Clean Energy Systems Integration Lab

Washington State University

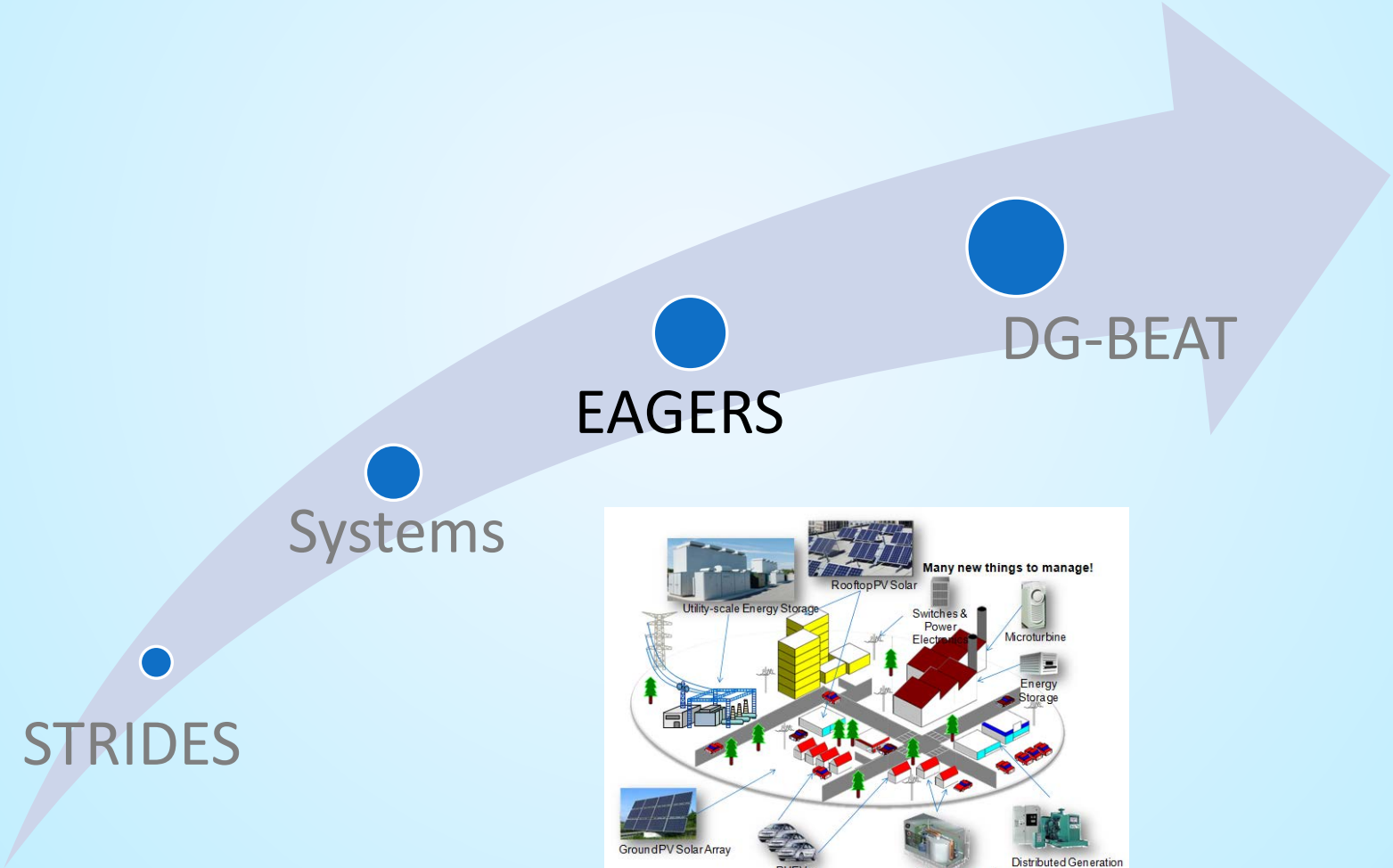
EAGERS

- NREL kick-off meeting

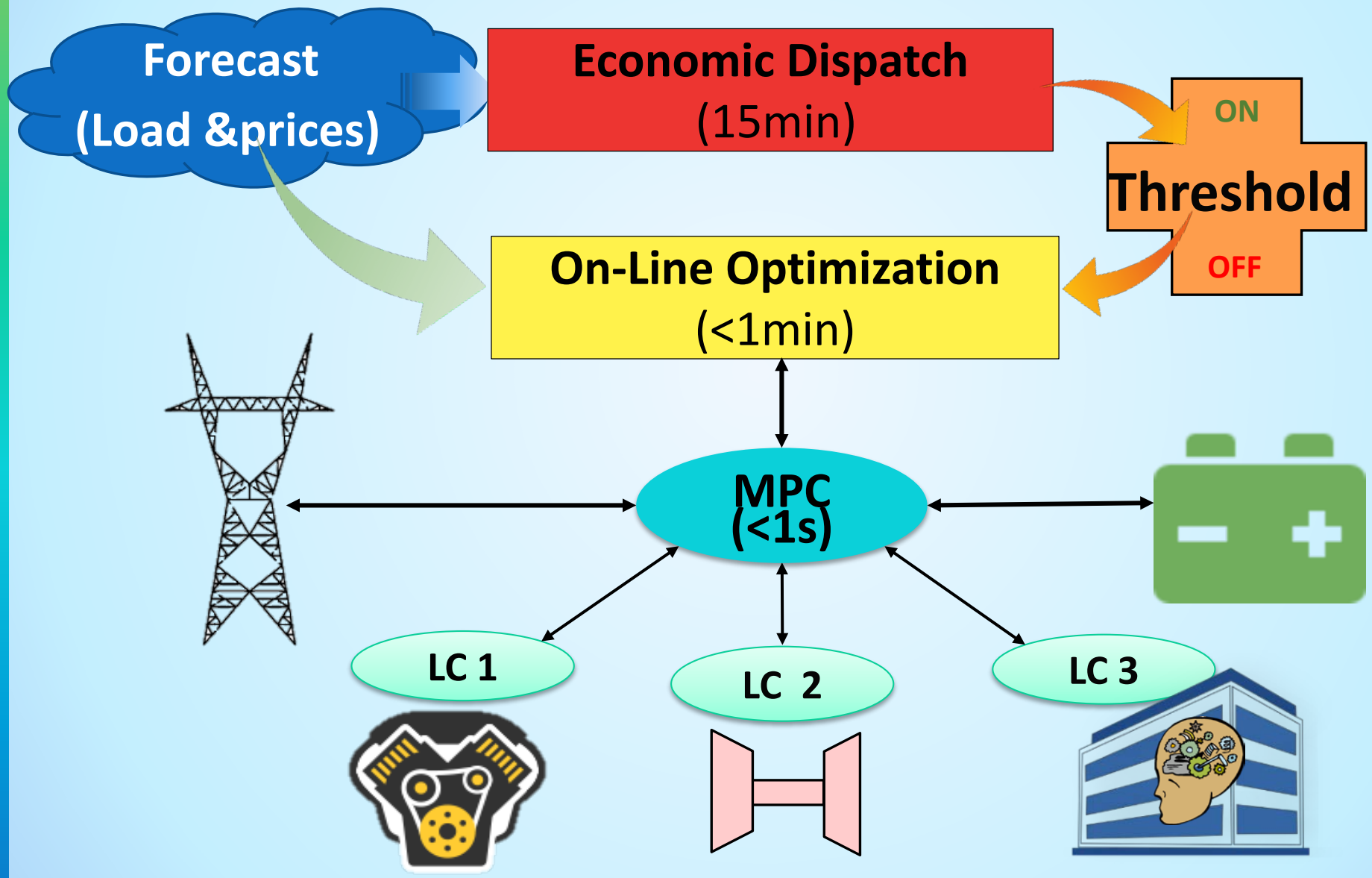
  9-14-16

Multi-scale dynamic modeling

How do generators and complementary systems integrate with a building and the grid?



