CLEAN ENERGY SYSTEMS
INTEGRATION LAB

WASHINGTON STATE UNIVERSITY

Micro-grid Optimization

- Dr. Dustin McLarty

ESIC Seminar Series 10-23-18

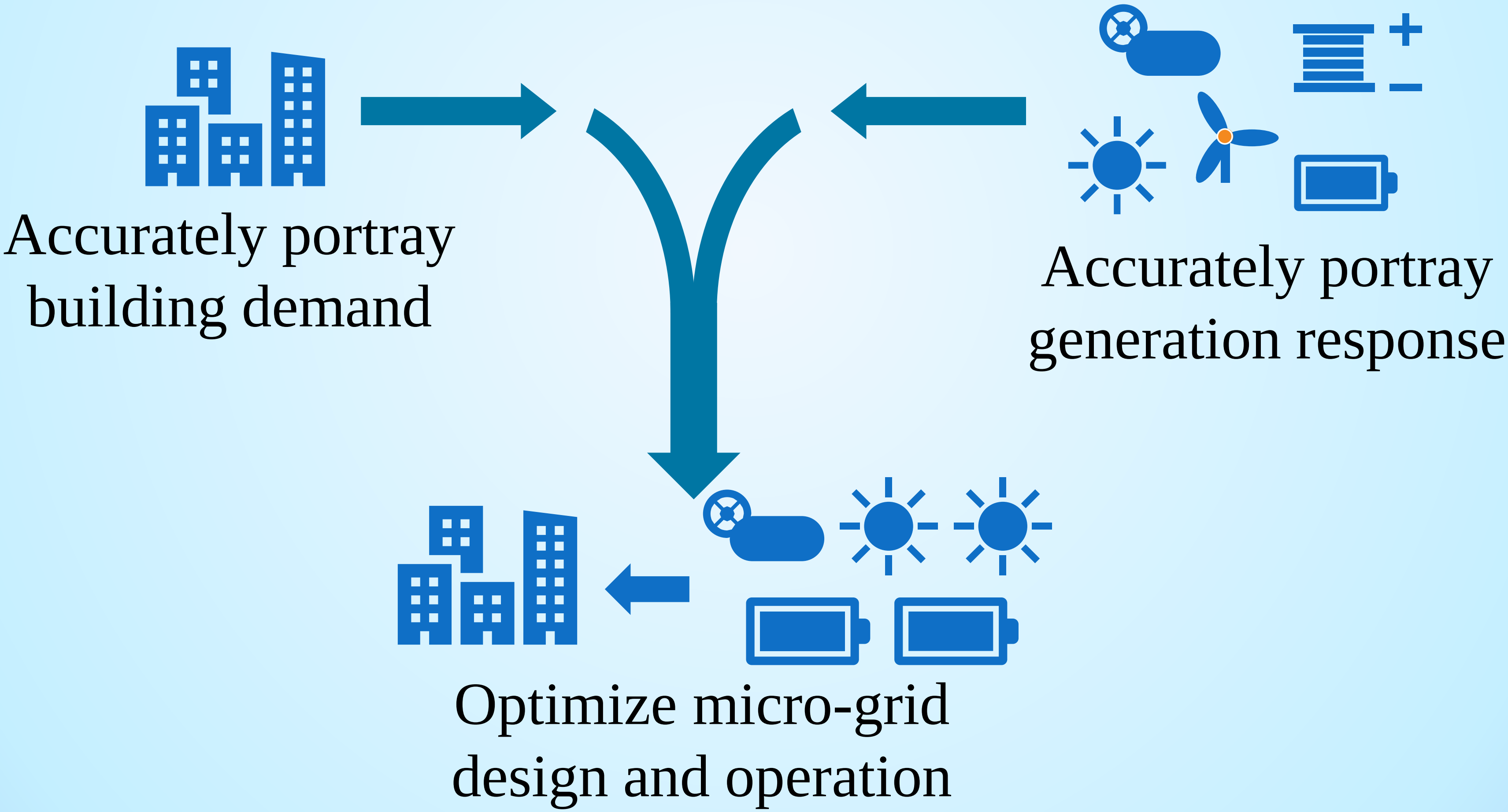
Washington State University

Why micro-grids?

- Campus heating & cooling
- Reliability
- Resilience
- Cost
- Smart buildings
- Emissions
- Integration of on-site renewables
- Demand response
- New distributed generation technologies

Outline

How do we maximize the value of distributed energy resources?



Accurately portray building demand

Accurately portray generation response

Optimize micro-grid design and operation

Physical building modeling

Temperature / Humidity response

Cost

Local linearization of building response

Boiler / Chiller / Cooling Tower / CHP / Energy storage Optimization

Building HVAC

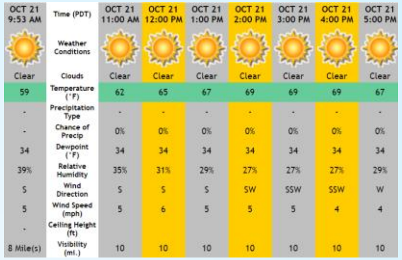
Outdoor air constraints

Air/water return loops

Are uncertainties less than auto-regressive errors?

Energy and mass balances: zones / surfaces / moisture

Incident solar

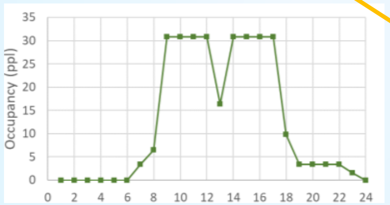


OCT 21 9:53 AM	Time (PDT)	OCT 21 11:00 AM	OCT 21 12:00 PM	OCT 21 1:00 PM	OCT 21 2:00 PM	OCT 21 3:00 PM	OCT 21 4:00 PM	OCT 21 5:00 PM
☀	Weather Conditions	☀	☀	☀	☀	☀	☀	☀
Clear	Clouds	Clear	Clear	Clear	Clear	Clear	Clear	Clear
59	Temperature (°F)	62	65	67	69	69	69	67
-	Precipitation Type	-	-	-	-	-	-	-
-	Chance of Precip	0%	0%	0%	0%	0%	0%	0%
34	Dewpoint (°F)	34	34	34	34	34	34	34
39%	Relative Humidity	35%	31%	29%	27%	27%	27%	29%
S	Wind Direction	S	S	S	SW	SSW	SSW	W
5	Wind Speed (mph)	5	6	5	5	5	4	4
-	Ceiling Height (ft)							
8 Mile(s)	Visibility (mi.)	10	10	10	10	10	10	10

