}_{t+k|t} \ge 0, \qquad k = 1, \ldots, N$$



“MPC” and “On-off” control results





Controller	Total input $[ft^3]$	Peak input $[ft^3/min]$	Total energy $[kWh]$	Running time $[s]$
Original control	45360	63	12.46	-
On-off control 68%	17520 66%	63 35%	4.62 73%	1.8
MPC	14870	42	3.33	102.4

Co-design Problem!

- The design of HVAC systems involves three main aspects:

  - Physical components and environment,
  - Control algorithm that determines the system operations based on sensing inputs,
  - Embedded platform that implements the control algorithm.

- In the traditional *top-down approach*, the design of the HVAC control algorithm is done without explicit consideration of the embedded platform.

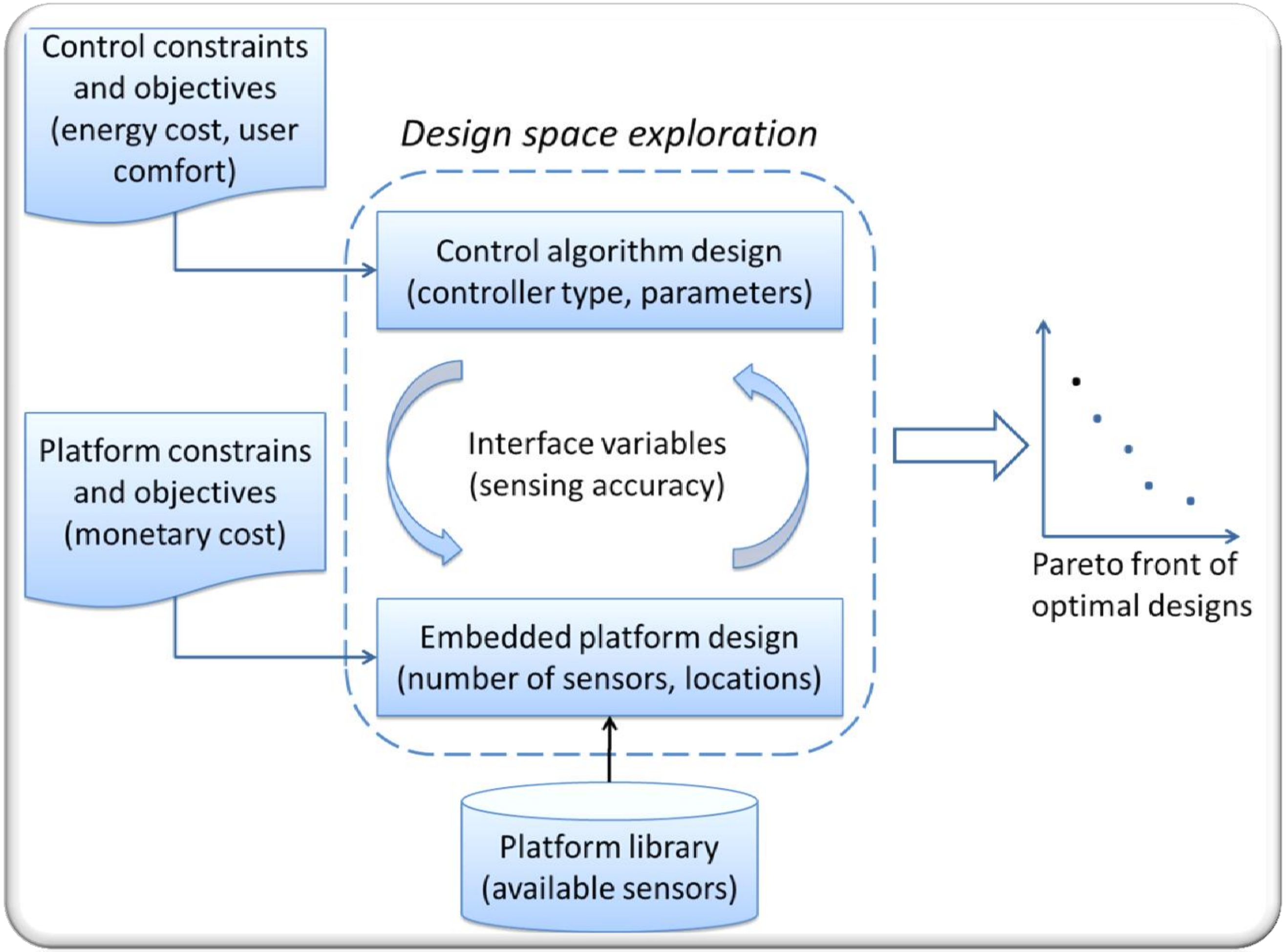
Co-design Problem, cont.