Hierarchal MPC Overview



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

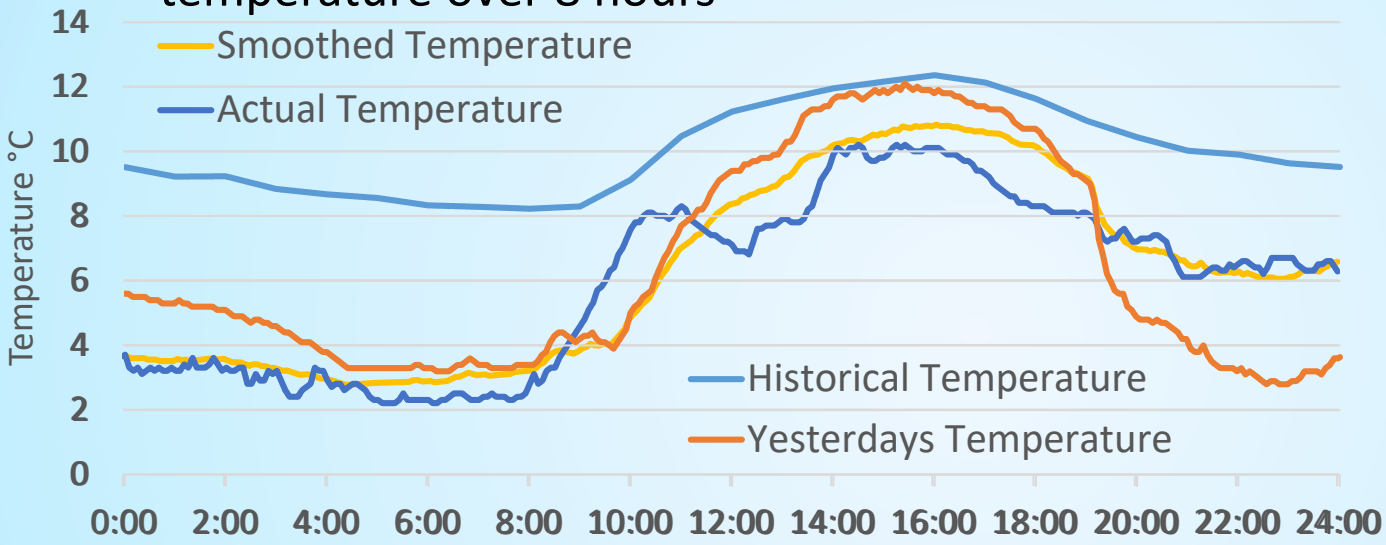
→ <1 sec

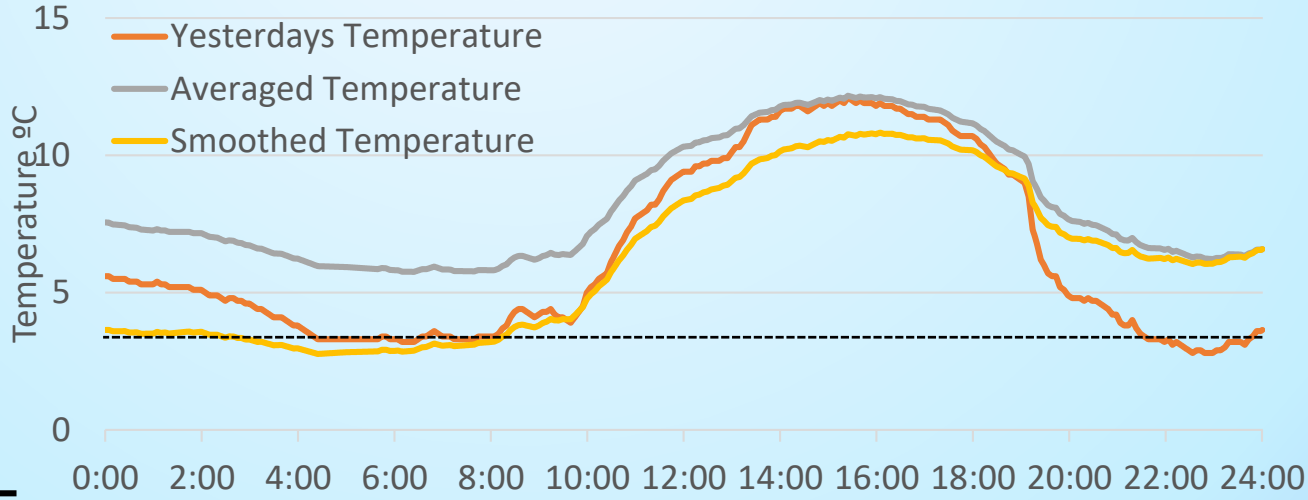
Forecast

» Step 1: Forecast Temperature

> Average of yesterday's temperature & historical profile for current season or month

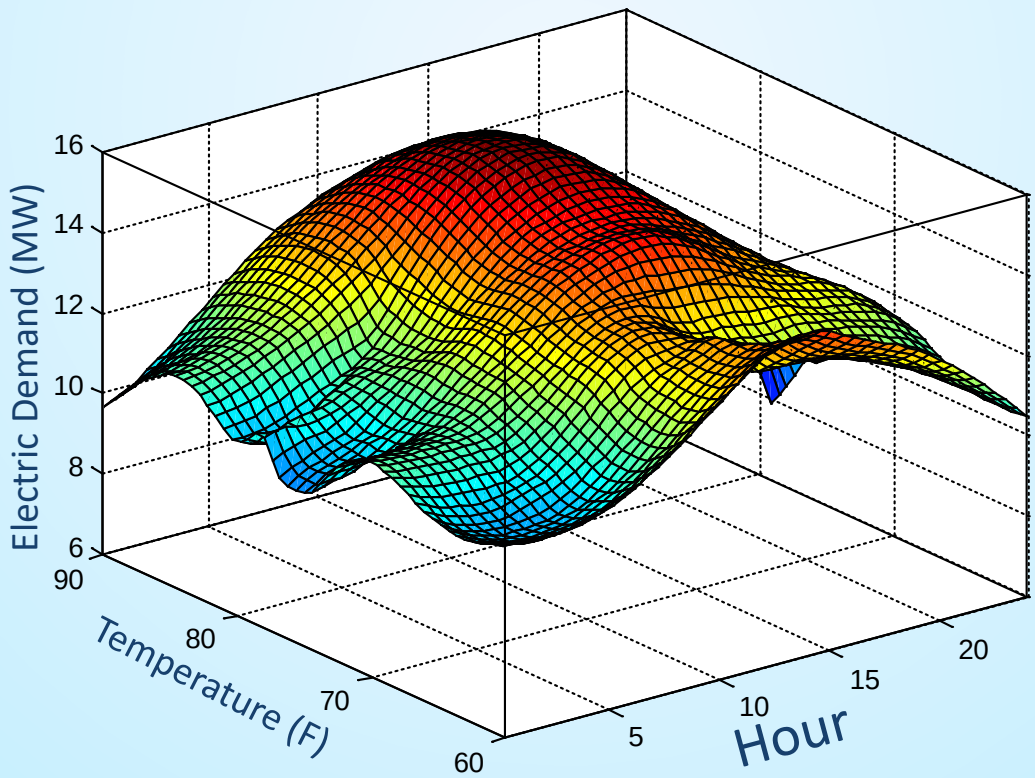
> Avoid Discontinuity: blend current temperature to forecasted temperature over 8 hours