Ambient Conditions

Orientation

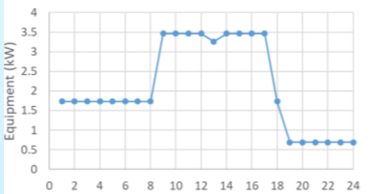
Occupancy schedules



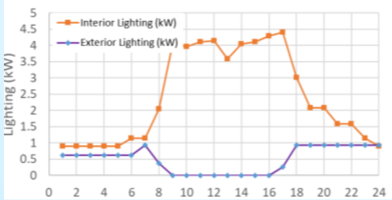
HVAC air supply conditions

Materials

Dimensions



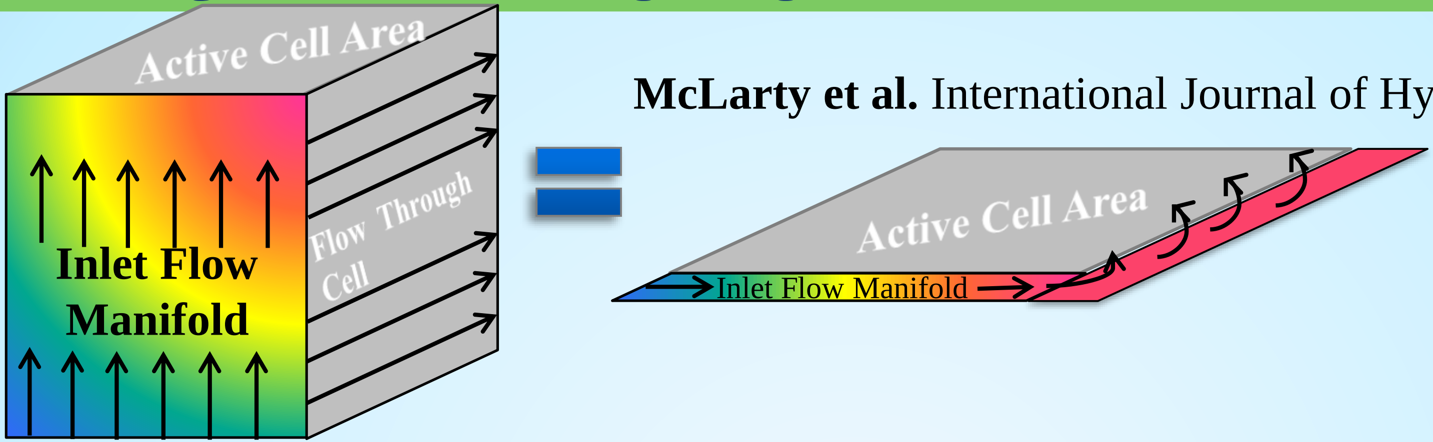
Equipment schedules

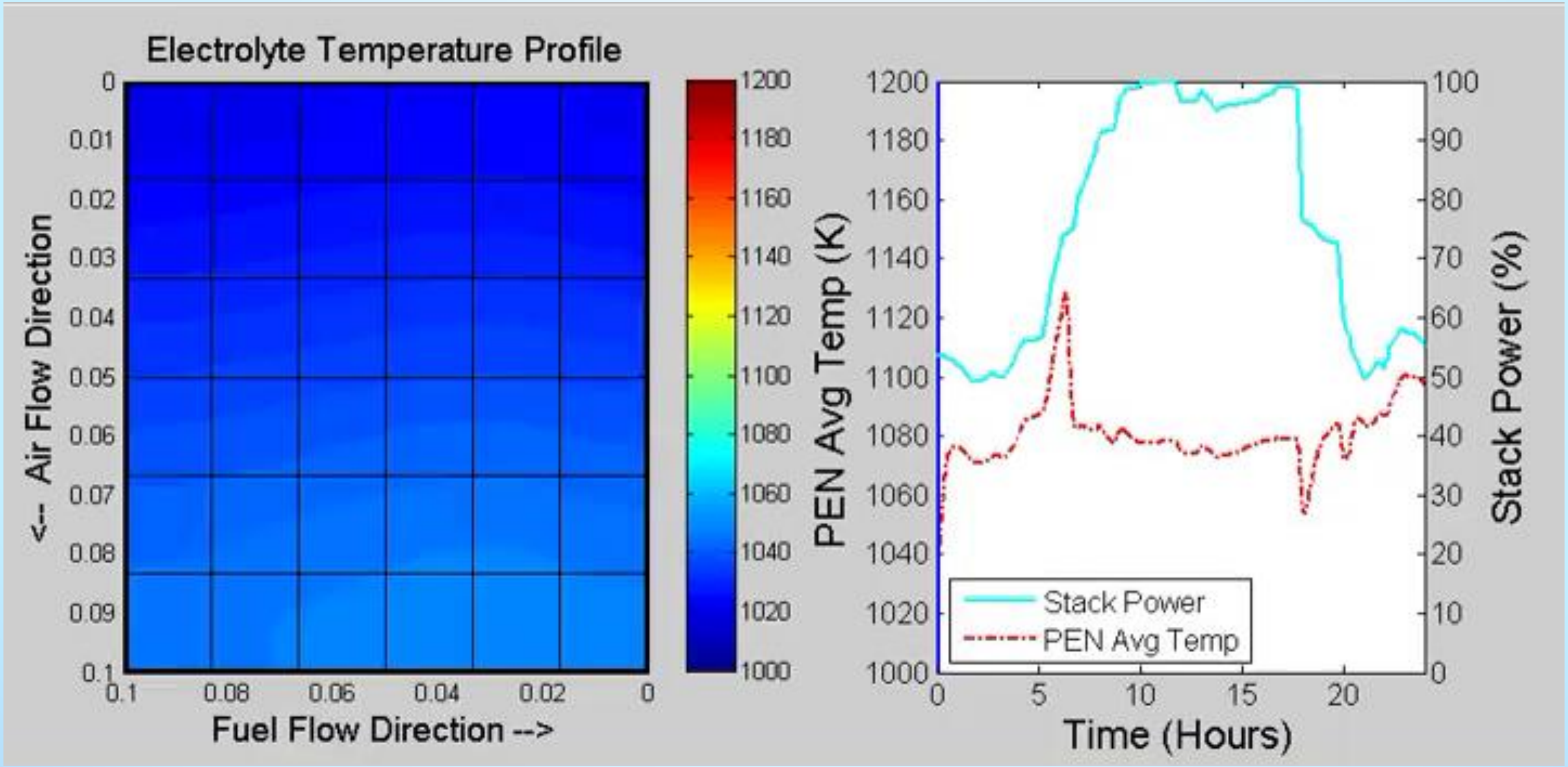


Lighting schedules

Physical Equipment Modeling

McLarty et al. International Journal of Hydrogen Energy 2013





Multiple Time-Scales

Forecast

- Temperature
- Loads
- Utilities

24 Hours

Dispatch

- Generators
- Heaters/Chillers
- Energy Storage

24 Hours

Threshold

- Time
- Demand
- SOC

15 min to 1 Hour

Control

- Re-optimize DER
- Adjust generator set-points
- Apply MPC

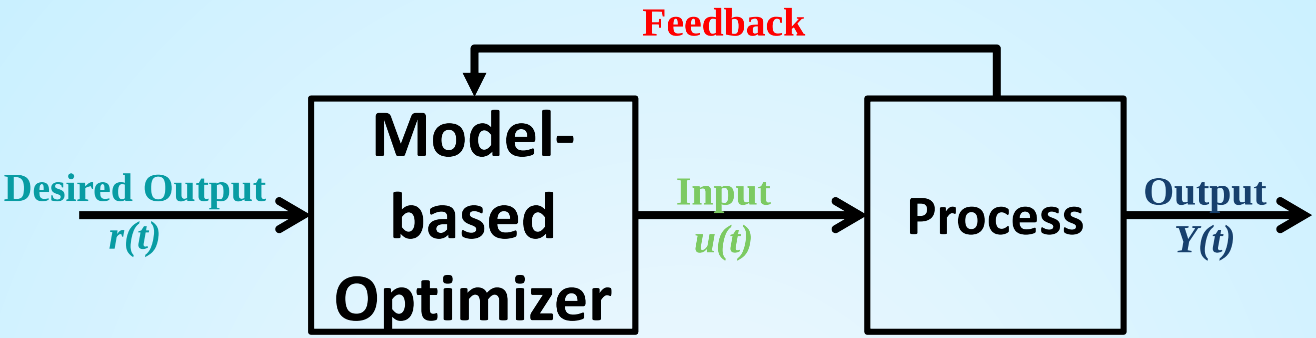
60 Seconds , 1 sec

Balance

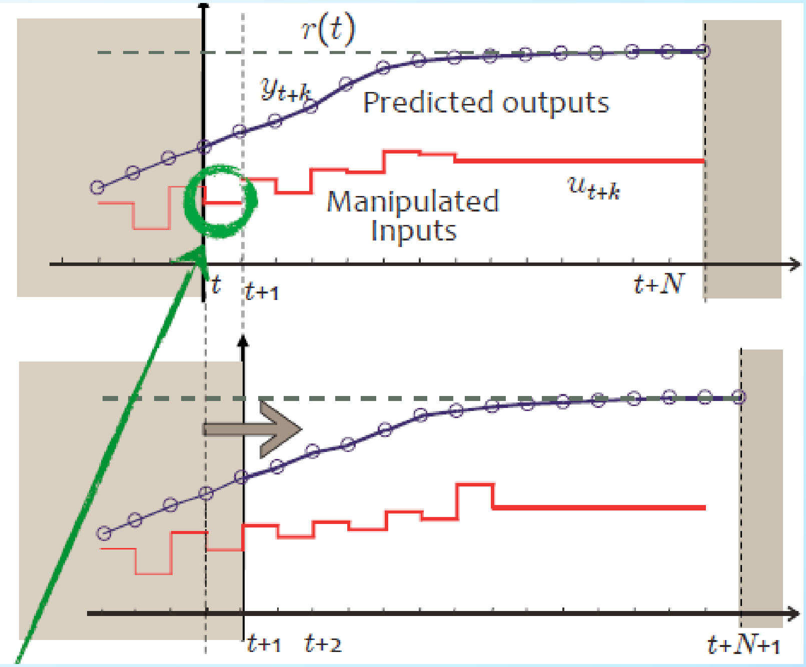
- Distribute un-met load between grid and ES

<1 sec

Overview of MPC



- **MPC:** Uses a DYNAMIC model to PREDICT the future response of the plant and OPTIMIZE the control signal
- **Receding Horizon:** solve an **optimal control** problem over a finite future horizon of *N* steps, and implement the control action of the 1st step



Apply 1st step only, then repeat optimization

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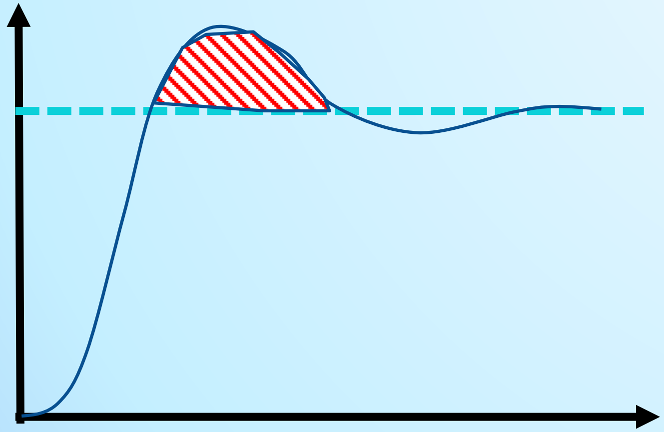
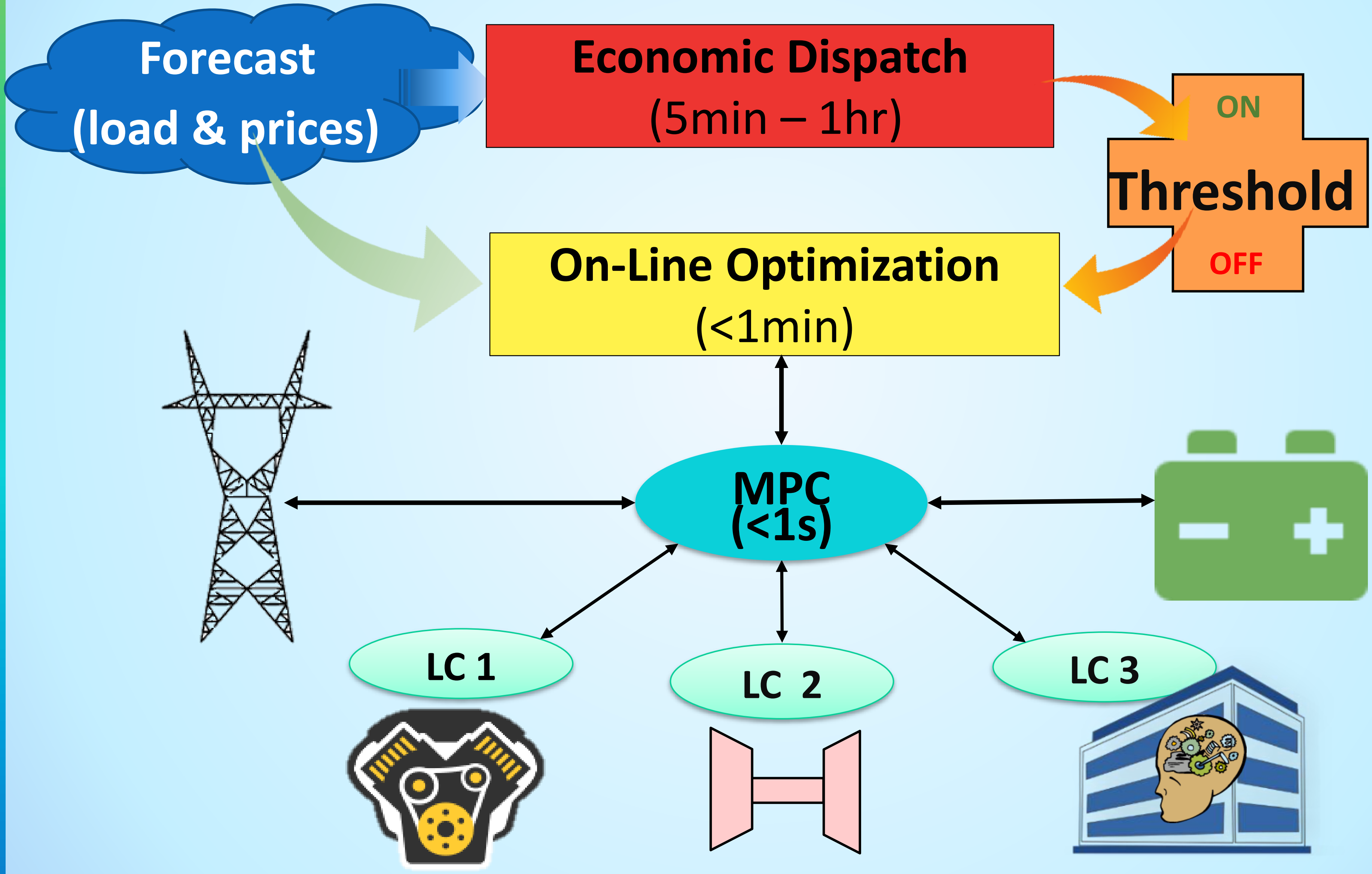
Constraint Handling

- An optimal input trajectory is only optimal if it satisfies constraints
  - MPC embeds constraints into the optimization
  - Most control strategies (e.g. PID, lead-lag) implement constraints through design & tuning (saturation, overshoot)
- Ex) Filling a tank with a PI control law
  - Good speed of response, good settling time…
  - Typically allow for 25% overshoot
  - What if we are trying keep the tank full near its maximum constraint?