With…

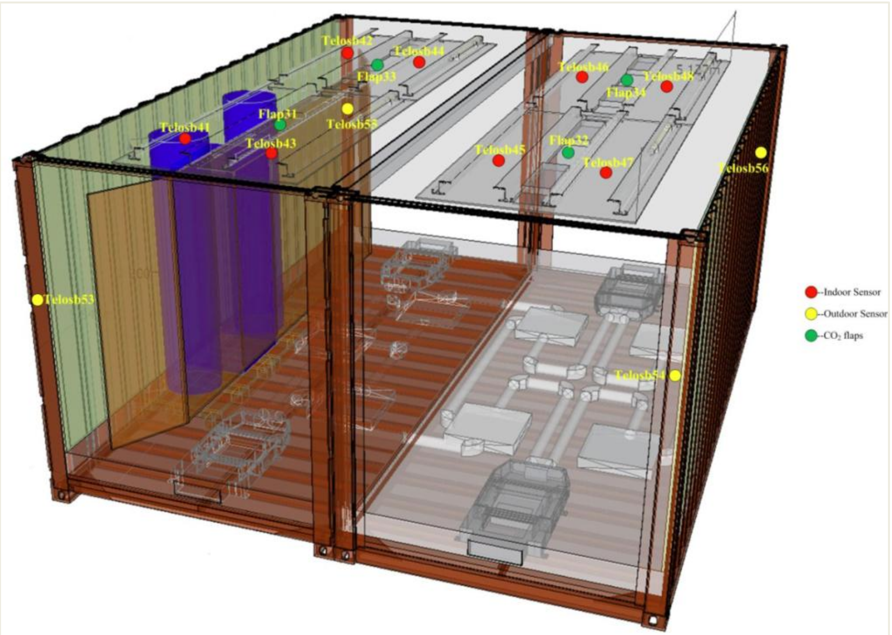
- *the employment of more complex HAVC control algorithms,*
- *the use of distributed networked platforms, and*
- *the imposing of tighter requirements for user comfort,*

the assumption that…
the embedded platform will always be sufficient for any control mechanism
is no longer true.

Co-design framework for HVAC systems



Sensing system setup



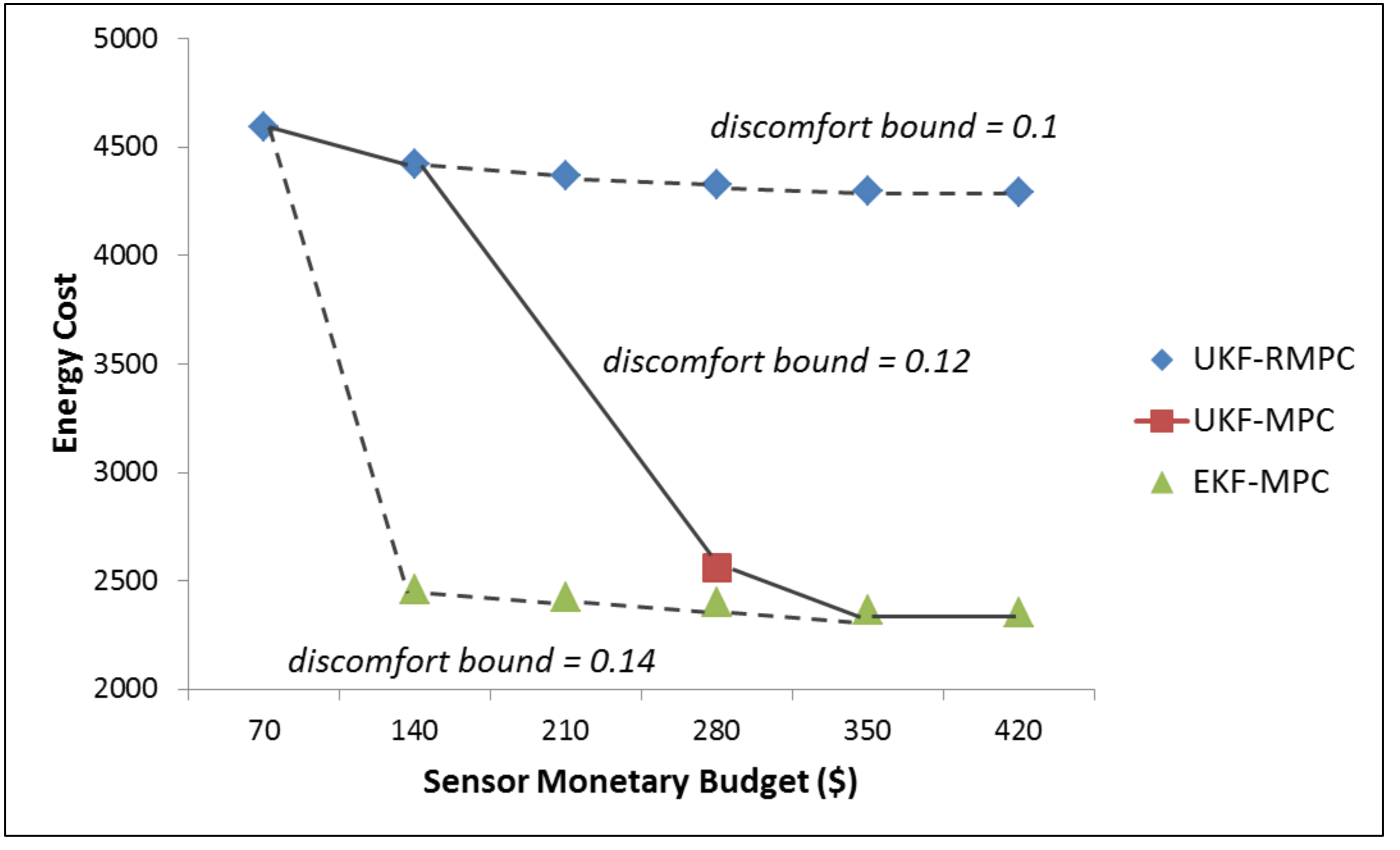
BubbleZERO Research Setup

Which is conceived as part of the Low Exergy Module development for Future Cities Laboratory (FCL)