Forecast

- Step 2: forecast loads
  - Use 2-D surface fits of historical data (electricity, heating, cooling)
  - Use forecasted temperature and time of day to interpolate load
  - Apply same technique to average yesterdays load & the historical load
  - Use different 2-D surface for weekdays & weekend/holidays



Solving the Dispatch Problem

» Minimize the cost of generators + utility + storage while meeting the demands at each time step, subject to constraints…

Mathematically:

$$\min \mathrm{C} = \sum_{k=1}^{\mathrm{N}} \left[\sum_{h=1}^{m} F_{h,k}\left(P_{h,k}\right) + \sum_{f}^{g} F_{f,k}\left(P_{f,k}\right) \right] + \sum_{r=1}^{s} F_r\left(SOC_{r,N}\right)/\eta_d$$

Demand constraint:

$$\sum_{h=1}^{m} P_{h,k} + P_{grid,k} + \sum_{r=1}^{s} \left(P_{r,k} - \phi_{r,k}\right) = P_{load,k} - P_{unctrl,k}$$

Range constraint:

$$P_{h,k}^{\min} \le P_{h,k} \le P_{h,k}^{\max}$$

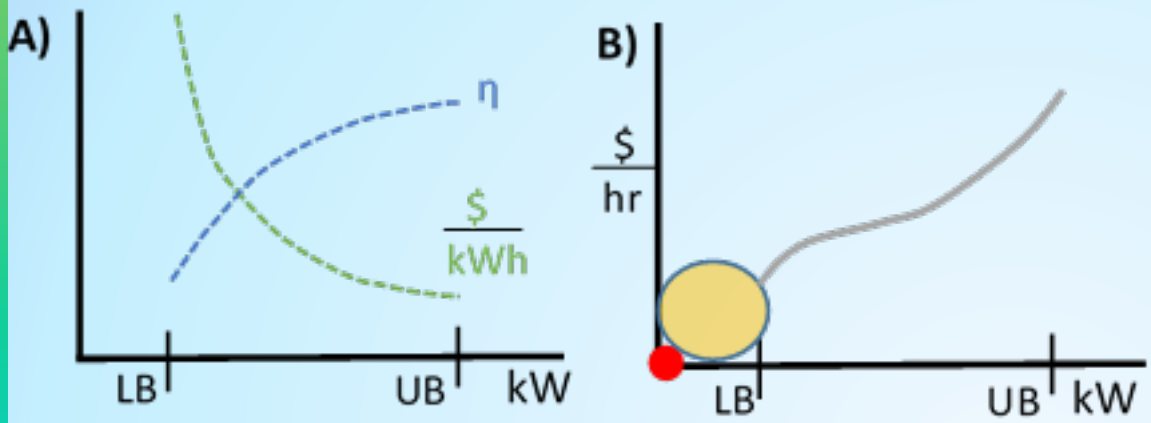
Ramp constraint:

$$\left|P_{h,k} - P_{h,k-1}\right| \le r_h^{\max} \cdot \Delta t_k$$

Grid constraint:

$$P_{grid,k}^{\min} \le P_{grid,k} \le P_{grid,k}^{\max}$$

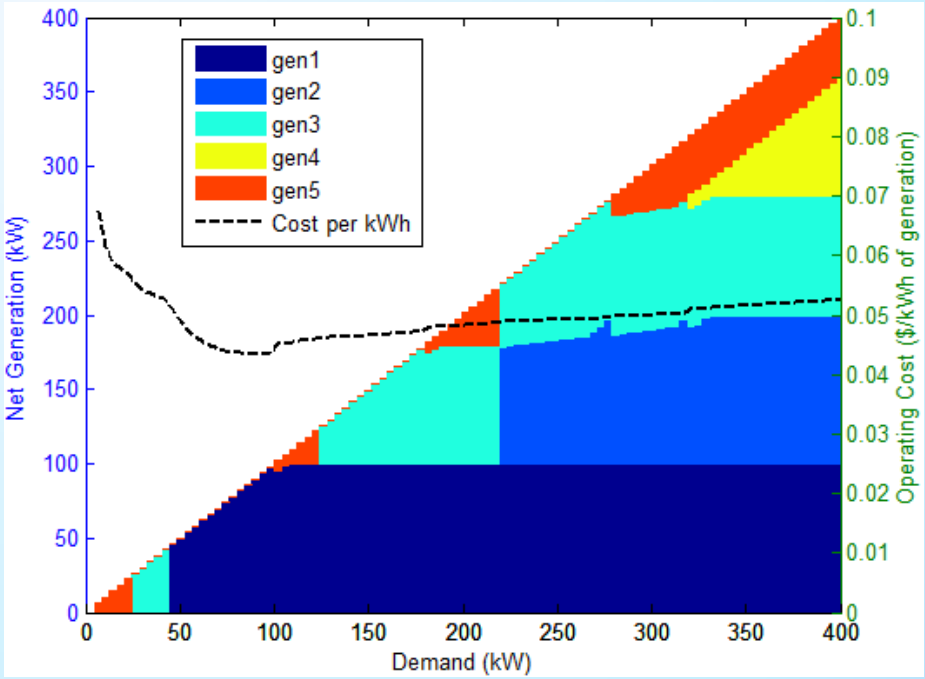
Why is this hard?



1) non-linear cost curve
2) Discontinuity: zero cost at zero power, finite cost at lower operating condition

> For any given demand you can solve he combinatorial problem and find the best configuration of generators to meet the demand

> 2^{m-1} combinations



How do you handle storage

- Does it have a cost?
- Do you need to solve the entire horizon simultaneously?
  - Now you have $2^{(m-1)*N}$ feasible combinations
- What about charging/discharging inefficiencies?