- **Predictive control will NOT propose a trajectory which allows the tank to overflow**
- **Nor will it allow an input that is not stabilisable before the constraint is reached**
- **The rise time might be slower, but it will be safe**
- **Works like auto-tuning maximum control input to the current operating point**

Hierarchal MPC Overview



Forecast
(load & prices)

Economic Dispatch
(5min – 1hr)

ON
Threshold
OFF

On-Line Optimization
(<1min)

MPC
(<1s)

LC 1

LC 2

LC 3

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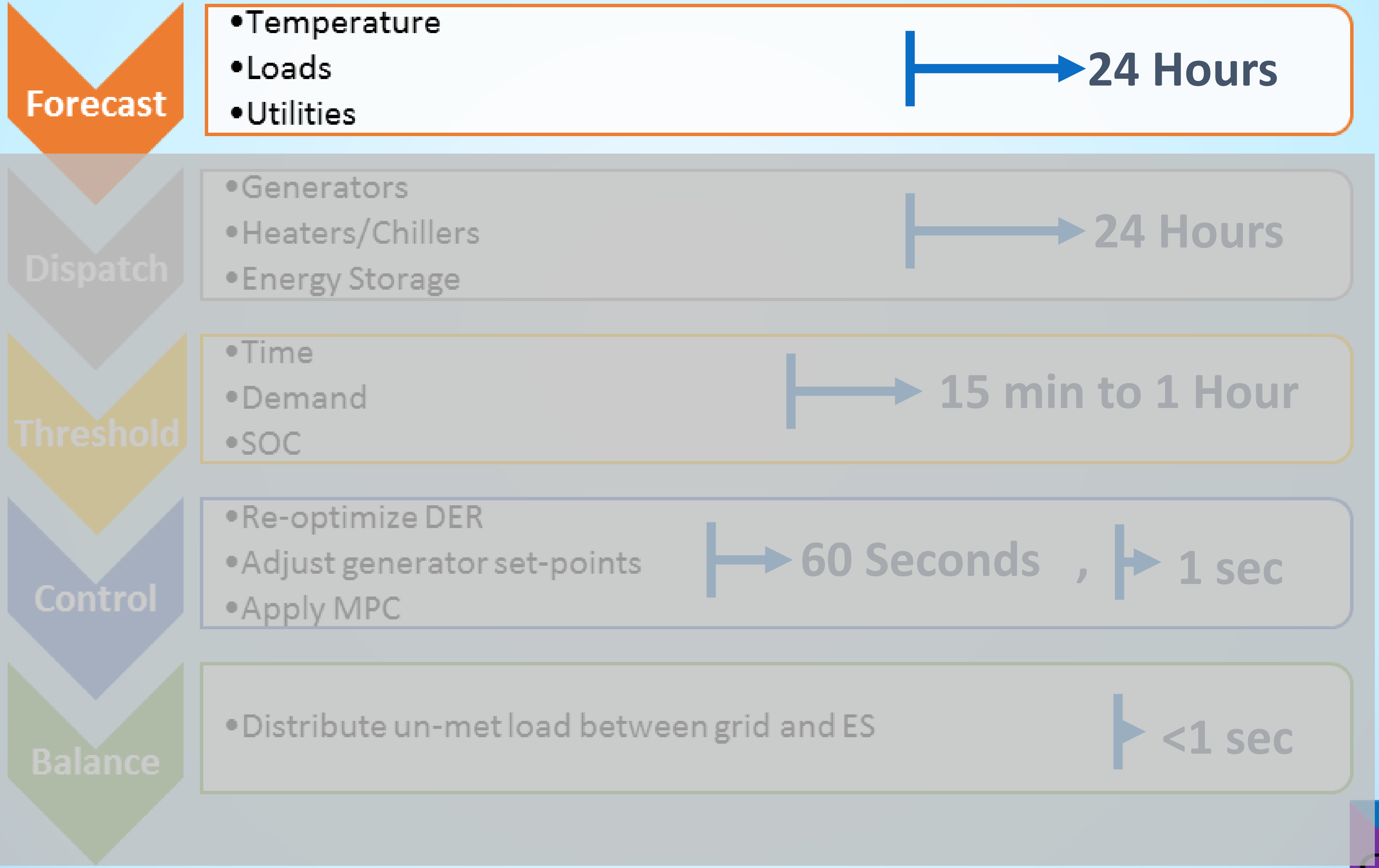
Multiple Time-Scales



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60 Seconds , 1 sec

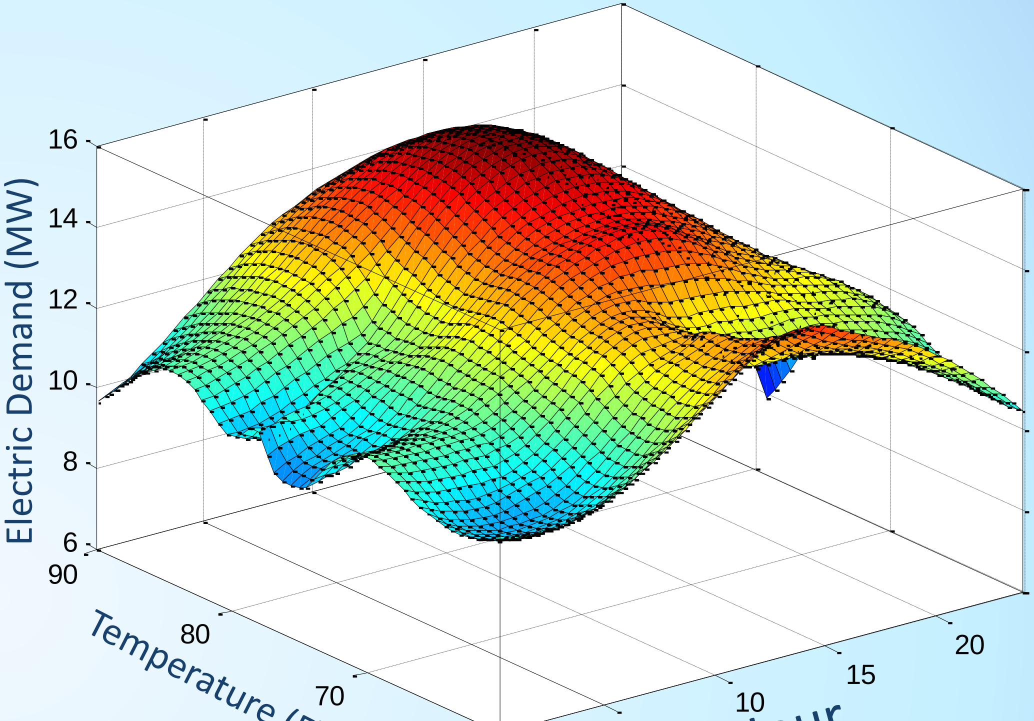
Balance

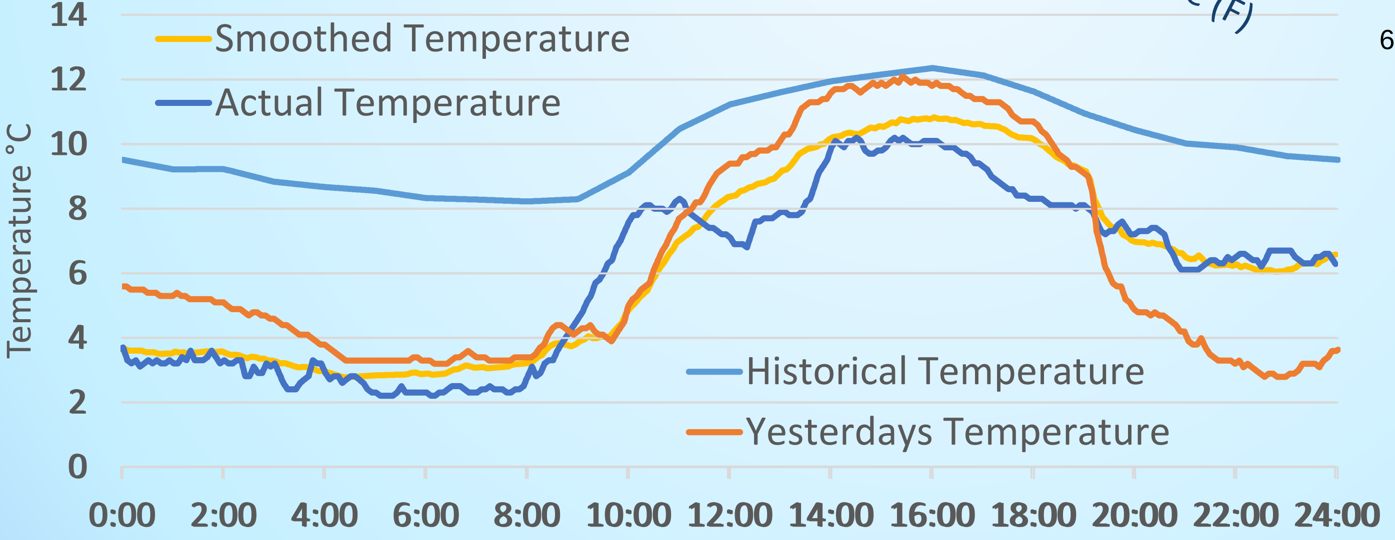
- Distribute un-met load between grid and ES

<1 sec

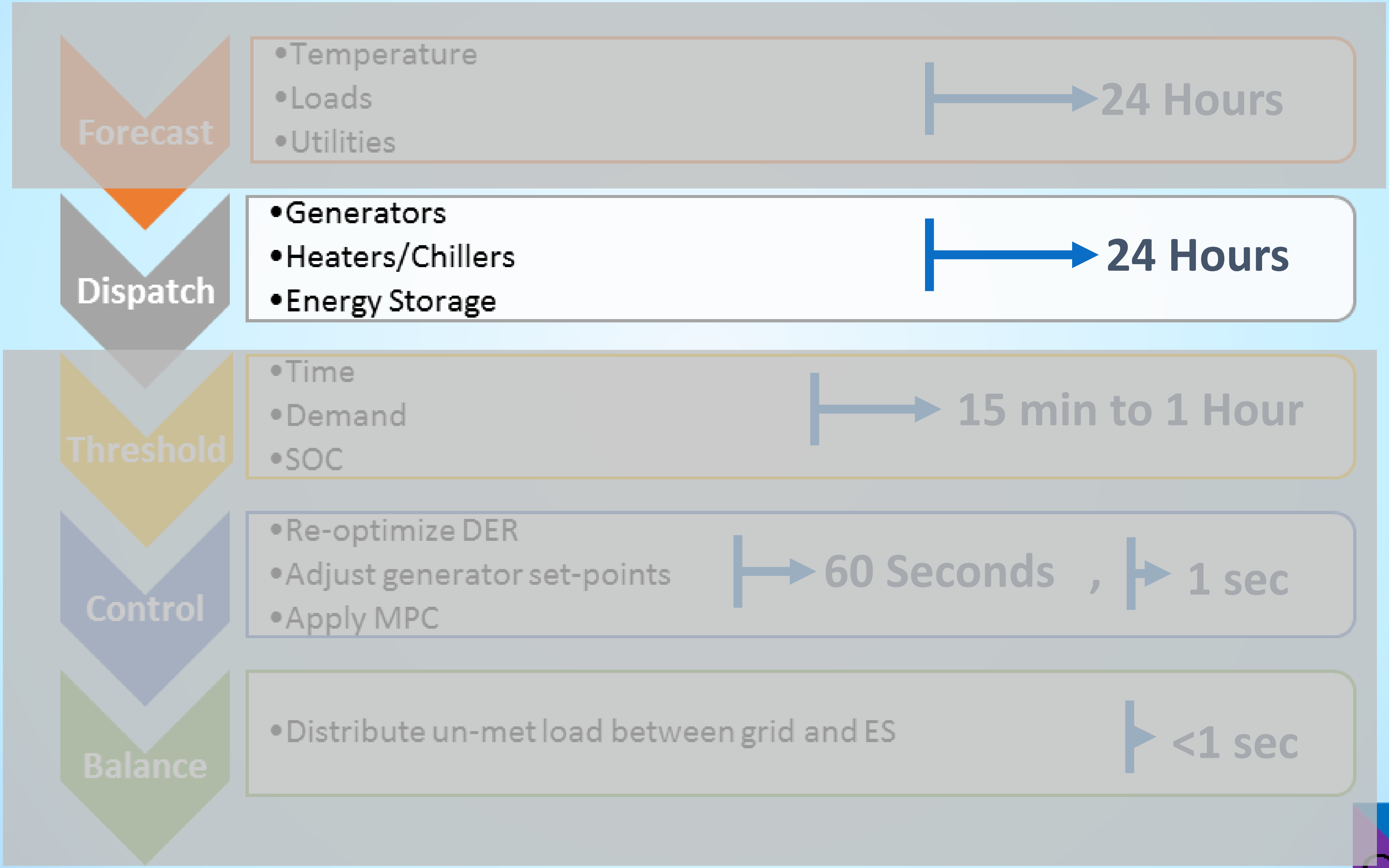
Forecast Methods

- » Physical modeling
- » Multi-dimensional modeling
- » Auto-regressive techniques