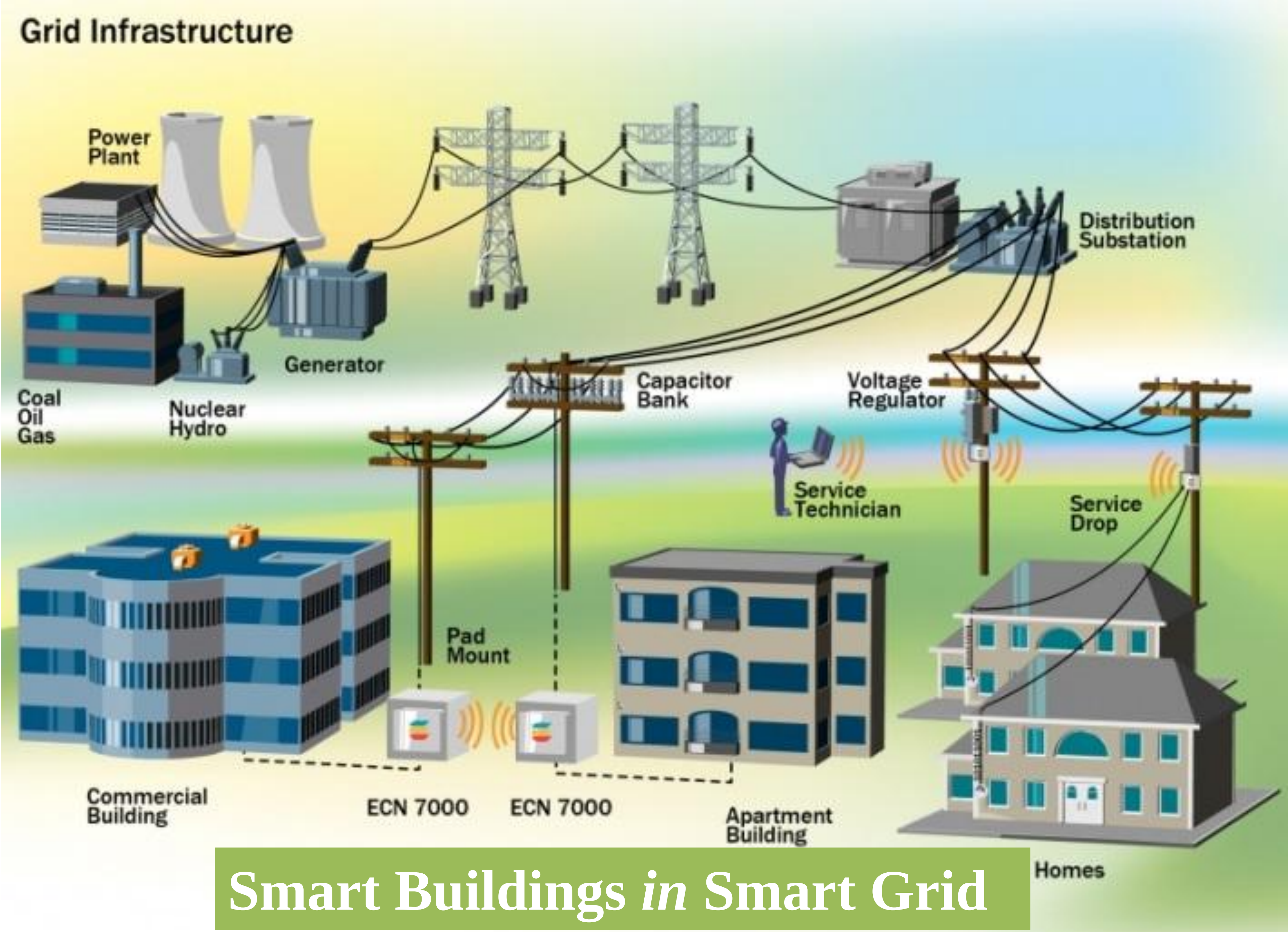
The environment sense system includes:

- 8 indoor sensors (Telosb41-48)
- 4 CO2 concentration sensors (flap31-34)
- 4 outdoor sensors (Telosb53-56)

Pareto front Under Discomfort index Contraints



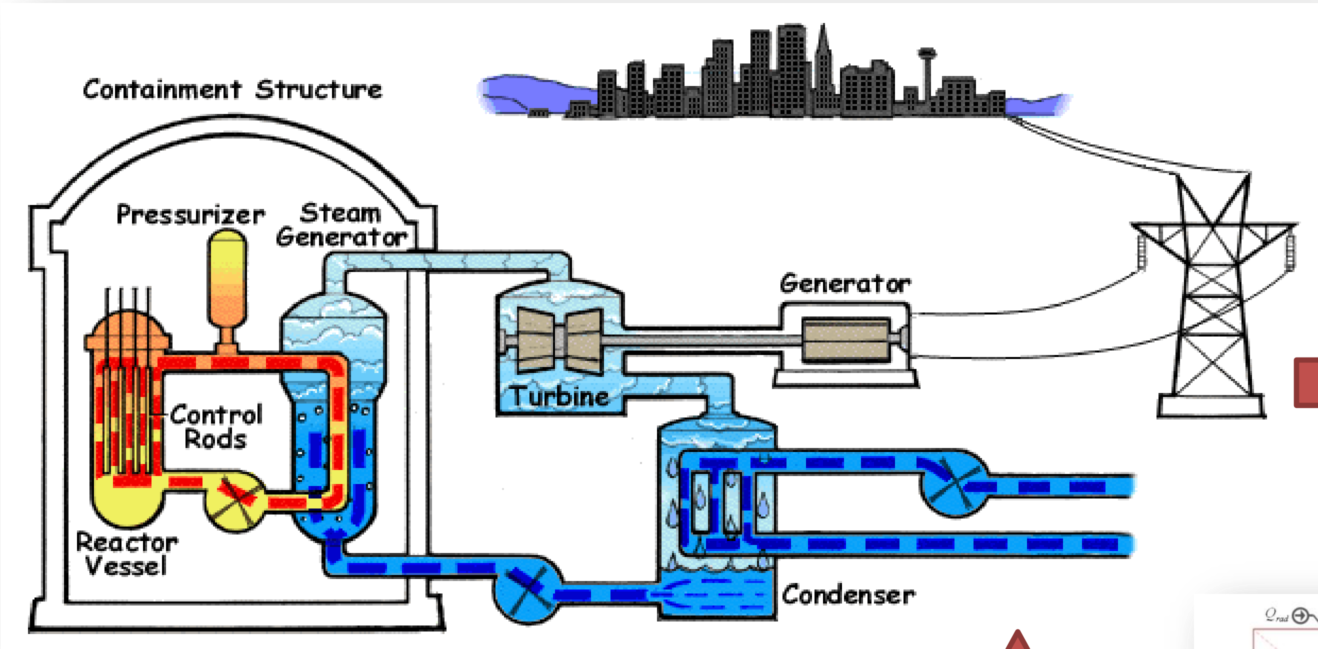
Pareto front under comfort constraints with best sensor locations