Our approach:

Relate Power to SOC:

$$P_{r,k} = \left(SOC_{r,k} - SOC_{r,k-1}\right) \cdot \eta_d / \Delta t_k$$

Charging penalty:

$$\phi_{r,k} \geq \left(SOC_{r,k-1} - SOC_{r,k}\right) / \left(\eta_c \cdot \Delta t_k\right) - P_{r,k}$$

$$\phi_{r,k} \geq 0$$

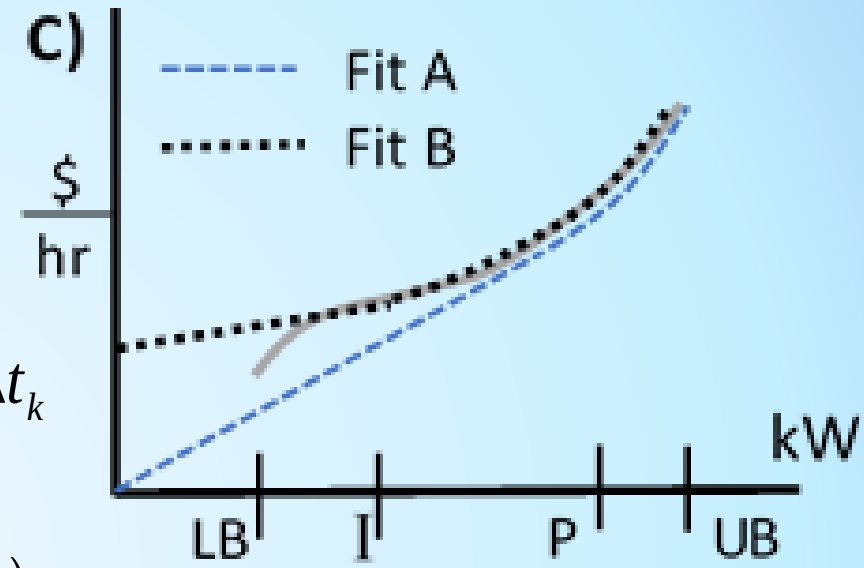
Bounds:

$$SOC_r^{\min} \leq SOC_{r,k} \leq SOC_r^{\max}$$

Costs

» Piecewise quadratic curves

> Best possible while remaining convex



Fit A: has zero y-intercept

$$F_{h,k}\left(P_{h,k}\right)=\left(a_{1,h}\beta_{h,k}+a_{2,h}\gamma_{h,k}+1/2\cdot a_{3,h}\gamma_{h,k}\right)\cdot\Delta t_k$$

Fit B: has non-zero y-intercept

$$F_{h,k}\left(P_{h,k}\right)=\left(b_{1,h}\beta_{h,k}+b_{2,h}\gamma_{h,k}+1/2\cdot b_{3,h}\gamma_{h,k}+b_{4,h}\right)\cdot\Delta t_k$$

Storage end condition value

> Prevents completely depleting storage

$$F_r\left(SOC_{r,N}\right)=c_{1,r}\cdot SOC_{r,N}+\frac{1}{2}c_{2,r}\cdot SOC_{r,N}{}^2$$

$$c_{1,r}=-1.05\cdot\max\left(\mathrm{b}_{2,\mathrm{h}}+\mathrm{b}_{3,\mathrm{h}}\cdot\left(UB_h-I_h\right)\right)$$

$$c_{2,r}=\left(-c_{1,r}-0.95\cdot\min\left(\mathrm{b}_{1,\mathrm{h}}\right)\right)/\left(2\cdot UB_h\right)$$

Complementary QP approach

Step 1) Solve the entire optimization with all constraints, except relax the lower boundary constraints (i.e. $P_{h,k}^{min}=0$ and $F_{h,k}(0)=0$) and use fit A. This creates Schedule 1

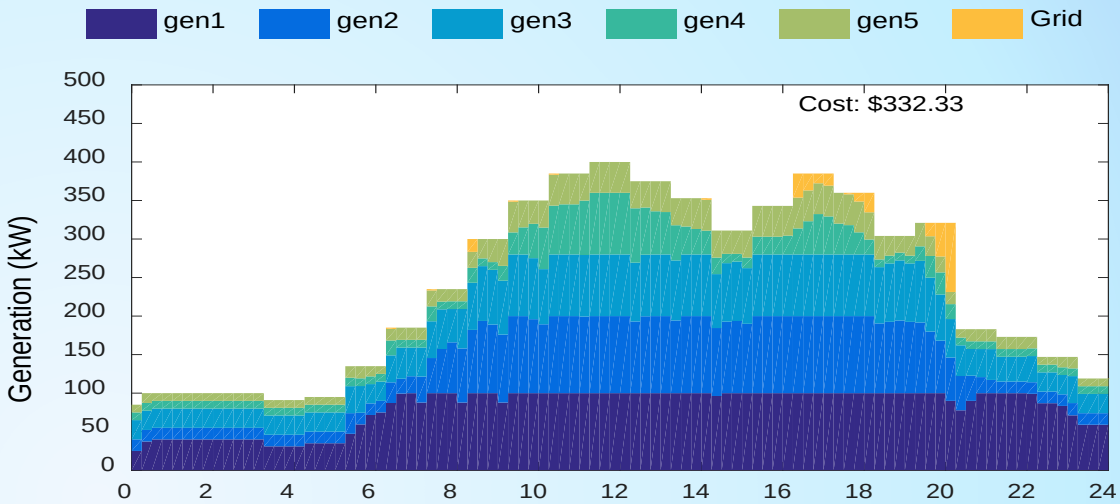
Step 2) Add up the generation at each step (including what charges the storage) and solve the combinatorial problem to find the best generator combo at that moment. Use fit B and enforce the lower boundary constraints. Ramping constraints are not considered, since it is only solving 1 step at a time. This becomes Schedule 2.

Step 3) Apply a series of rules to Schedule 1 and Schedule 2 to determine when generators are on and off. Then solve the full optimization at all steps, with all constraints enforced. This results in Schedule 3, which is used for the next step.

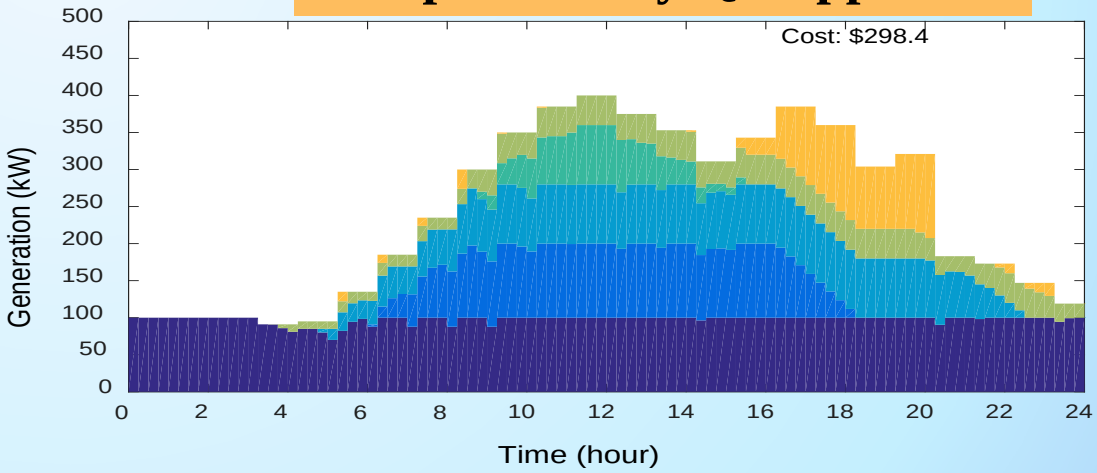
Example Result A

Name	Capacity (kW)	Lower Limit	Peak eff (%)
Gen1	100	25.0	39.3
Gen2	100	15.0	31.9
Gen3	80	25.0	33.0
Gen4	80	10.0	27.9
Gen5	40	10.0	30.5
Chiller	Capacity (kW)	Lower Limit (kW)	Peak COP
Chiller1	200	100	6.3
Chiller2	120	60	5.6
Chiller3	80	40	4.8
Storage	Capacity (kWh)	Peak Out (kW)	Eff (%)
Battery	500	130	96
TES	4,000	800	99