Multiple Time-Scales



Forecast
- Temperature
- Loads
- Utilities

⊢→ 24 Hours

Dispatch
- Generators
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⊢→ 24 Hours

Threshold
- Time
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- SOC

⊢→ 15 min to 1 Hour

Control
- Re-optimize DER
- Adjust generator set-points
- Apply MPC

⊢→ 60 Seconds , ⊢→ 1 sec

Balance
- Distribute un-met load between grid and ES

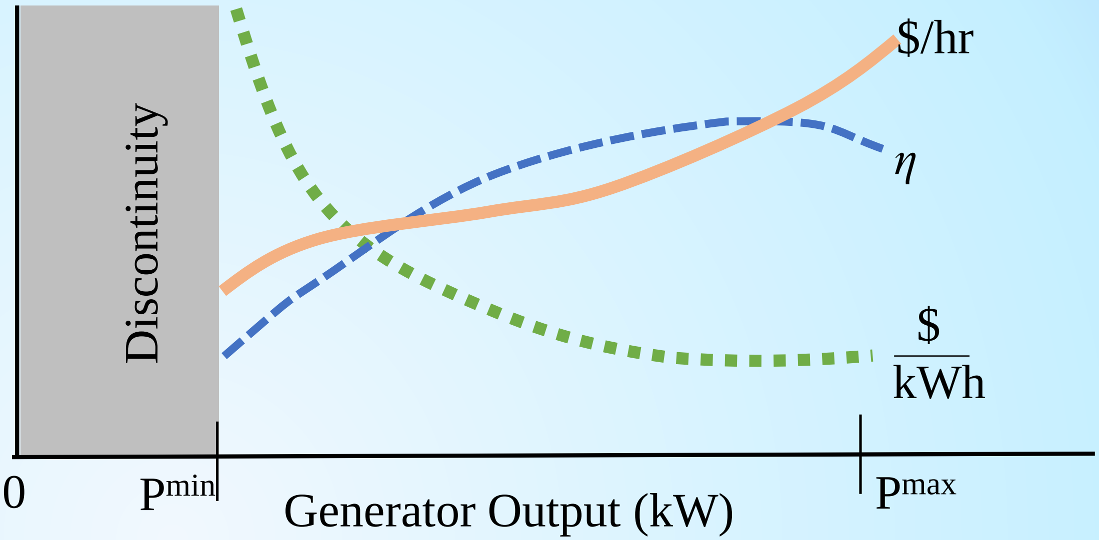
⊢→ <1 sec

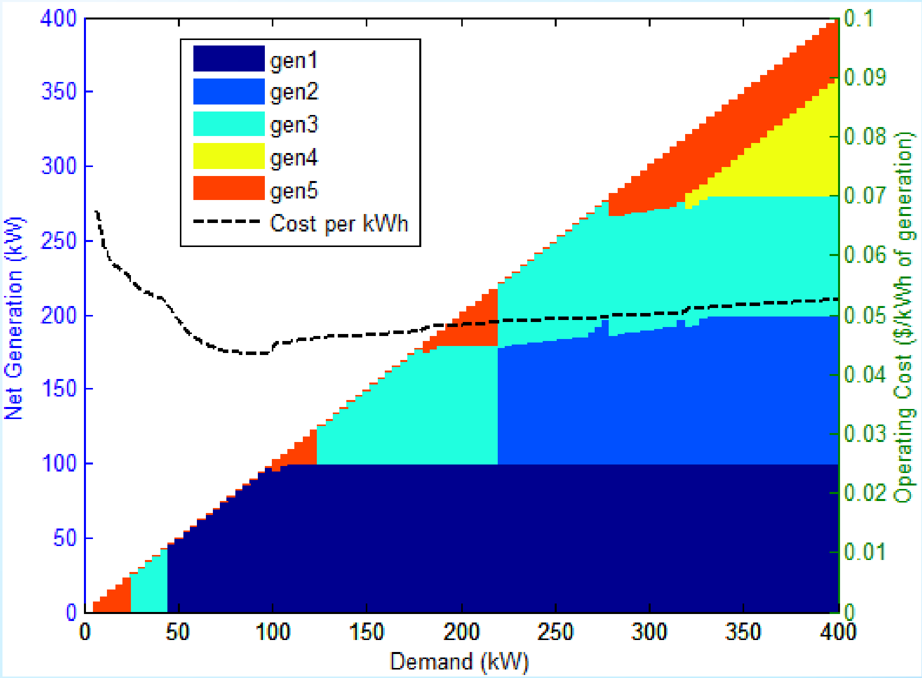
Ten Micro-grid Dispatch Challenges

1. Non-linear equipment performance
2. Discrete states (on/off)
3. Energy storage: Electric, thermal, mechanical
4. Equipment start-up and response rates
5. Transmission limitations and losses
6. Integrated energy systems: heating + cooling + electric
7. Energy market participation
8. Resilient solutions: spinning/non-spinning reserve
9. Fast solutions
10. Benchmarking solution speed and robustness

1. Non-Linear equipment performance

- The efficiency of a generator, chiller, or boiler is not constant
- Efficiency may depend on external factors
  - Humidity, air temperature, cooling tower return water temperature
- Operation window may not be continuous from off to full power
- ‘Instantaneous’ optimal map solves for lowest net cost to produce ___kW of power





2. Discrete equipment states (on/off)

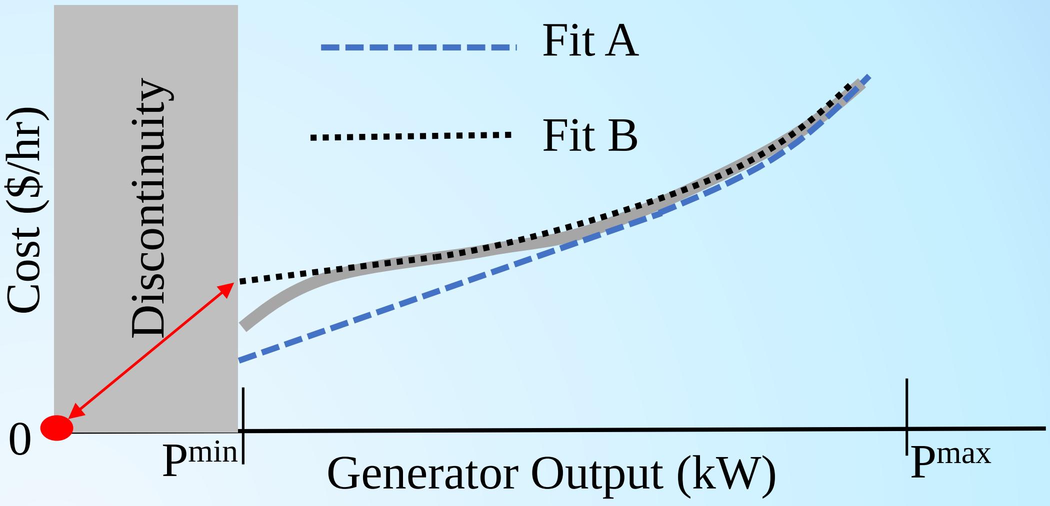
- A piecewise quadratic fit can approximate as convex function

$$Cost_k = F\left(P_{gen}\right) = a_0 + \sum_{j=1}^{m}\left\{a_j \cdot S_j + b_j \cdot S_j^2\right\}$$

- But.... enforcing operating limits requires a binary constraint

$$U_k \cdot P^{min} \leq P_k \leq U_k \cdot P^{max}$$

- Mixed-integer problem: 2^G
  - Even system of only 3 generators has 8 possible configurations



Gen# Combo	1	2	3
1	On	Off	Off
2	Off	On	Off
3	Off	Off	On
4	On	On	Off
5	Off	On	On
6	On	Off	On
7	On	On	On
8	Off	Off	Off

3. Energy Storage

Combo \ Gen#	1	2	3
1	On	Off	Off
2	Off	On	Off
3	Off	Off	On

Combo \ Gen#	1	2	3
1	On	Off	Off
2	Off	On	Off
3	Off	Off	On
4	On	On	Off
5	Off	On	On
6	On	Off	On
7	On	On	On
8	Off	Off	Off

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7	On	On	On
8	Off	Off	Off

» Instantaneous value of stored energy?

- > marginal utility at any and all future times
- > Thermal storage can provide ‘value’ to electric dispatch

» Links together time-steps increases mixed-integer problem: $2^{G \cdot N}$

- > 3 generators @ 24 hourly intervals has $4.7\mathrm{x}10^{21}$ possible configurations

» Charging/Discharging efficiency

$$P_k = -\frac{\{SOC_k - SOC_{k-1}\} \cdot \eta_d}{\Delta t_k} - \phi_k$$

$$\phi_k \geq \frac{\{SOC_k - SOC_{k-1}\}}{\Delta t_k} \cdot \left(\frac{1}{\eta_c} - \eta_d\right)$$

$$\& \;\; \phi_k \geq 0$$

» Self-discharging losses

- > Fixed rate (κ) and proportional to state-of-charge (κ^*)

$$P_k = -\frac{\{SOC_k - (1 - \kappa^* \cdot \Delta t_k) \cdot SOC_{k-1} - \kappa\} \cdot \eta_d}{\Delta t_k} - \phi_k$$

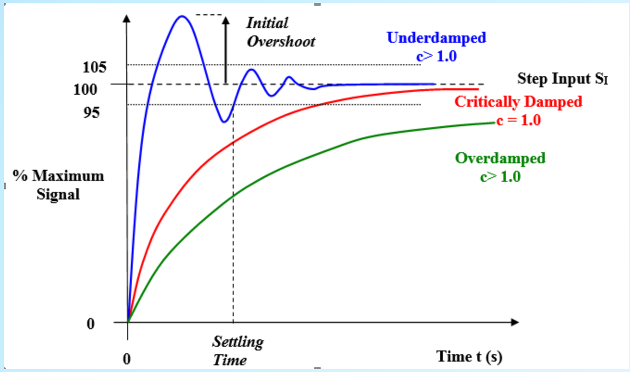
» End of horizon constraint

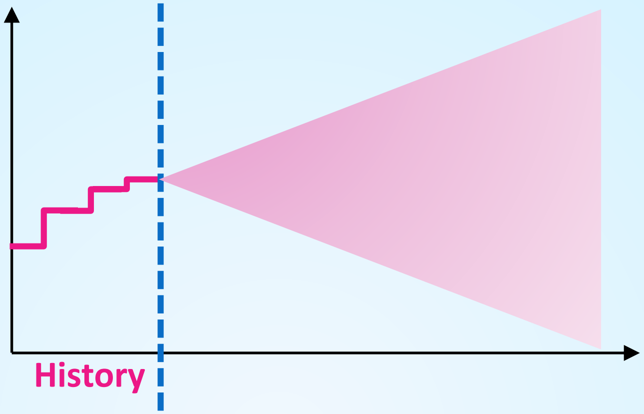
- > Fixed at a value, e.g. 50% $SOC_N = 50\%$
- > Equal to current status, i.e. zero net charge $SOC_N = SOC_0$
- > Floating value

$$F(SOC_N) = a_1 \cdot SOC_N + \frac{1}{2} a_2 \cdot {SOC_N}^2$$

4. Equipment response & startup

- Full range, P^{min} to P^{max}, not always available





$$|P_k - P_{k-1}| \leq r^{\max} \cdot \Delta t_k$$

- Like energy storage, this constraint links time-steps
- Start-up: extra fuel, wear and tear results in additional cost
  - Also links time-steps and requires binary variable

$$F(U) = \sum_{k=1}^{N} C_{start} \cdot (U_k > 0 \ \ \& \ U_{k-1} = 0)$$

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5. Transmission: DC Power Flow

