Outline

1. Introduction
2. Statistical Analysis
3. Production Simulation Analysis
4. Quasi-Steady-State Analysis, QSS
   - Overview of QSS Analysis
   - Illustration of System Performance
   - Illustration of Potential Mitigation Methods
   - Linkages to Statistical & Production Simulation Analyses
5. Operational Implications and Mitigation Methods
6. Conclusions and Recommendations

Objectives of Quasi-Steady State Analysis

- Provide Validation & Context for MAPS & Statistical Analysis
  - Cases Selected from Statistical Analysis
  - Boundary Conditions Set by MAPS Analysis
- Evaluate Impact of Significant Wind Generation
  - Load Following & Ramp Rate Requirements
  - Regulation/AGC Requirements
- Illustrate Performance Issues
- Illustrate Mitigation Measures

Quasi Steady State (QSS) Analysis

- QSS is a Time Dependent Sequence of Static Power Flows over a Selected 3-Hour Study Period
- At 1-Minute Intervals
  - All CA Loads Vary
  - All Wind Plant and Solar Plant Outputs Vary
  - Necessary Regulating Power Provided by AGC Equivalent
- At 5-Minute Intervals
  - Simplified Economic Dispatch
  - Participating Load Following Units Identified in MAPS Analysis
  - Participating Units Scheduled Up/Down for Successive Intervals
  - Individual Unit Ramp Rate Limits Respected (MW/Min)
  - Individual Range Limits Respected (Maximum and Minimum MW)

Input Data for QSS Analysis

- 2010T and 2010X Power Flows (DPC)
  - Other Analyses Showed 2010X More Stressed than 2020 Scenario
- Data for 1-minute Profiles
  - 1-minute Wind Plant Output (AWST)
  - 4-second Load Data (CAISO)
  - Solar Data
    - 15-minute PV data for 13 CA zip codes (CPUC SGIP)
    - 1-minute Golden, CO irradiation data (NREL, ARSC SUNY Albany)
    - Hourly Stirling plant data (NREL, SES)
    - 3-minute Desert Rock, NV irradiation data (NREL, ARSC SUNY Albany)
    - 1-minute Sungen/Luz profiles (CAISO and UC-Davis)
- Confidential Generating Unit Ramp Rate Data (CAISO)
  - Calculated Weighted Average by Type (e.g., Steam, Hydro) for Analysis
- Generation Dispatch Derived from MAPS Analysis (GE)

Linkage of QSS with Statistical Analysis

- Case Selection
  - Objective: Challenging but Credible System Conditions
  - Use Hourly Statistical Data to Identify Study Periods with
    - Large 1-hour and 3-hour Changes in System Load
    - Large 1-hour and 3-hour Changes in Wind & Solar Generation
    - High Levels of Wind & Solar Generation
    - High Levels of Wind & Solar Penetration
    - Low Load Levels
- Compare QSS Case Characteristics to Statistical Results
  - Hourly Decile (e.g., Maximum Wind, Minimum Load, Average Penetration)
  - Duration Curves (e.g., # of times load changes by >= X MW per year)
- Compare QSS Results to Statistical Results
  - Sub-hourly Full Year and Light Load (e.g., σ of 1-minute and 5-minute Deltas)
  - Additional Connections Discussed in Operational Impacts/Mitigation Section

Linkage of QSS with MAPS Analysis

- MAPS Results Define Boundary Conditions for QSS Analysis
  - Initial WECC Generation Dispatch, HVDC Tie & CA Import Power Flows
  - Comparison of MAPS Results, From Beginning of Study Period to End, Identifies
    - CA Units with Changing Dispatch over Study Period
    - HVDC Tie & CA Import Power Flow Changes
- During QSS Simulation
  - Selected CA Units (e.g. 3hour dispatch delta > 25MW) used in Economic Dispatch
  - HVDC Tie Flows Ramp from Initial Condition to Final Condition
  - CA Import Unchanged to Ensure All Load Following & Regulation Performed by CA Units
  - Calculation of Performance Metrics – Only CA Units that Participate in QSS Economic Dispatch are Included in Performance Metrics
- Compare QSS Results to MAPS Results
  - Total Power Range and Ramp Rate Capability
  - Additional Connections Discussed in Operational Impacts/Mitigation Section