Standard Dynamic Economic Dispatch

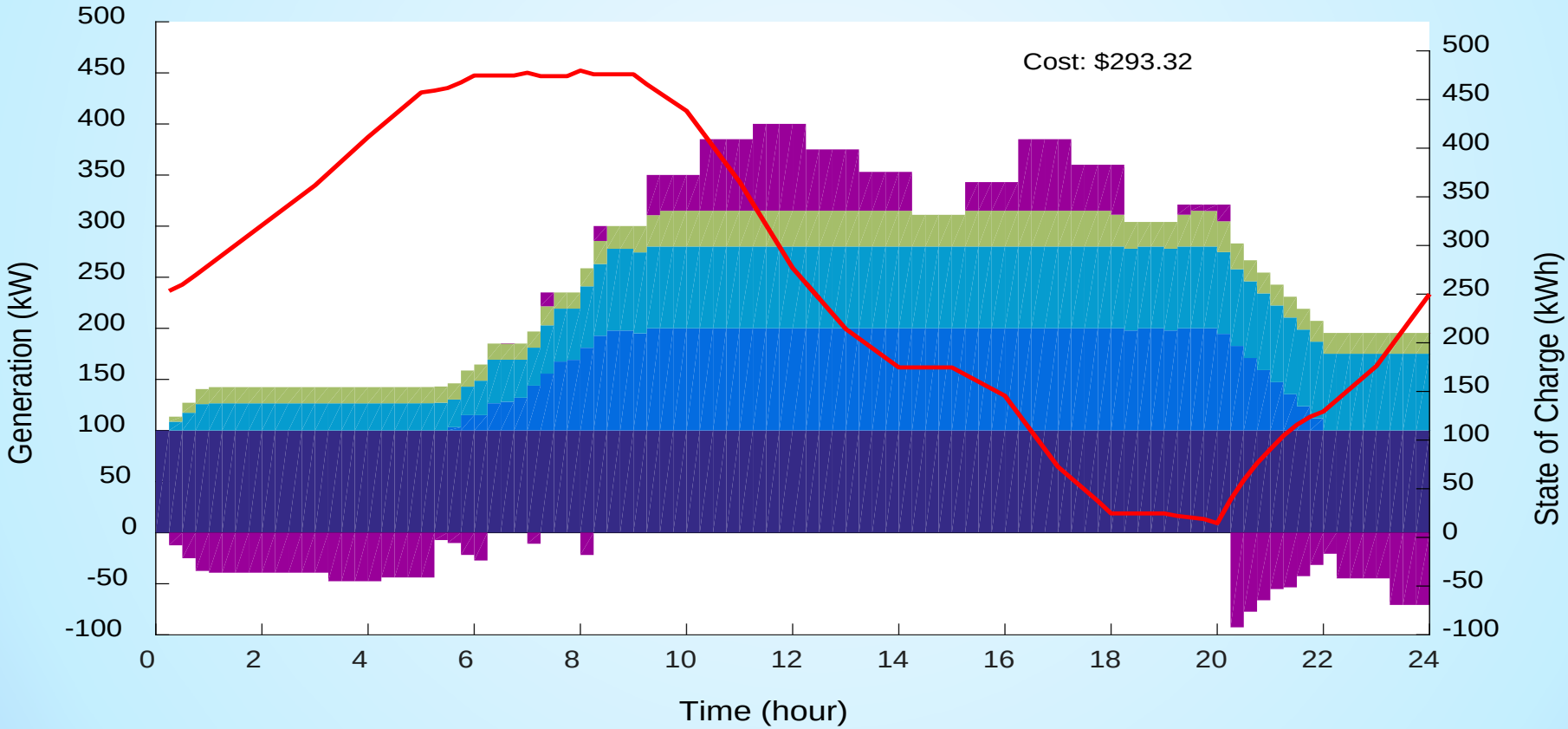


Complementary QP Approach



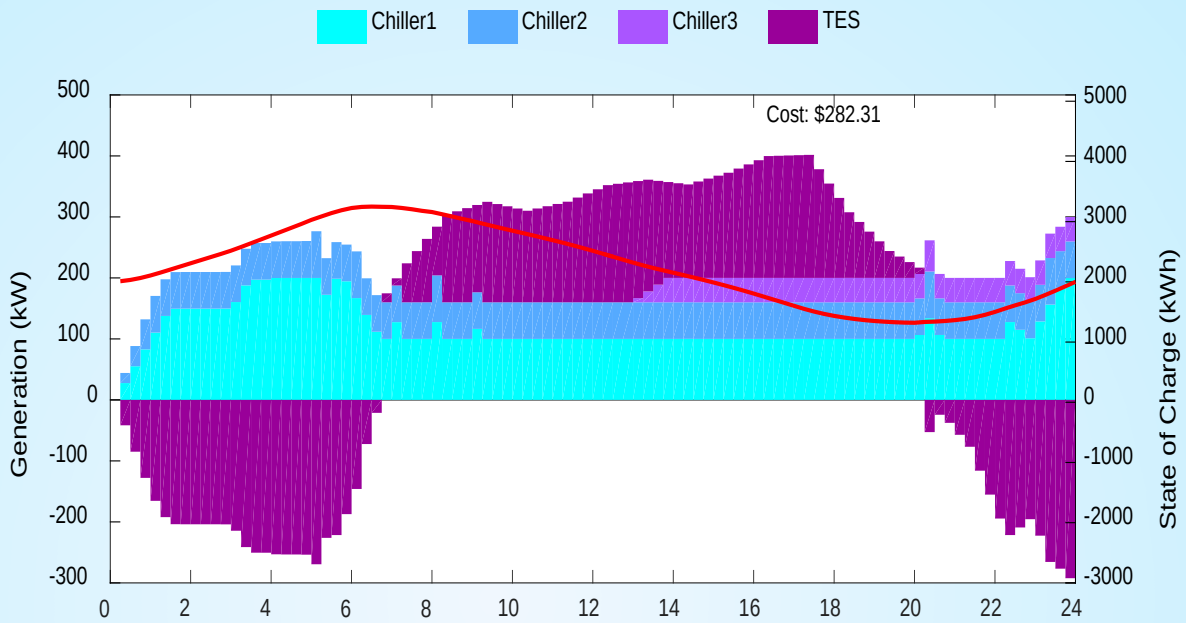
Example Result B

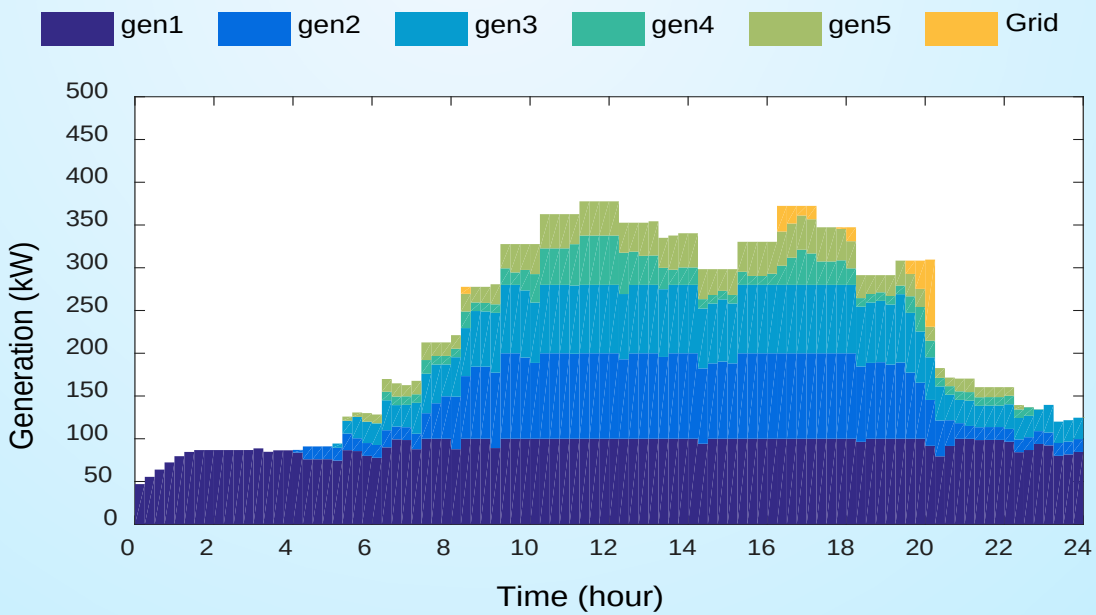
Electric storage can keep generator #4 off



Example Result C

Thermal storage can work like electric storage





Summary of Dispatch Features

- *List of attributes*
  - Utilizes quadratic rather than linear cost functions for each generator
  - Determines best use of energy storage by optimizing over time horizon
  - No arbitrary costs assigned to use of storage (no solution shaping)
  - Respects lower operating constraints of generators & start-up costs
  - Computation scales linearly with # of intervals ($t \cdot 2^n$ rather than $2^{n \cdot t}$)
- *Current Functionality*
  - Considers electricity+heat+cooling together
  - Incorporates charging/discharging inefficiencies
  - Incorporates self-discharging (losses) of energy storage
  - Variable time step horizon
- *Future functionality*
  - Ambient temperature dependence of generator limits/cost
  - Co-production of steam (for steam turbine) or hydrogen
  - Spinning reserve
  - Transmission constraints & line losses

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Threshold

- ***Uncertainty & error in prediction***
  - Just because your prediction says you should turn a generator on (or off), does not mean you should