- Known line energy flow direction:
  - Losses are fixed, ζ, or proportional, ξ, to energy transfer
  - Loss terms are 0, -1 in sending node energy balance

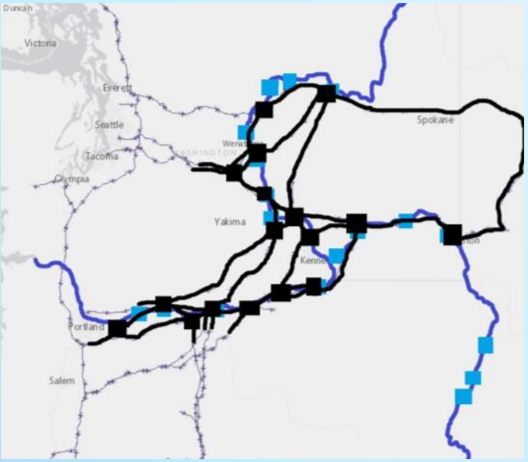
$$\forall j,k \quad \left\{\sum_{i=1}^{G_j} P_i + \sum_{r=1}^{S_j} (P_r - \phi_r) + \sum_{l=1}^{T_j} \xi \cdot P_l - \zeta\right\}_k = L_{j,k}$$

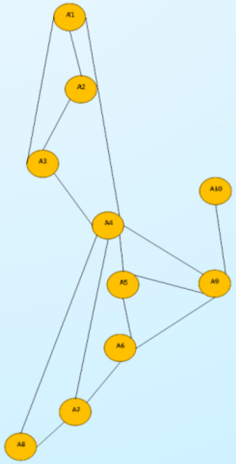
- Unknown energy flow direction:

$$\forall j,k \quad \left\{\sum_{i=1}^{G_j} P_i + \sum_{r=1}^{S_j} (P_r - \phi_r) + \sum_{l=1}^{T_j} (P_l - \sigma_{\leftrightarrow})\right\}_k = L_{j,k}$$

$$\sigma_{\rightarrow} \geq P_l \cdot (1 - \eta_{\rightarrow}) \quad \& \quad \sigma_{\rightarrow} \geq 0$$

$$\sigma_{\leftarrow} \geq P_l \cdot (1 - \eta_{\leftarrow}) \quad \& \quad \sigma_{\leftarrow} \geq 0$$





- District heat or river network has known flow direction
- Electric Network has unknown flow direction

5b. Transmission: AC Power Flow

- Apparent Power: $S = \max(V) \cdot \max(I)$
- Real Power: $P = S \cdot \cos(\theta)$
- Reactive Power: $Q = S \cdot \sin(\theta)$
- Power Flow Equations:

$$P_i = \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\cos(\theta_{ik}) + B_{ik}\sin(\theta_{ik}))$$

$$Q_i = \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\sin(\theta_{ik}) - B_{ik}\cos(\theta_{ik}))$$

- Become the power flow constraints:

$$P_m = G_{mm}x_m + \sum_{n=1,n\neq m}^{N} G_{mn}y_{mn} + B_{mn}z_{mn}$$

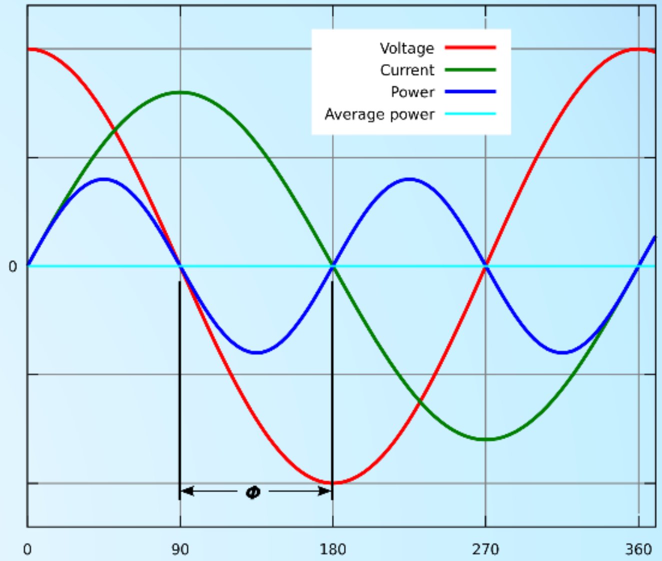
$$Q_m = -B_{mm}x_m - \sum_{n=1,n\neq m}^{N} B_{mn}y_{mn} - G_{mn}z_{mn}$$

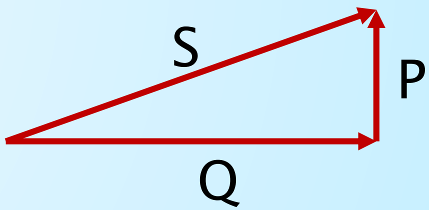
- Voltage and line current:

$$v_{m_{min}}^2 \leq x_m \leq v_{m_{max}}^2$$

$$(G_{mn}^2 + B_{mn}^2)(x_m + x_n - 2y_{mn}) \leq I_{nm_{max}}^2$$

- Unit commitment: $U_k \cdot S_n^{min^2} \leq P_n^2 + Q_n^2 \leq U_k \cdot S_n^{max^2}$





Voltage stability constraints, and line current constraints, assume fixed transformer tap settings

6. Integrated energy

» Heating

- Related to electric problem through CHP and building energy balance

$$\forall k \quad \left\{\sum_{i=1}^{CHP} \varepsilon\left(\frac{1-\eta}{\eta}\right) P_i + \sum_{m=1}^{nH} H_i + \sum_{r=1}^{TS} (H_r - \phi_r) + \sum_{l=1}^{DH} \xi H_l - \sum_{b=1}^{B} \bar{H}_b - H_{loss}\right\}_k = \sum_{b=1}^{B} H_{0_b}$$

$$Cost\colon\ F(H_k) = U_k\left(a_0 + \sum_{j=1}^{m}\{a_j \cdot H_j + b_j \cdot H_j^2\}\right)$$

$$U_k \cdot H^{\min} \leq H_k \leq U_k \cdot H^{max}$$

» Cooling & Cooling Tower Loop

- Related to electric problem through power consumption of electric chillers and cooling tower fans

$$\forall k \quad \left\{\sum_{i=1}^{Chiller} C_i + \sum_{r=1}^{TS} (C_r - \phi_r) + \sum_{l=1}^{DC} \xi C_l - C_{loss}\right\}_k = \sum_{b=1}^{B} C_b$$

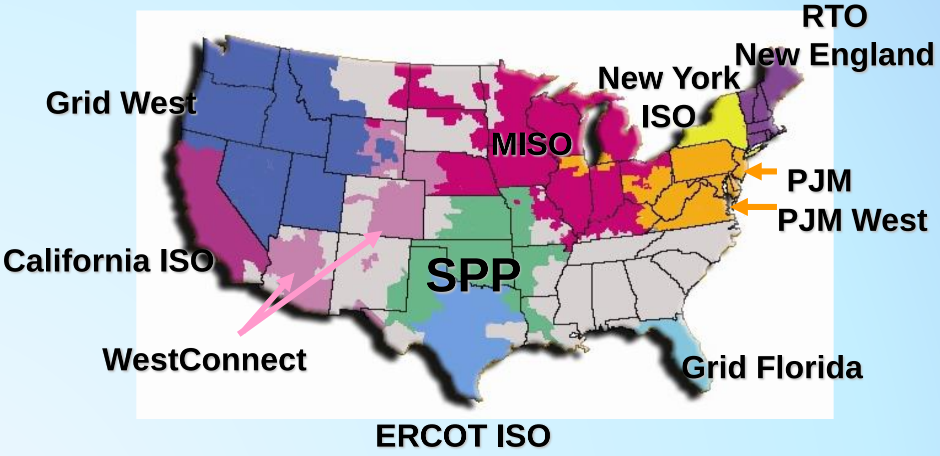
$$E(C_i)_k = U_k\left(a_0 + \sum_{j=1}^{m}\{a_j \cdot C_j + b_j \cdot C_j^2\}\right) + \lambda_i(WT_k - WT_{set})$$

$$U_k \cdot C^{\min} \leq C_k \leq U_k \cdot C^{max}$$

$$E(HR_f)_k = \sum\nolimits_{j=1}^{m}\{\alpha_j \cdot S_{j,k}\} - \lambda_f(WT_k - WT_{set})$$

$$WT_k = WT_{k-1} + \frac{\Delta t}{Cap_{coolLoop}} \cdot \left\{\sum_{i=1}^{Chiller} (C_i)_k + E(C_i)_k - \sum_{i=f}^{CT} (HR_f)_k\right\}$$

7. Energy Market Participation



- How will DER participate?
  - Differences in bidding/settlement between markets
  - Contract Options:
    - Like DR, fixed pre-negotiated commitment
  - Bidding options:
    - Day-ahead, hour-ahead
  - Regulation market?
- How do you optimize your participation?
  - Forecast LMP?
  - Bid only after meeting self reserve requirements?
  - Biding flexible capacity (storage)?

$$F(MC_{bid})_k = \beta \cdot LMP_k$$

LMP = System Energy Price + Transmission Congestion Cost + Cost of Marginal Losses

- Meeting your firm commitment

$$\forall k \quad \left\{ \sum_{i=1}^{G} P_i + P_{grid} + \sum_{r=1}^{S} (P_r - \phi_r) - \sum_{i=1}^{Chiller} E(C_i)_k - \sum_{f=1}^{CT} E(HR_f)_k - (MC_{commit} + MC_{bid})_k \right\}_k = L_k$$

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8. Spinning and non-spinning reserve

- Cumulative spare capacity must exceed requirements

$$\sum_{i=1}^{G} SR_i + \sum_{r}^{S} SR_r + \sum_{b}^{B} DR_b \geq SR_{target} + MR_{committed} + MR_{bid}$$