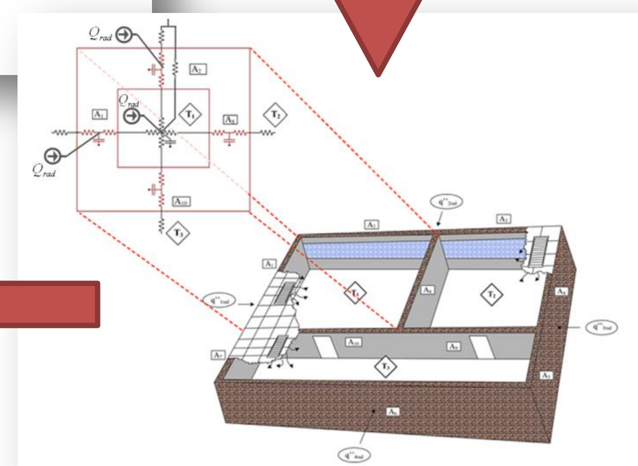
Smart Buildings *in* Smart Grid

Source: www.engineerlive.com

Smart Grid and Buildings

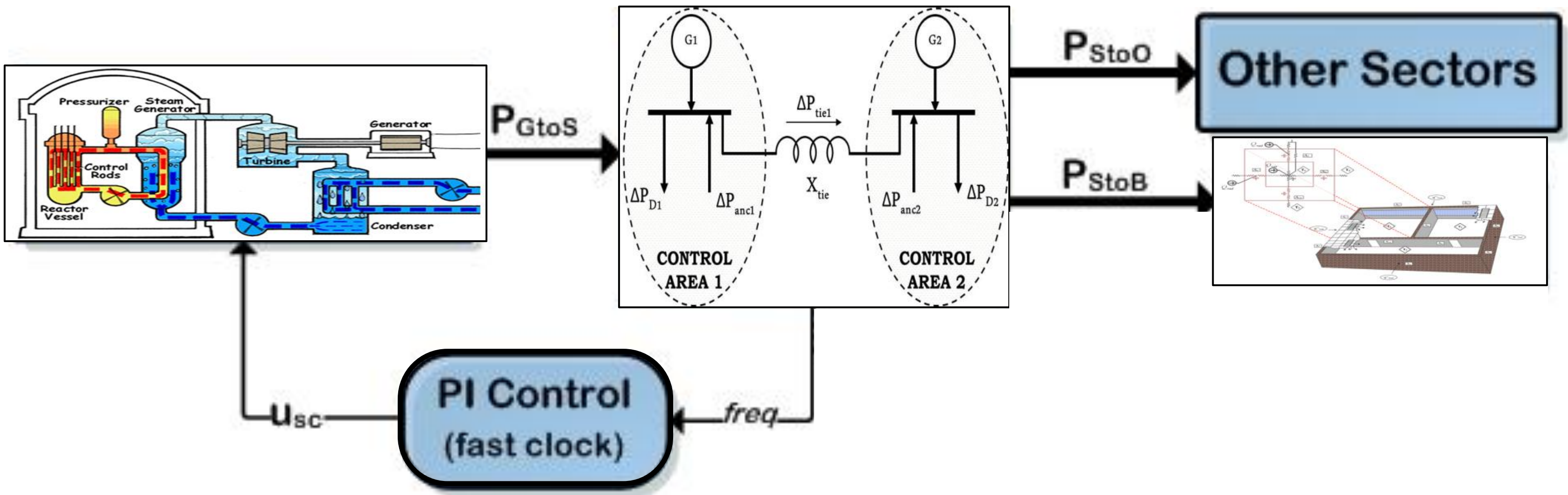


Source: http://evergreennuclear.blogspot.com/2011/08/primer-on-how-pressurized-water-reactor.html