  - Setting thresholds, upper and lower boundaries, and waiting for the load to pass this threshold before taking action is one way to adjust for errors in prediction
  - Thresholds can also be set by time or by SOC for a storage system

Control

- Every ~60 sec: re-optimize generator output
  - Horizon is the time interval of the dispatch (15 min)
  - Boundaries for generators determined from dispatch
    - Ex) may need generator #1 to be ramping up continuously
  - SOC of storage targets an end condition determined by dispatch (end of 1st dispatch interval)
    - penalties for over or under charging (larger penalty for under charging)
  - Send targets to MPC controller
- Every ~1sec: MPC controller sends updated set-point to generators

Balance

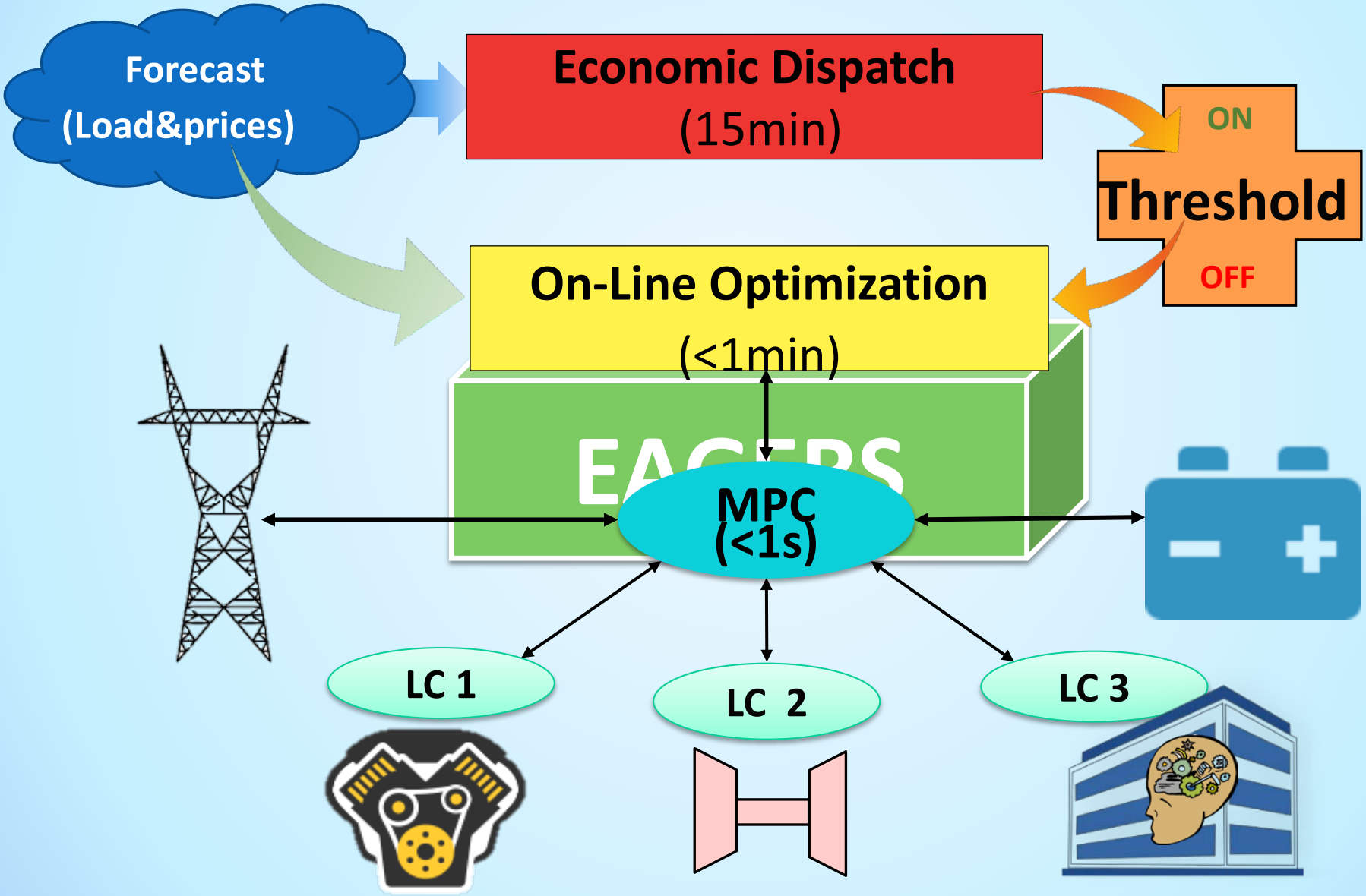
A. Grid Only
   > Purchase any additional power necessary to balance supply & demand
   > Excess power is dumped onto grid

B. Storage Only
   > Balance demand by charging/discharging storage

C. Grid & Storage
   > Dispatch determines a target amount of charging/discharging for current step
   > If charging:
   > If discharging:

Over-production	Under-production
Over-production	**Under-production**
1) Reduce discharging	1) Reduce power sold to grid
2) Reduce grid purchases	2) Increase grid purchases
3) Sell power back to grid	3) Discharge more storage