- Each type of equipment has reserve constraints

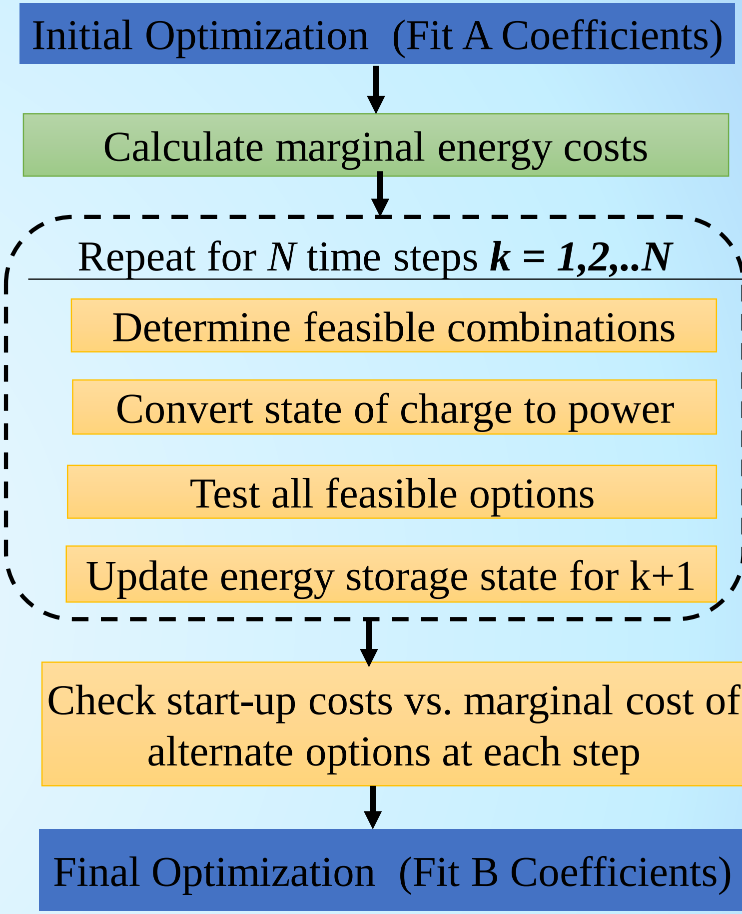
$$(SR_i)_k \leq (P_i)_{k-1} - (P_i)_k + {r_i}^{max} \cdot \Delta t_k \qquad (SR_r)_k \leq (SOC_r)_{k-1} \cdot \eta_d / \Delta t_k$$

$$(SR_i)_k \leq {P_i}^{max} - (P_i)_k \qquad (SR_r)_k \leq {P_r}^{max} - \frac{\{(SOC_r)_k - (SOC_r)_{k-1}\} \cdot \eta_d}{\Delta t_k}$$

- How to avoid double counting battery ‘reserves’?
  - Can you double count energy storage reserves?
  - What is the probability at any moment that the reserve capacity is used?
  - Which reserves do you use first: generation or storage?

$$\forall k \quad \sum_{t=k}^{N} (SR_r)_k \cdot \Delta t_k < (SOC_r)_k \cdot \eta_d$$

9. Fast Solutions



Initial Optimization (Fit A Coefficients)

Calculate marginal energy costs

Repeat for *N* time steps ***k* = *1,2,..N***

Determine feasible combinations

Convert state of charge to power

Test all feasible options

Update energy storage state for k+1

Check start-up costs vs. marginal cost of alternate options at each step

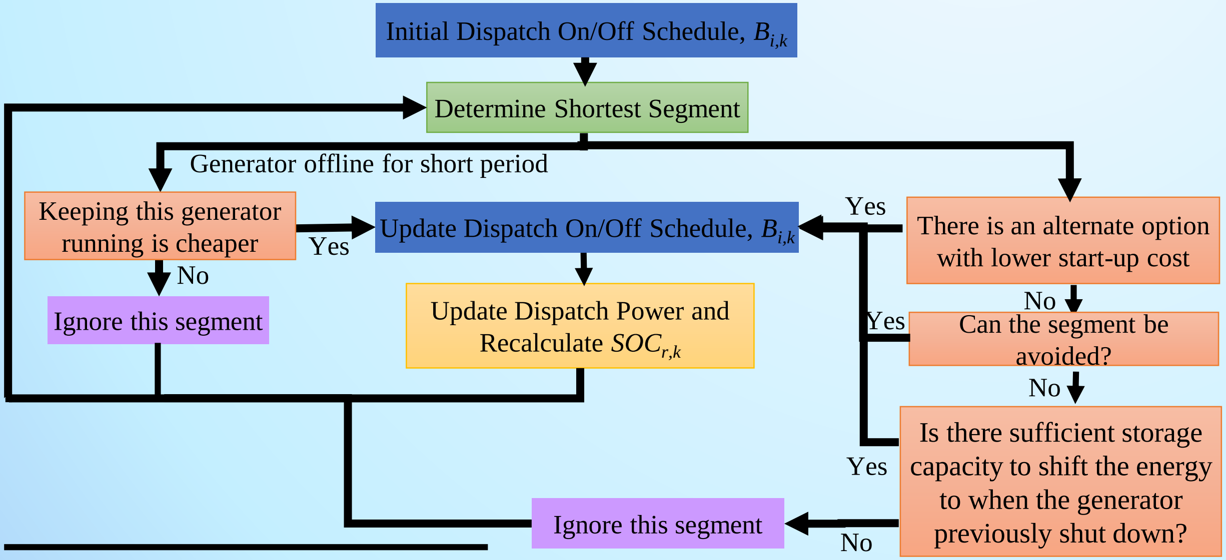
Final Optimization (Fit B Coefficients)

- Start with a simplified problem
  - No binary states
- Eliminate impossible solutions

$$\sum_{i=1}^{G}\{P_i{}^{min}\cdot B_{i,k}\} + P_{grid}{}^{min} + \sum_{r}^{S} P_r{}^{min} \le L_k - P_{unctrl_k}$$

$$\le \sum_{i=1}^{G}\{P_i{}^{max}\cdot B_{i,k}\} + P_{grid}{}^{max} + \sum_{r}^{S} P_r{}^{max}$$

- Solve the time steps independently
- Incorporate start-up costs



Initial Dispatch On/Off Schedule, $B_{i,k}$

Determine Shortest Segment

Generator offline for short period

Keeping this generator running is cheaper

Yes

No

Ignore this segment

Update Dispatch On/Off Schedule, $B_{i,k}$

Update Dispatch Power and Recalculate $SOC_{r,k}$

There is an alternate option with lower start-up cost

Yes

No

Can the segment be avoided?

Yes

No

Is there sufficient storage capacity to shift the energy to when the generator previously shut down?

Yes

No

Ignore this segment

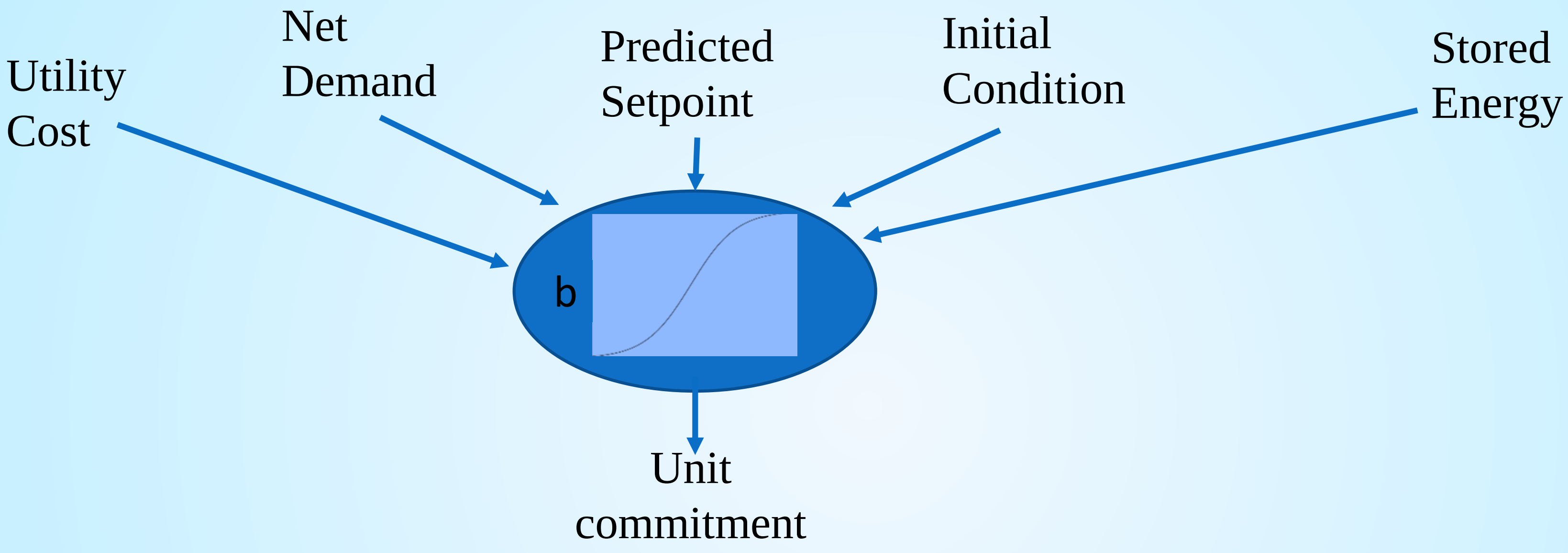
- Put all the pieces together

$$2^{N\cdot G} \rightarrow N\cdot 2^{G}$$

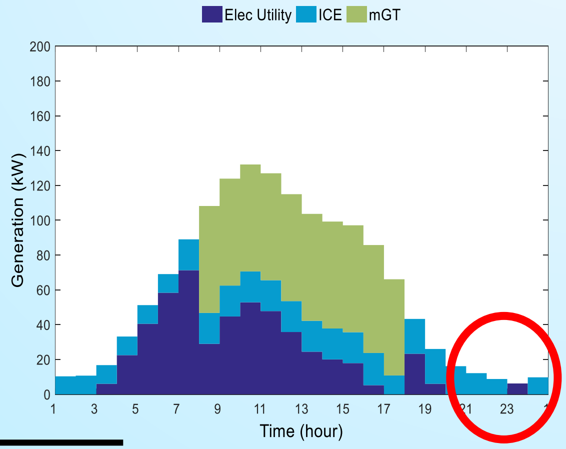
9b. Very Fast Solutions

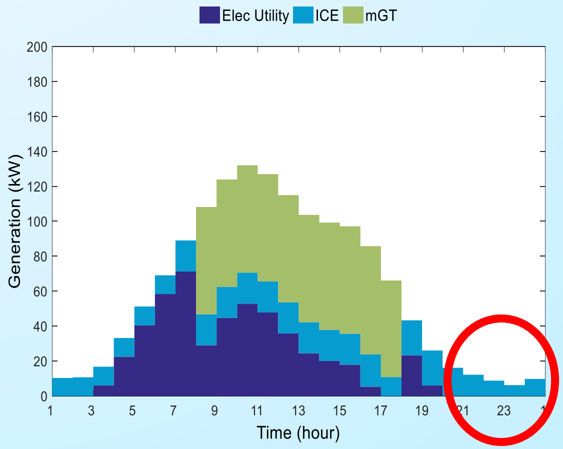
- Neural network

$$2^{N\cdot G} \rightarrow N\cdot 2^{G} \rightarrow 1$$



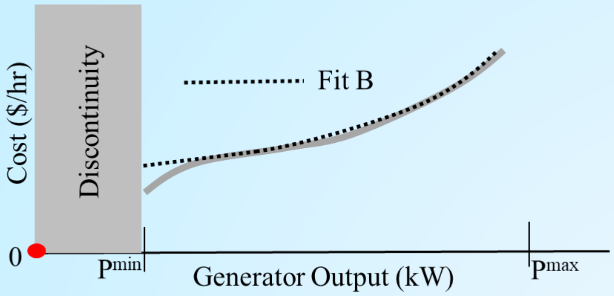
- Network training can implicitly improve robustness

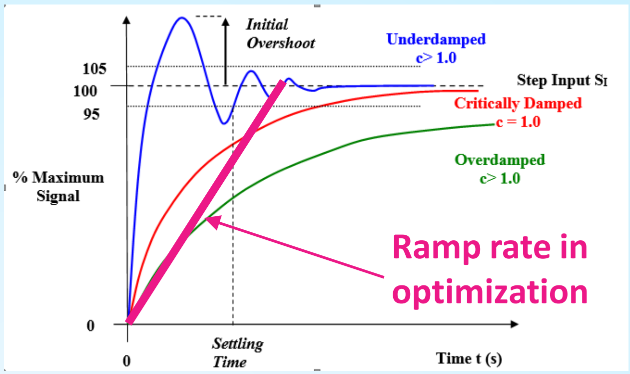




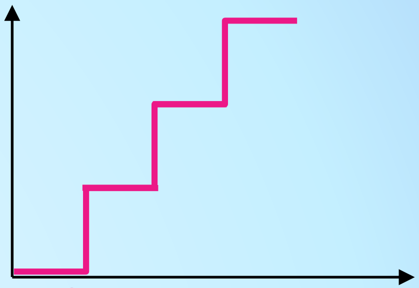
10. Benchmarking and robustness

- Modeling error



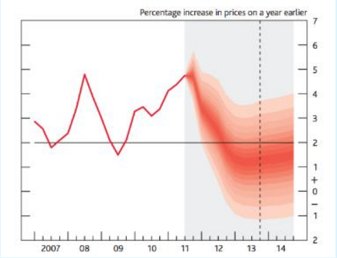


Ramp rate in optimization



What optimization sees

- Forecast uncertainty



- Disturbance rejection
  - OK to change plan 12+ hours from now
  - Less desirable to change plan 15 min from now

- Single-case optimal, or in-practice costs?