Main idea:
Ancillary Services via
Control of HVAC Systems

Ancillary service to Grid from Buildings



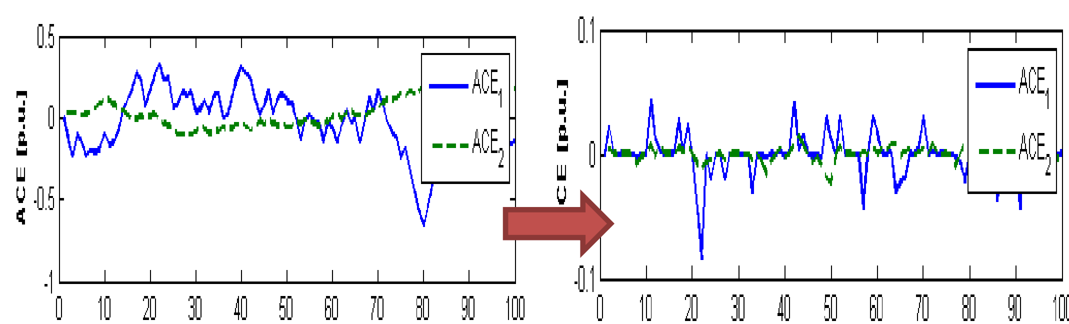
$$\min_{u_{anc}} \quad \sum_{i=1}^{n} \int (ACE^i(t))^2\, dt$$

$$\text{s.t.} \quad x(k+1) = Ax(k) + B_2 u_{anc}(k) + Ed(k)$$

$$U_{anc}^{min}(k) \le u_{anc}(k) \le U_{anc}^{max}(k)$$

$$|u_{anc}(k) - u_{anc}(k+1)| \le L_{anc}^{max}(k)$$

Where: $ACE_i = \Delta P_{tie}^i + \beta^i x_1^i$



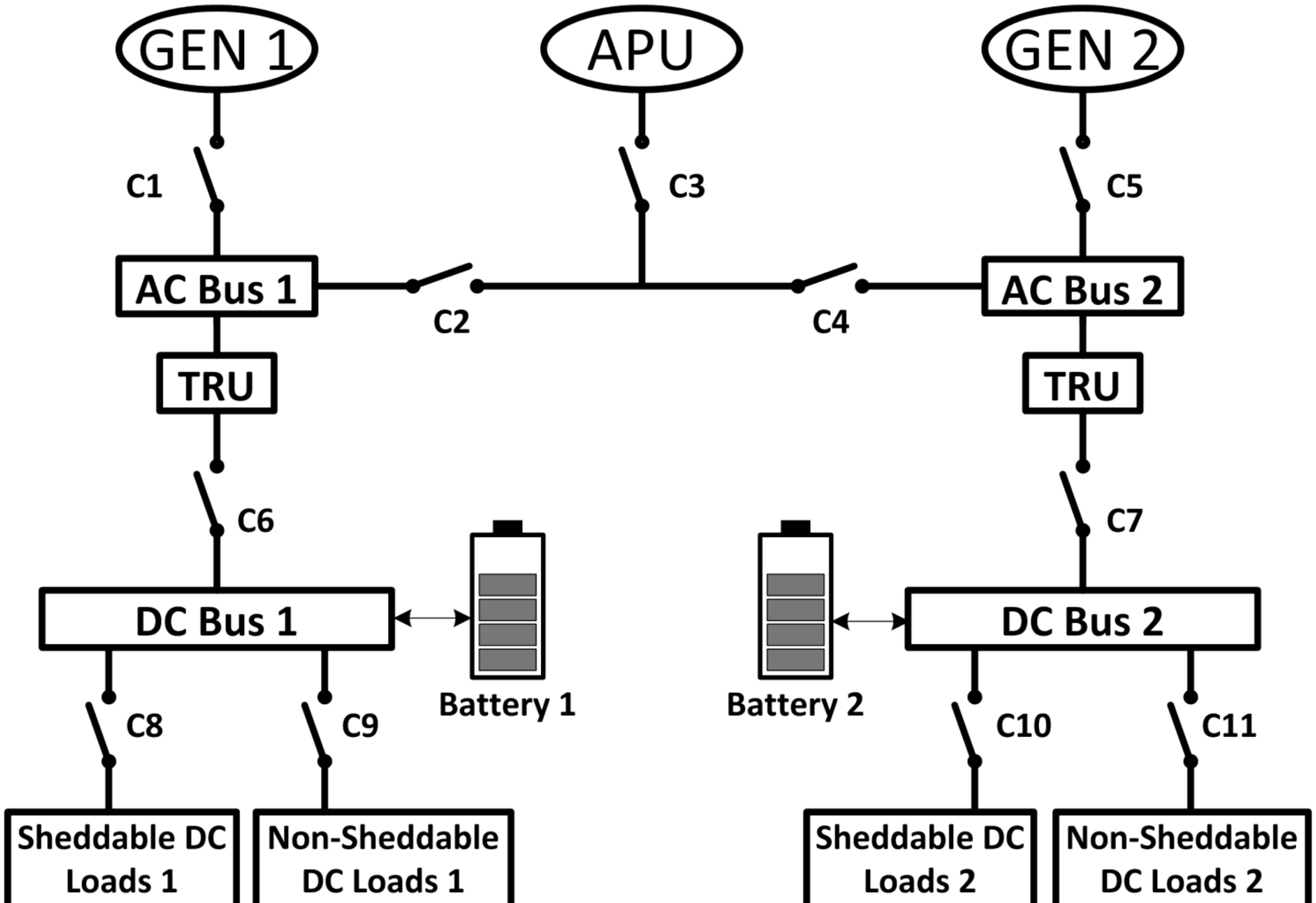
ACE(rms)=1.06
No Ancillary

20X reduction

ACE(rms)=0.05
With Ancillary

Optimal Load Management of Aircraft Power Systems

Single Line Diagram (SLD)



Specifications

- **Safety:**
  - **NO parallelization of AC sources;**
  - $15 \leq \tau_{\text{contactor closure}} \leq 25\ [msec]$.
  - $10 \leq \tau_{\text{contactor opening}} \leq 20\ [msec]$.
  - $\tau_{\text{AC buses unpowered}} \leq 50\ [msec]$.
  - $\tau_{\text{DC buses unpowered}} = 0\ [msec]$.
  - **Percentage of working motor drives** = 50%

- **Reliability:**
  - **reliability level for** each component $\sim 10^{-4} : 10^{-7}$.
  - **System** must be designed to be safe to 10^{-9} under all conditions.