Hierarchal MPC Overview



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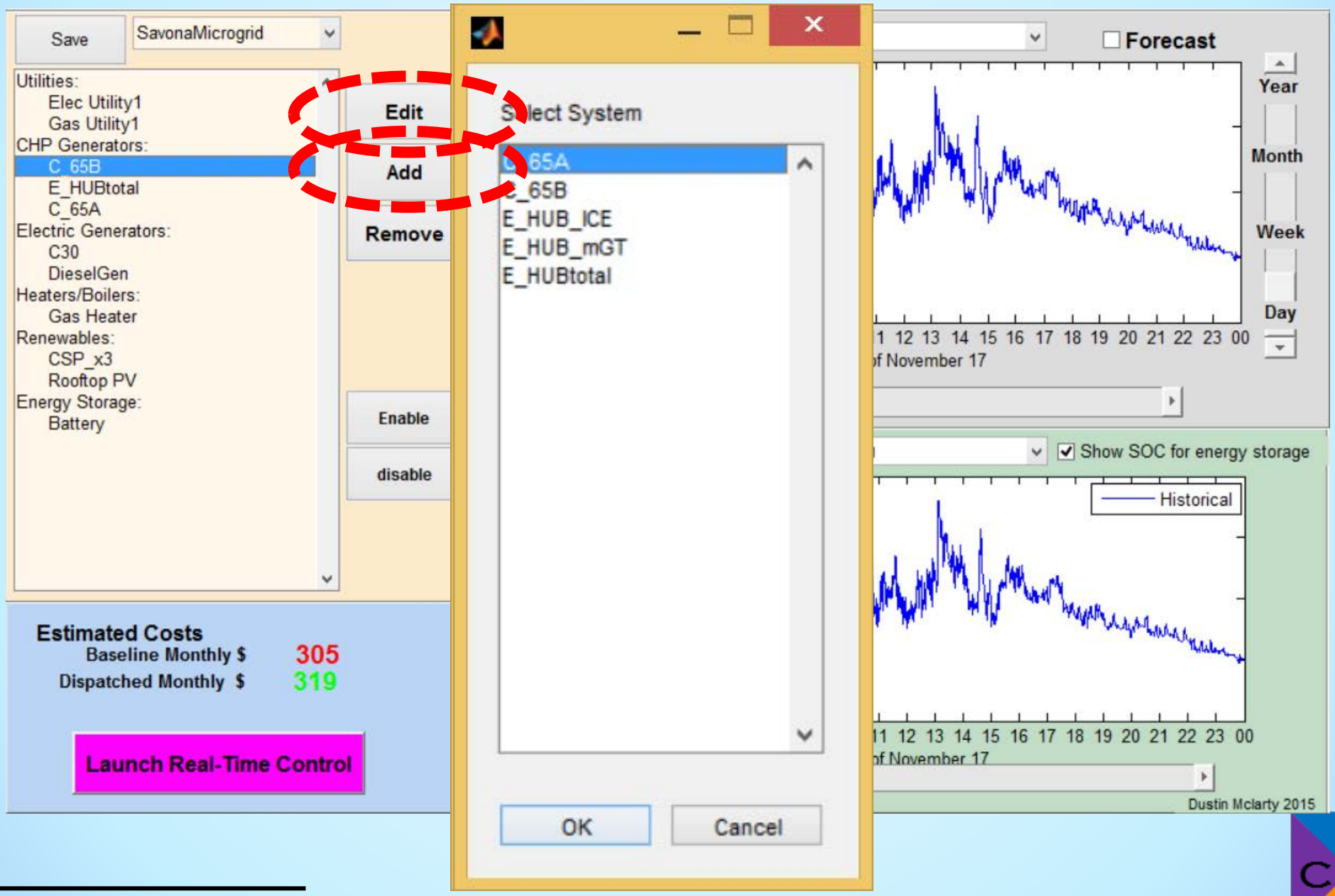
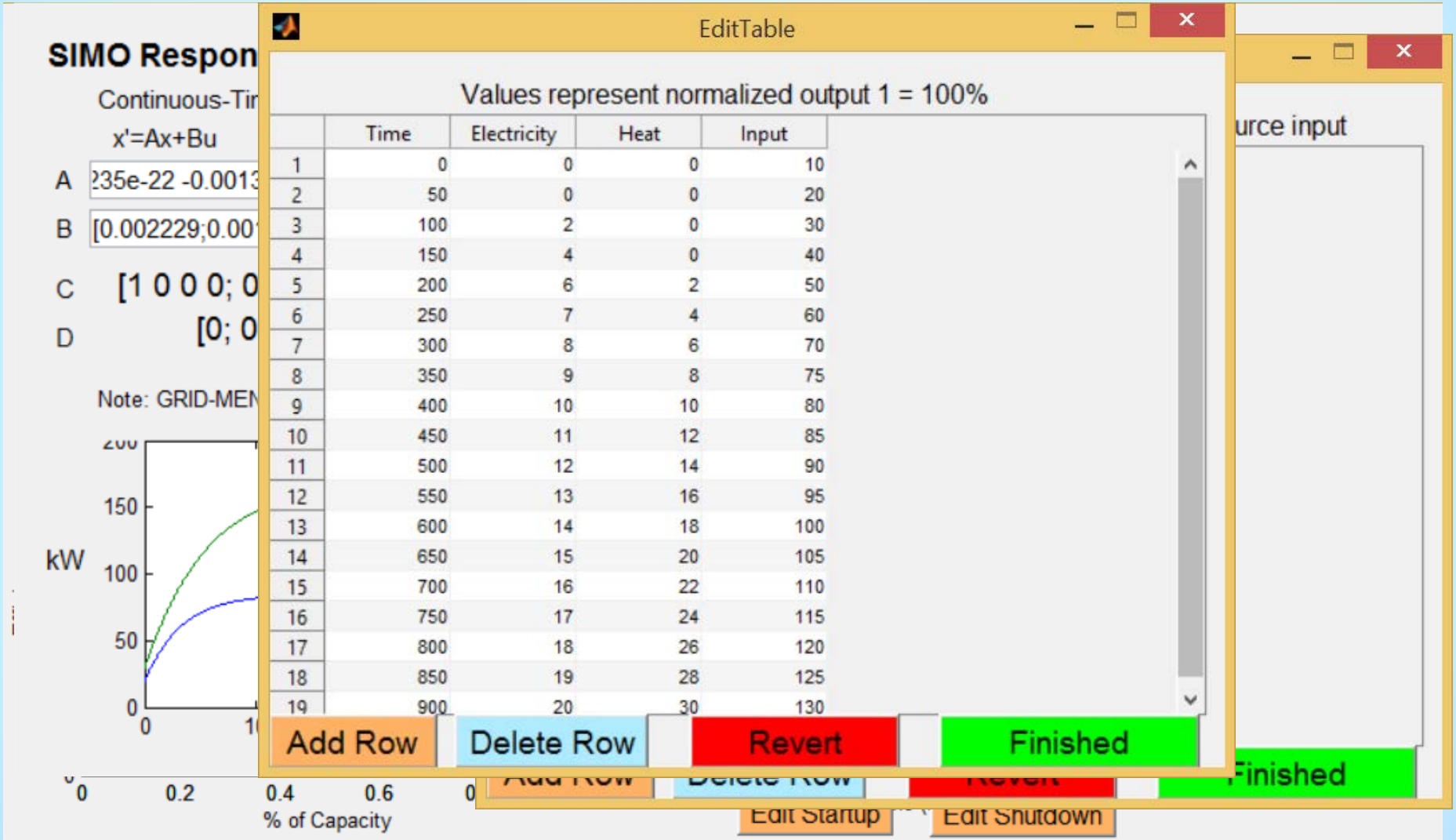