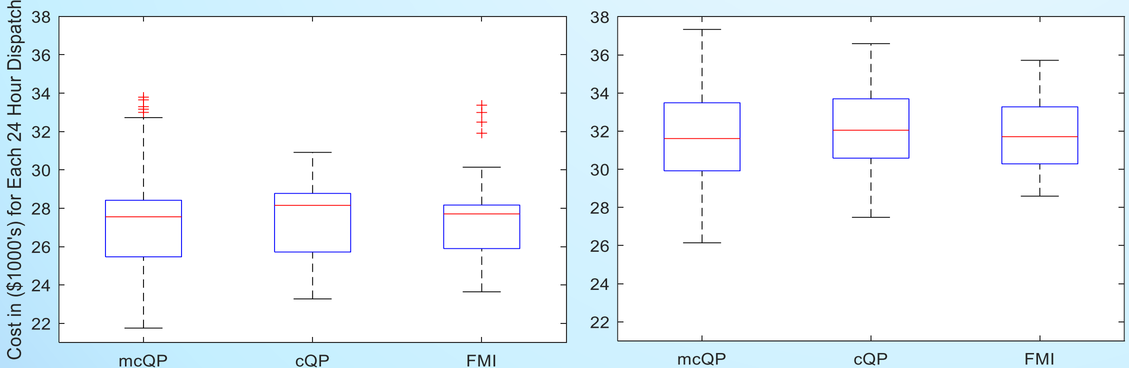
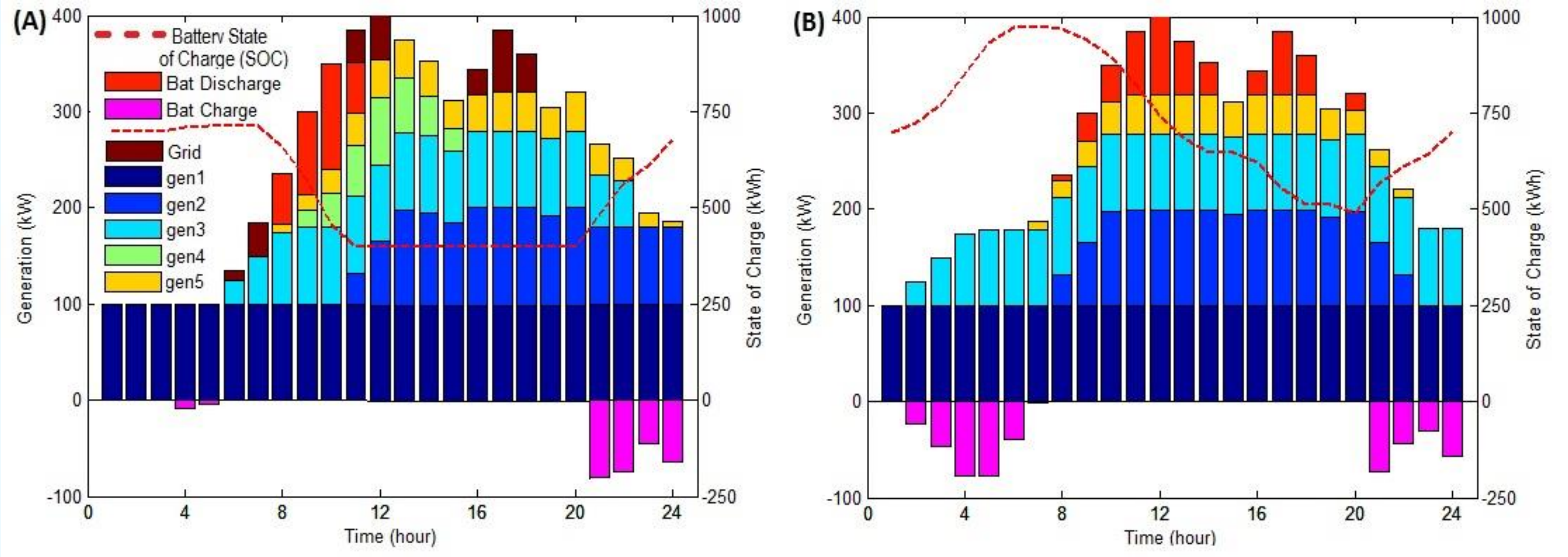


Figure: Distribution of operating costs for each optimization of the 24-hour horizon for winter (left) and summer (right). Identical initial conditions are used for solving the mcQP, cQP, and FMI methods. Red crosses indicate outliers which are data points farther than 2.7σ from the median.

Example: Solving the dispatch horizon



Feed-forward Approach

H-MPC Approach

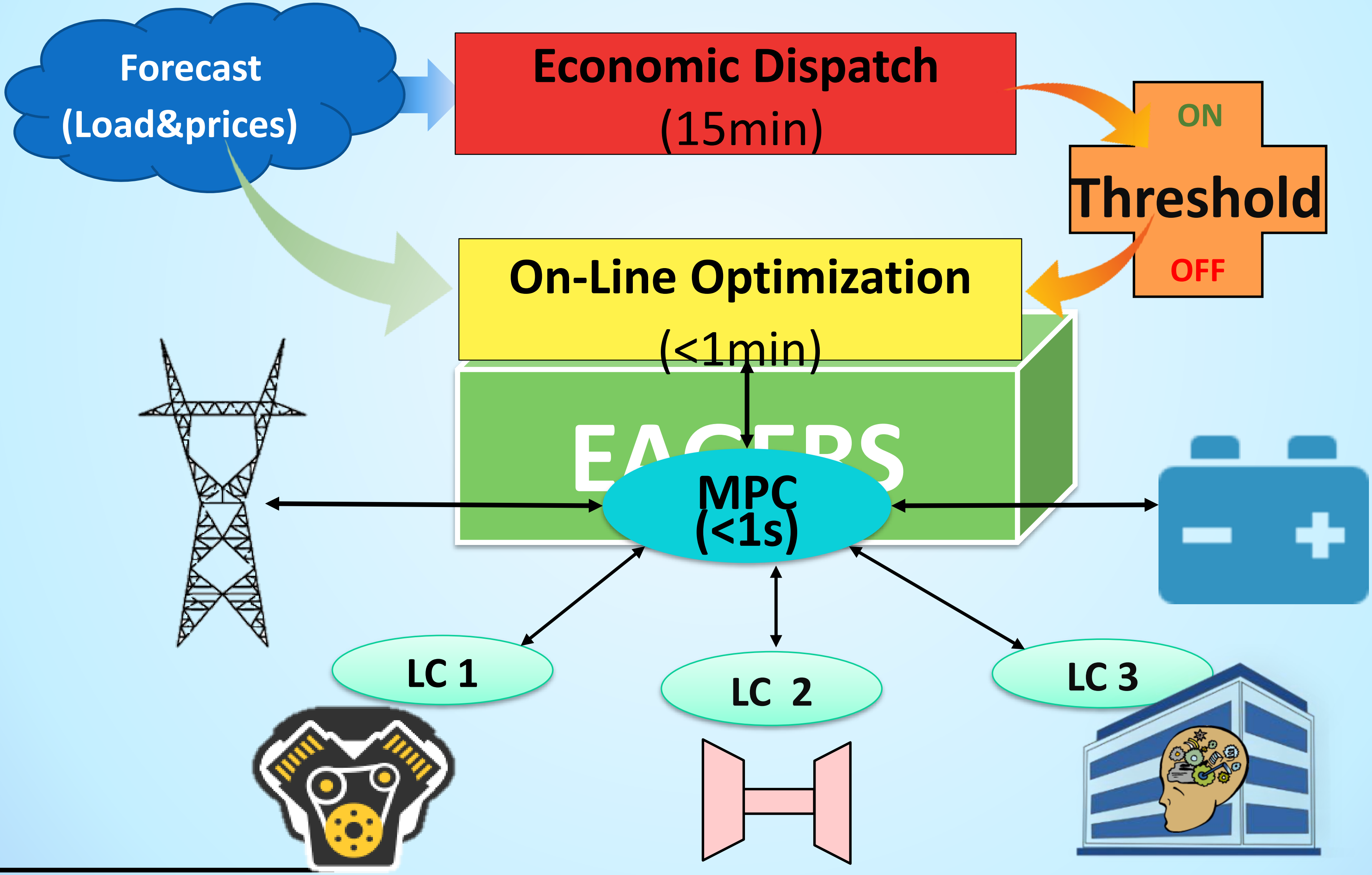
General Solution: 5 generators @1 hour resolution requires evaluating 1.33e+36 QP problems, each with 360 states

Feed-Forward Solution: Solve 32 optimizations with 15 states at each time step (24 hours = 768 total optimizations)

H-MPC Solution: solve 768 QP optimizations with 15 states plus 2 QP optimizations with 360 states.

Neural Network Solution: Solve 1 optimization after network determines unit commitment

Efficient Allocation of Grid Energy Resources including Storage



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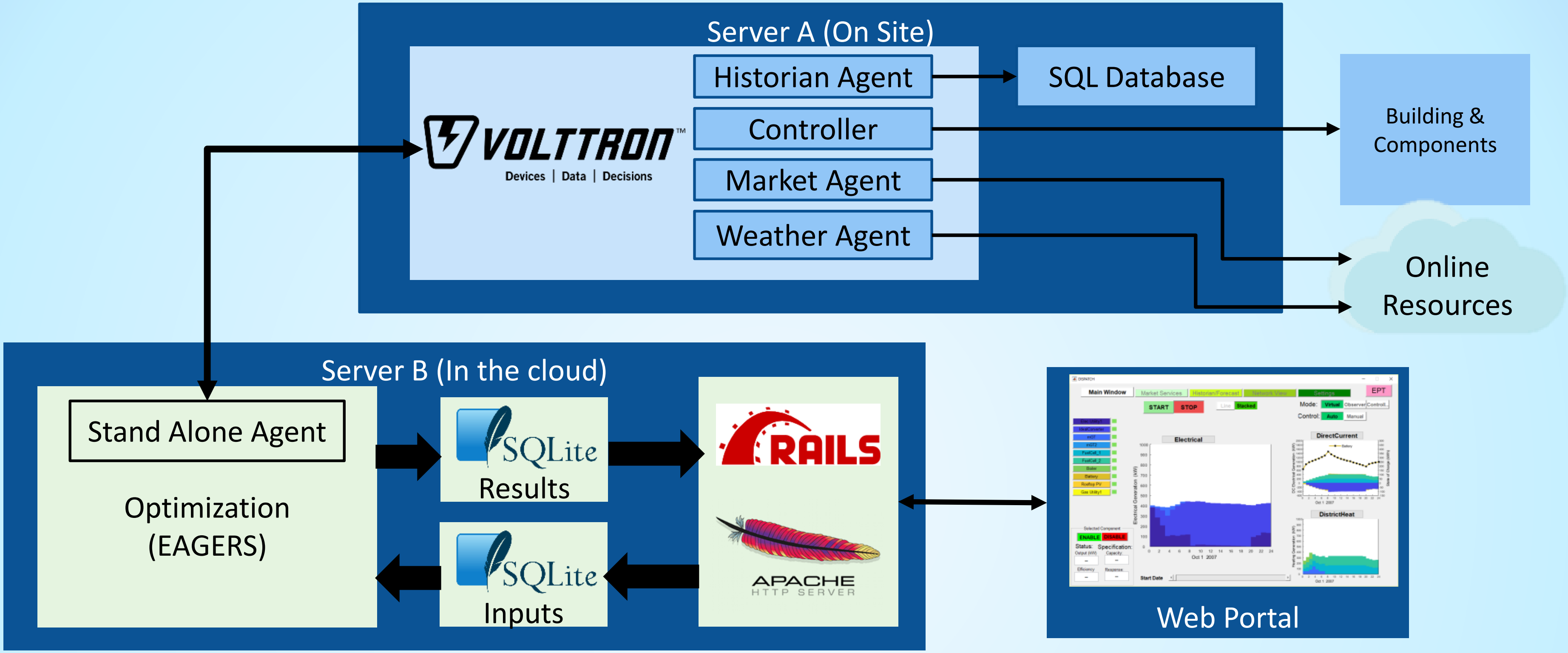
EAGERS Application Configuration