- **Performance:**
  - **Priority**: Each bus has a priority list of which generator will be used to provide power first.
  - **No bus has priority over another bus.**
  - **Load shedding priority:**

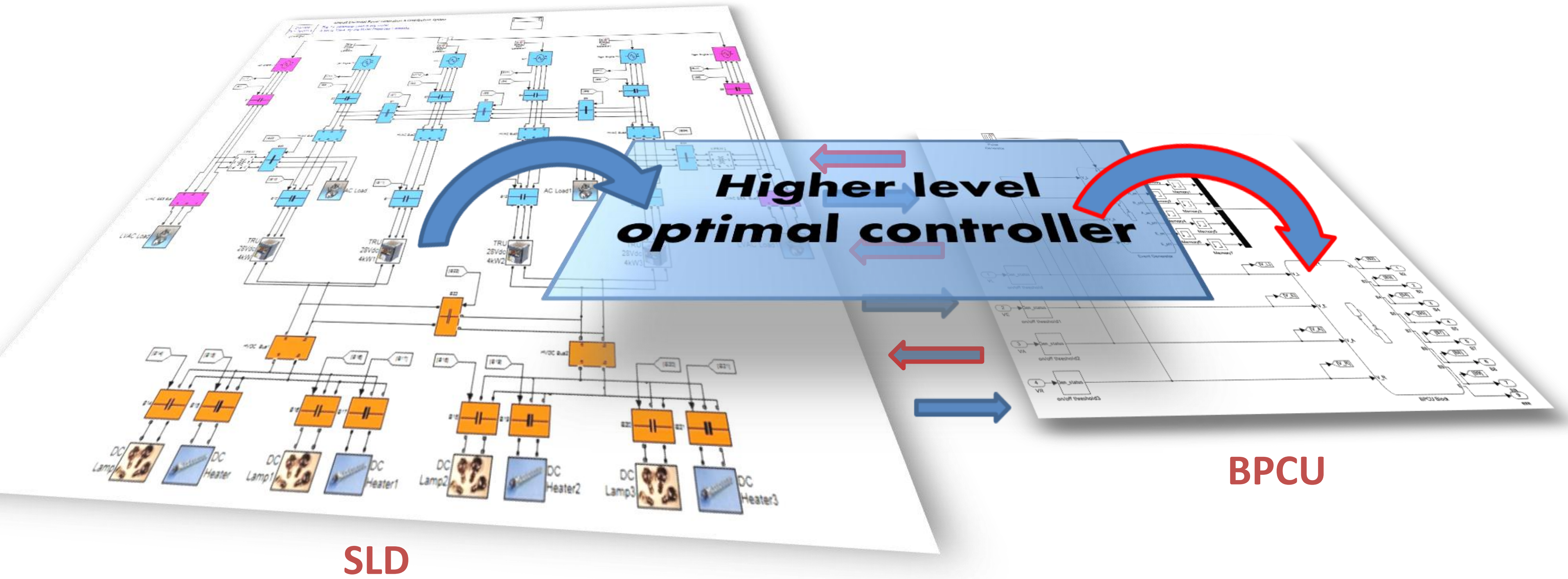
BUS PRIORITY TABLE.

Priority	HVAC 1	HVAC 2
1	Eng 1 HV-VFG	Eng 2 HV-VFG
2	Eng 2 HV-VFG	Eng 1 HV-VFG
3	APU-VFG	APU-VFG

LOAD PRIORITY TABLE FOR HVAC BUS 1.

Non-sheddable load (W)	sheddable load (W)	Shed priority
1000	1000	1
1000	1000	5
2000	1000	7
2000	1000	10
5000	2000	4
5000	2000	8
500	2000	9
500	2000	3
1000	5000	6
1000	5000	2