Specifying Generators



	Time	Electricity	Heat	Input
1	0	0	0	10
2	50	0	0	20
3	100	2	0	30
4	150	4	0	40
5	200	6	2	50
6	250	7	4	60
7	300	8	6	70
8	350	9	8	75
9	400	10	10	80
10	450	11	12	85
11	500	12	14	90
12	550	13	16	95
13	600	14	18	100
14	650	15	20	105
15	700	16	22	110
16	750	17	24	115
17	800	18	26	120
18	850	19	28	125
19	900	20	30	130

Utilities

Winter

month 10 / day 1

	Energy Charge ($/kWh)	Demand Charge ($/kW)
1. Off-Peak	0.10826	0
2. Partial Peak	0.14156	0
3. Peak	0.14156	0

Hour of Day

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Sunday	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Monday	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1
Tuesday	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1
Wednesday	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1
Thursday	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1
Friday	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1
Saturday	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Summer

month 6 / day 1

	Energy Charge ($/kWh)	Demand Charge ($/kW)
1. Off-Peak	0.11215	0
2. Partial Peak	0.21541	0
3. Peak	0.45244	0

Hour of Day

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Sunday	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Monday	1	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3	3	2	2	2	2	2	1
Tuesday	1	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3	3	2	2	2	2	2	1
Wednesday	1	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3	3	2	2	2	2	2	1
Thursday	1	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3	3	2	2	2	2	2	1
Friday	1	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3	3	2	2	2	2	2	1
Saturday	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Utility Name: Los Angeles1

Minimum Import Threshold 0 kW

Grid Sell Back

- (●) None
- ( ) Fixed Rate 0 $/kWh
- ( ) Reversed Meter (%) of tarrifs: 0

Done | Save Utility

- » Same idea for electric & gas utilities
- » Also can create district heating/cooling utilities

Energy Storage + Renewables

Solar Power Setup

Name: CSP_x3

Location: Vermont

Size (kW): 3

Size (m2): 15.7895

Conversion Efficiency (%): 0.19

Azimuth Angle (Degrees): 180

Tilt Angle (Degrees): 40.9524

Optimal Zenith

Solar Type
- ○ Flat Panel
- ● Concentrated

Solar Tracking
- ○ Fixed
- ○ Single Axis
- ● Dual Axis

DC--AC Conversion

	Value	Min	Max
DC rating	0.9500	0.8000	1.0500
Inverter/Transformer	0.9200	0.8800	0.9800
Mismatch	0.9800	0.9700	0.9950
Diodes/connection	0.9950	0.9900	0.9970
DC wiring	0.9800	0.9700	0.9900
AC wiring	0.9900	0.9800	0.9930
Soiling	0.9500	0.3000	0.9950
System availability	0.9800	0	0.9950
Shading	1	0	1
Sun-Tracking	1	0.9500	1
Age	1	0.7000	1

Save As | Save Only To Plant | Cancel

Efficiency

99 Charging Efficiency (%)

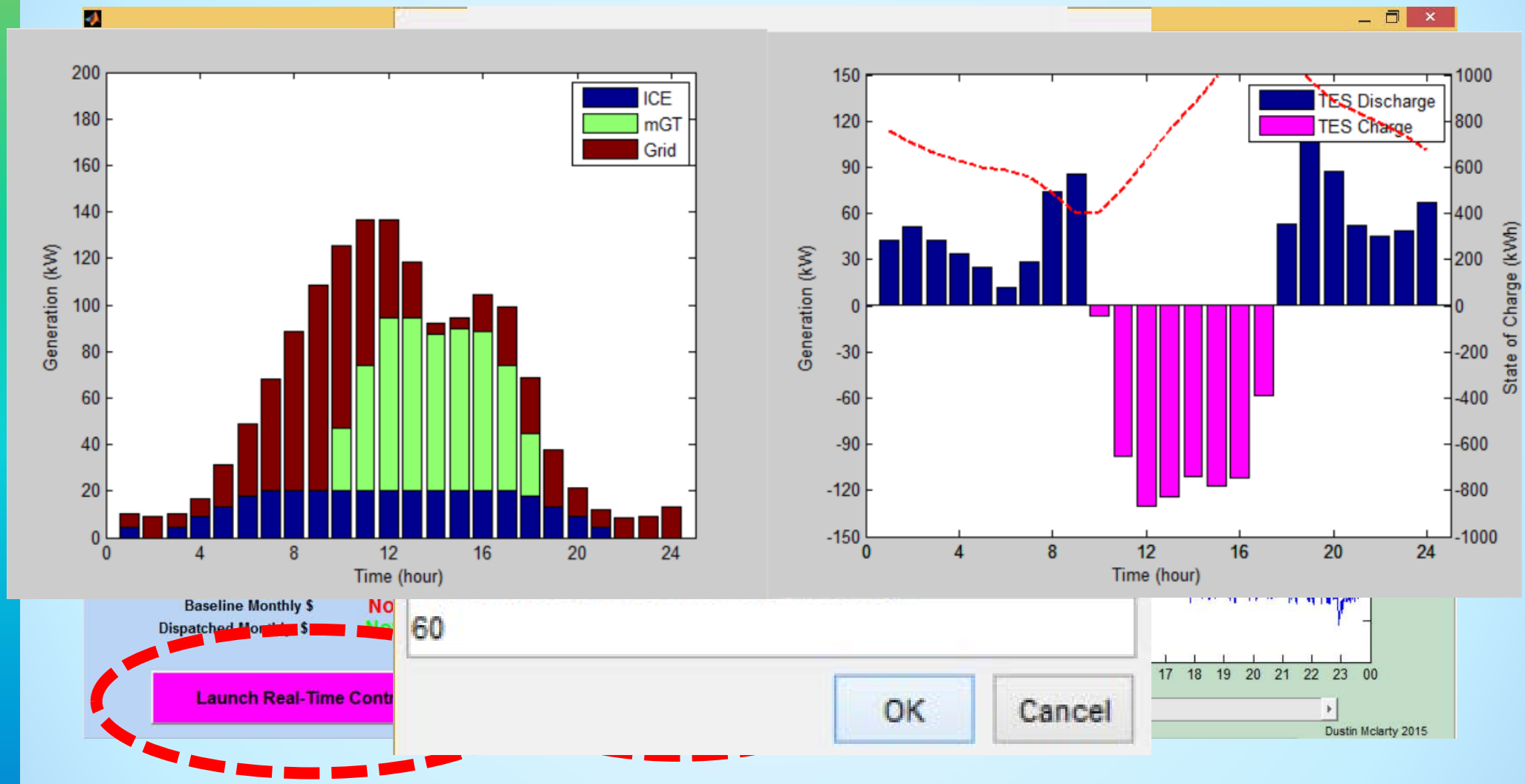
99 Discharging Efficiency (%)

4 Self-discharge (% Lost per day)

Save To Library

Cancel

Running a Test



Communicates with LabView

Uses user-supplied SS model to simulate generator response

Test Results