Server A (On Site)

Historian Agent

SQL Database

Controller

Market Agent

Weather Agent

Building & Components

Online Resources

Server B (In the cloud)

Stand Alone Agent

Optimization (EAGERS)

Results

Inputs

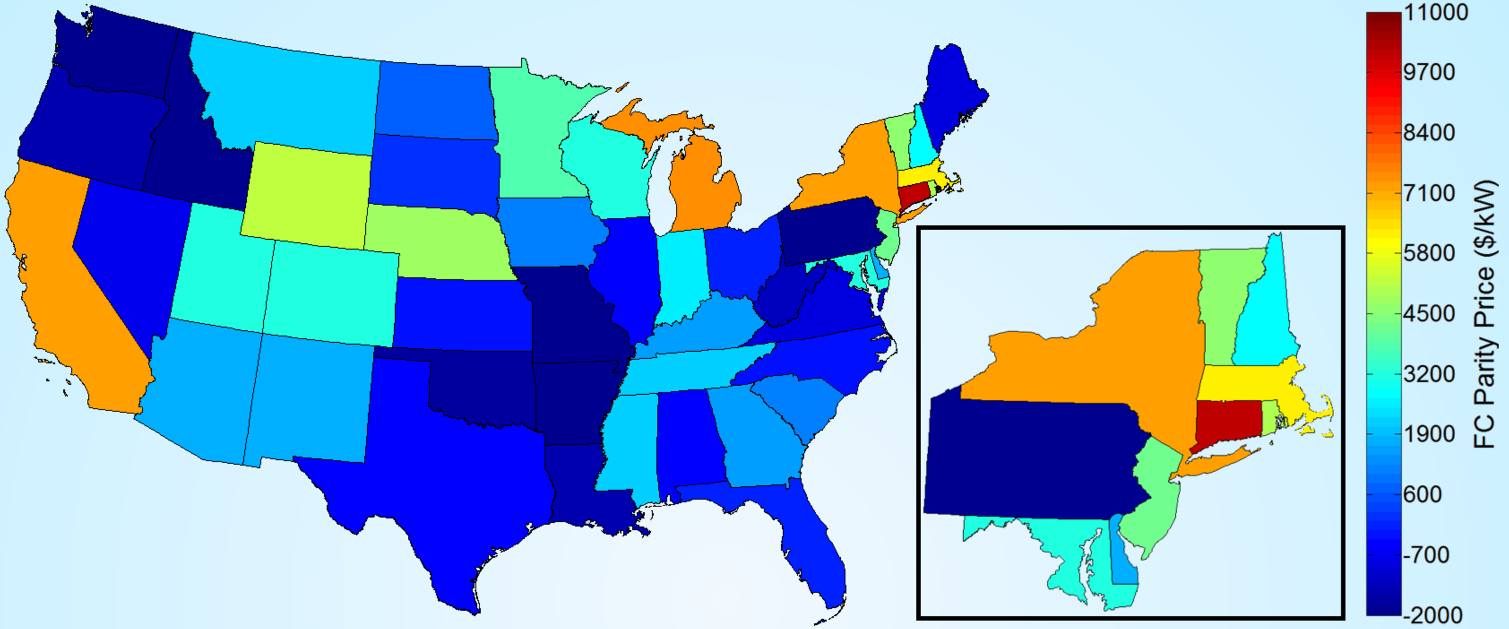
Web Portal

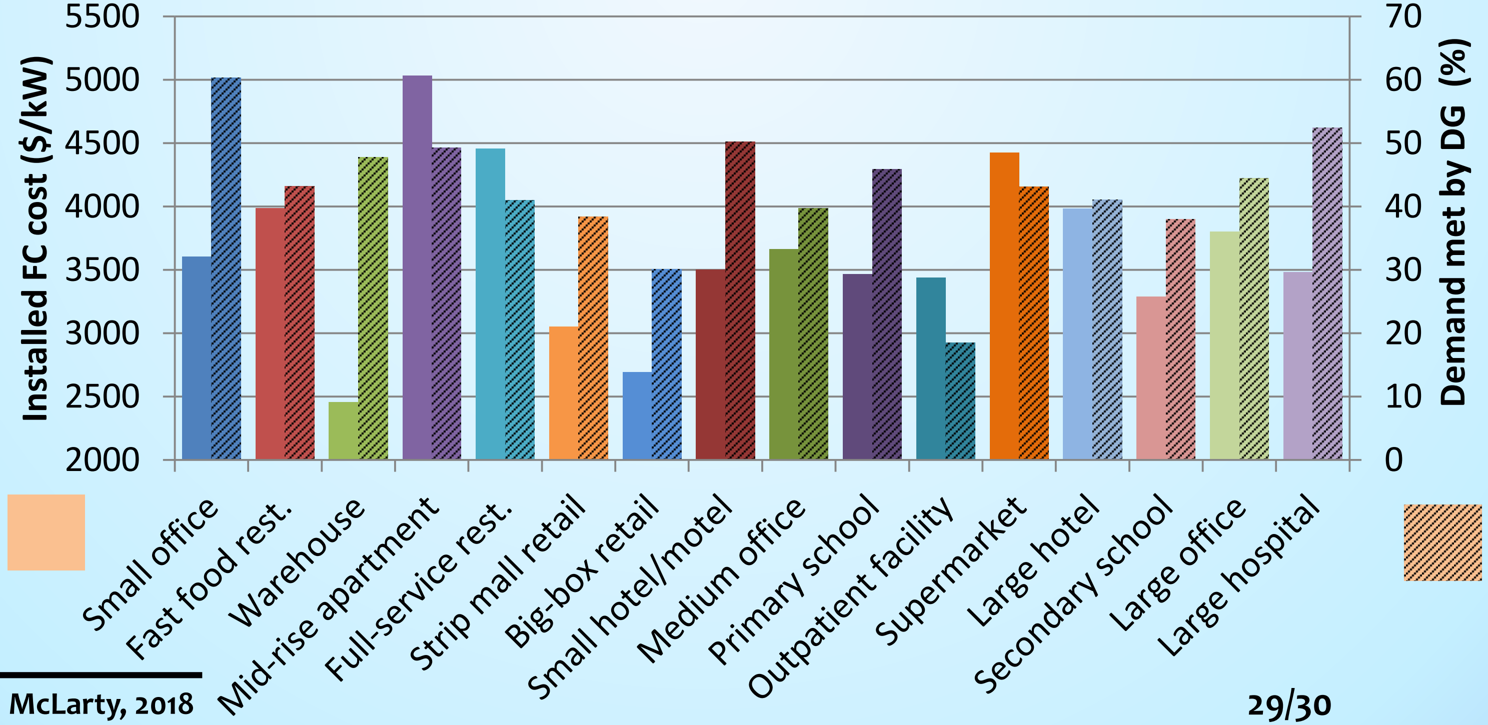
» Zero licensed software and no new installations

» Single connection point to Volttron which communicates with buildings and equipment through BACnet

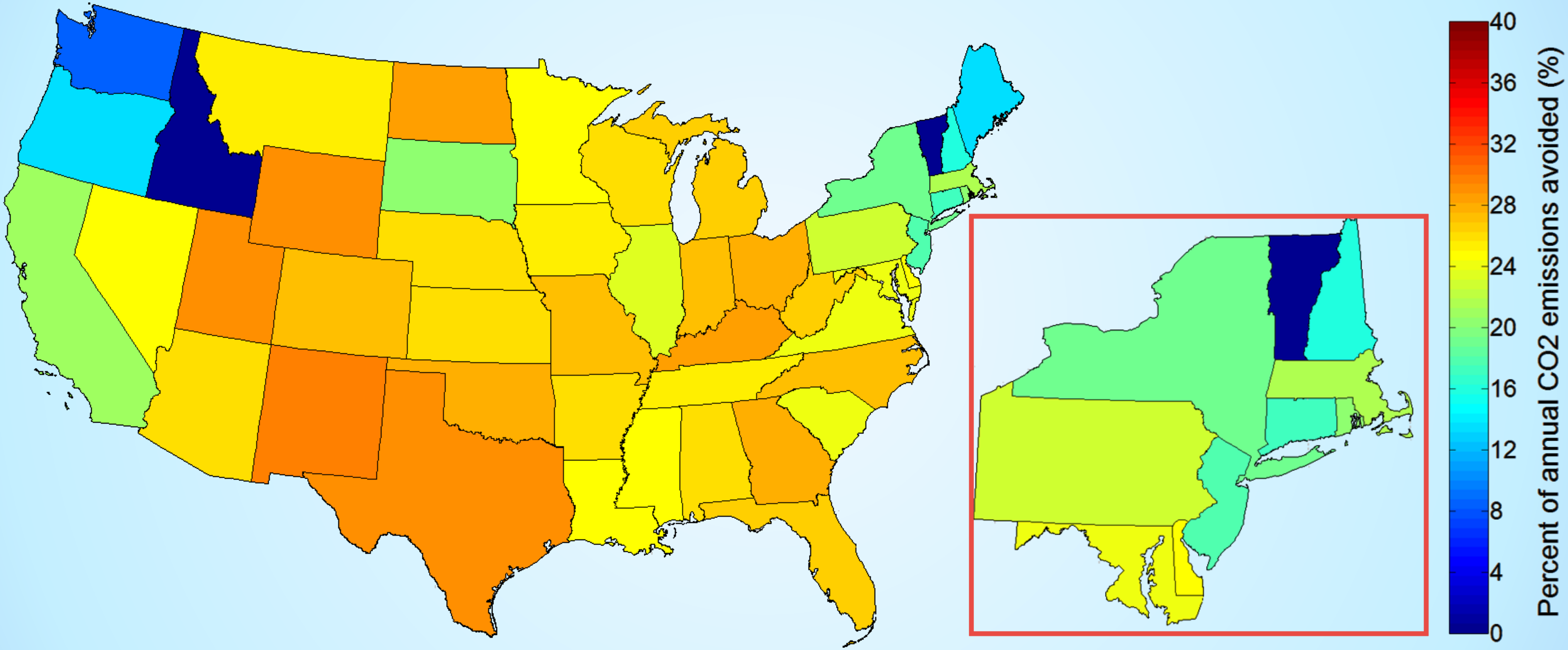
» Planning tool useful for equipment sizing and impact studies

Results – Grid Parity Cost





Annual CO2 reductions



Thank You!