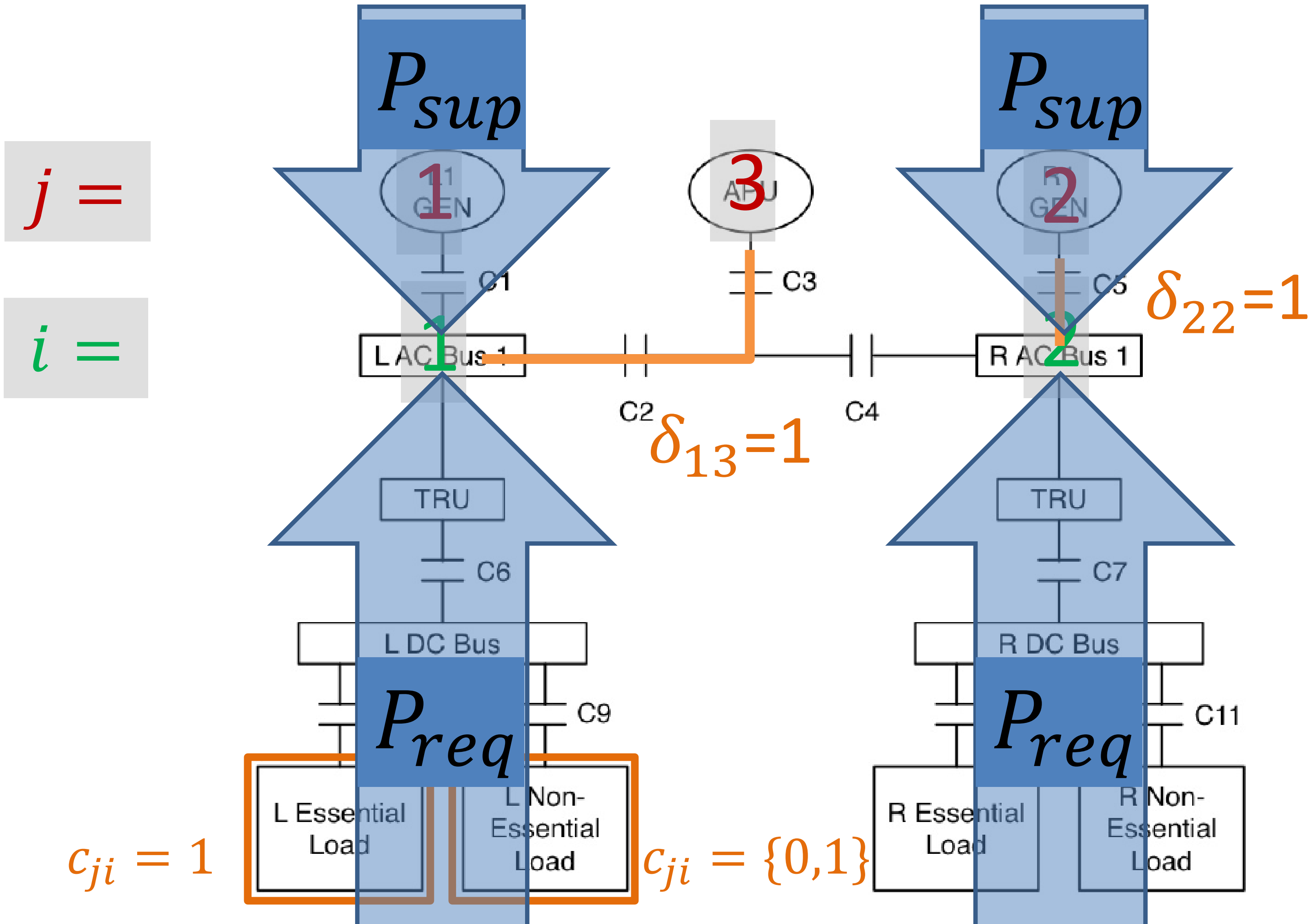
Our Approach: Hierarchical Control Architecture



Data (generator and contactor statuses)

Control Signal

Single Line Diagram Schematic



Load shedding priority constraint

LOAD PRIORITY TABLE FOR HVAC BUS 1.

Non-sheddable load (W)	sheddable load (W)	Shed priority
1000	1000	1
1000	1000	5
2000	1000	7
2000	1000	10
5000	2000	4
5000	2000	8
500	2000	9
500	2000	3
1000	5000	6
1000	5000	2

$$c_{j1}(t) \leq c_{j2}(t) \leq \ldots \leq c_{jn_j}(t) \quad \forall t \geq 0$$

Where:

$$c_{ji}(t) = 1 \quad \forall j = 1,2 \quad \forall i \in I_{NS} \quad \forall t \geq 0$$
$$c_{ji}(t) = \{0,1\} \quad \forall j = 1,2 \quad \forall i \in I_S \quad \forall t \geq 0$$

n_j: number of sheddable loads of bus j

Note that loads l_{ji} in this formulation are ranked based on their priority number.

Bus Priority Table

- Formulated as a "***penalty***" term in the cost function:

BUS PRIORITY TABLE.

Priority	HVAC 1	HVAC 2
1	Eng 1 HV-VFG	Eng 2 HV-VFG
2	Eng 2 HV-VFG	Eng 1 HV-VFG
3	APU-VFG	APU-VFG

$$\sum_{j=1}^{2} \int_{t_0}^{t_f} \Lambda_j^T \Delta_j(t)\, \mathrm{d}t$$

Where:

$$\Lambda_j = [\lambda_{j1} \quad \lambda_{j2} \quad \lambda_{j3}]^T$$

Weighting matrix

$$\Delta_j(t) = [\delta_{j1}(t) \quad \delta_{j2}(t) \quad \delta_{j3}(t)]^T$$

Decision variables

e.g. : $\lambda_{13} \gg \lambda_{12}, \quad \lambda_{11} = 0$

Optimal Control Policy

$$\min_{S} \sum_{t=t_0}^{t_f} \left\{ \sum_{j=1}^{N^b} [\Gamma_j^T (1 - C_j(t)) + \Lambda_j^T \Delta_j(t)] + \mu \sum_{j=1}^{N^s} \alpha_j(t) \right\}$$

subject to:

$$\sum_{k=1}^{n_i} c_{ik}(t) L_{ik}^s(t) + \sum_{k=n_i+1}^{N_i} c_{ik}(t) L_{ik}^{ns}(t) = P_{sup_i}(t) - \beta_i(t)$$

$$i = 1, ..., N^b$$

$$\sum_{k=1}^{N^s} \delta_{ik}(t) P_{ktoi}(t) = P_{sup_i}(t) \quad i = 1, ..., N^b$$

$$\sum_{k=1}^{N^b} \delta_{kj}(t) P_{jtok}(t) = \alpha_j(t) P_j^{max}(t) \quad j = 1, ..., N^s$$

$$\sum_{k=1}^{N^s} \delta_{ik}(t) = 1 \qquad i = 1, ..., N^b$$

$$\delta_{ji}(t) = \{0, 1\} \; j = 1, ..., N^b \; i = 1, ..., N^s$$

$$c_{j1}(t) \leq c_{j2}(t) \leq ... \leq c_{jN_j}(t) \quad j = 1, ..., N^b$$

$$c_{ji}(t) = 1 \qquad j = 1, ..., N^b \quad \forall \; i \in I_j^{ns}$$

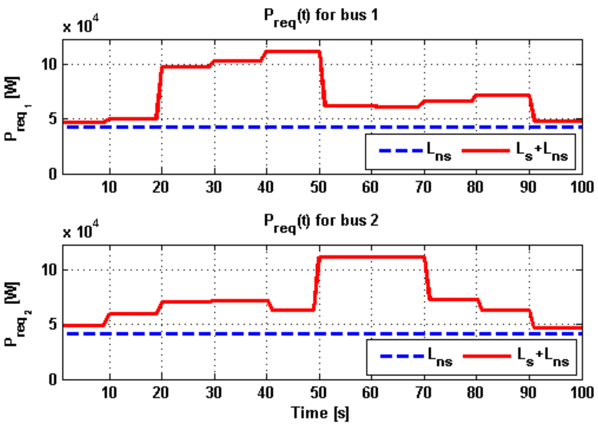
$$c_{ji}(t) = \{0, 1\} \qquad j = 1, ..., N^b \quad \forall \; i \in I_j^s$$

$$\alpha_i(t) = \{0, 1\} \qquad i = 1, ..., N^s$$

$$SoC_j(t+1) = SoC_j(t) + \beta_j(t) \qquad j = 1, ..., N^b$$

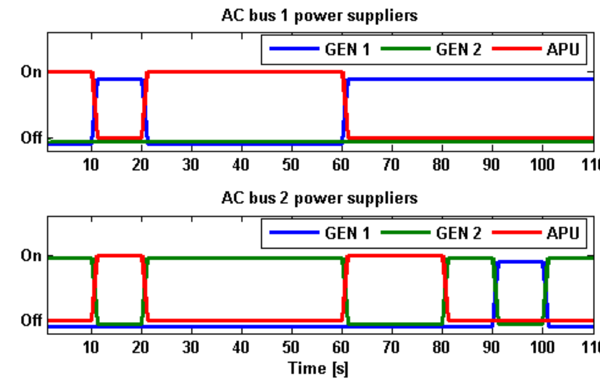
$$SoC_j(t) \geq SoC_j^{min} \quad j = 1, ..., N^b$$

Simulation Results

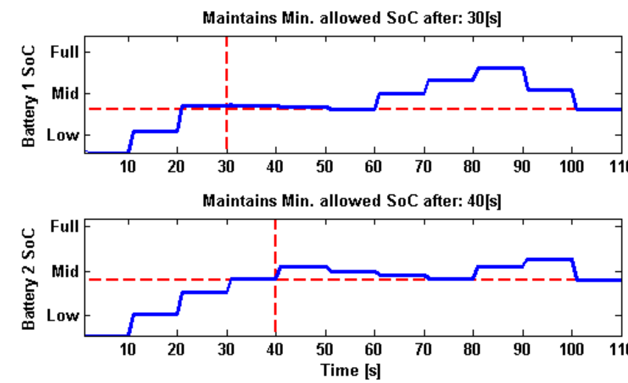


Max Power of Engine 1: 1e5
Max Power of Engine 1: 1e5
Max Power of APU : 104e3

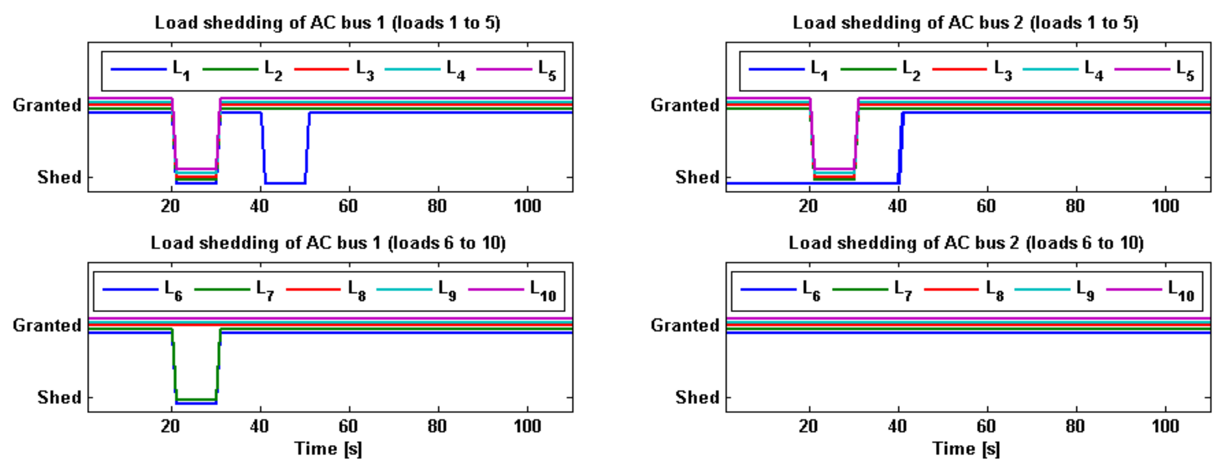
Power source allocation to AC bus 1 and 2.



State of Charge for battery set 1 and 2.



Load shedding for AC bus 1 and 2.



Thank You!

Questions?