July Morning Case (2010T Mix)

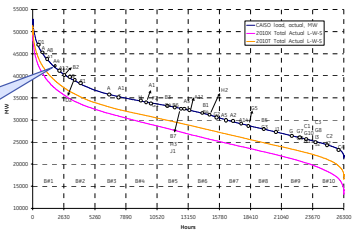
~7,500MW Total CA Wind Capacity
98 Individual Wind Plants
~1,900MW Total CA Solar Capacity
12 Concentrating Solar Plants, 136 PV Sites
2004 Load Shape

3hr Study Period of High Load Rise

Total Load Increase ~8,200 MW
Total Wind Decrease ~2,100 MW
Total Solar Increase ~450 MW
Wind & Solar Penetration 13% -> 6%

Case selected to examine potential for problems with rapid load rise compounded by wind drop-off.

July Morning: Total CA Load



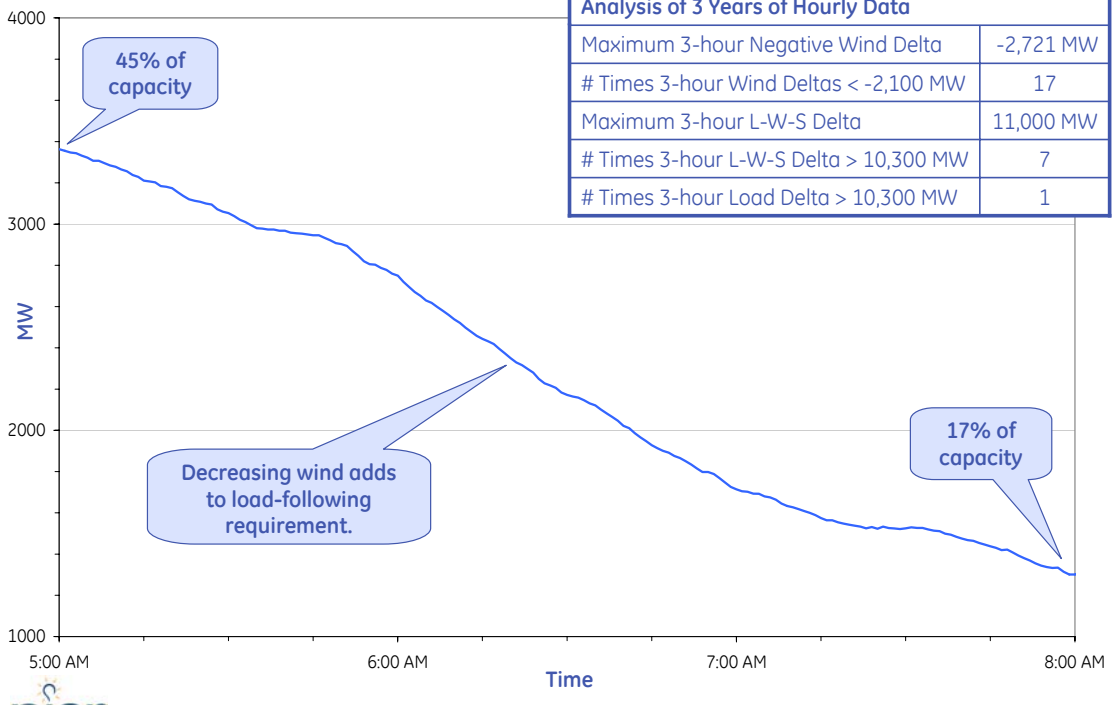
This load rise case.

Analysis of 3 Years of Hourly Data	
Maximum 3-hour Load Delta	10,900 MW
% 3-hour Load Deltas > 8,200 MW	~1 %

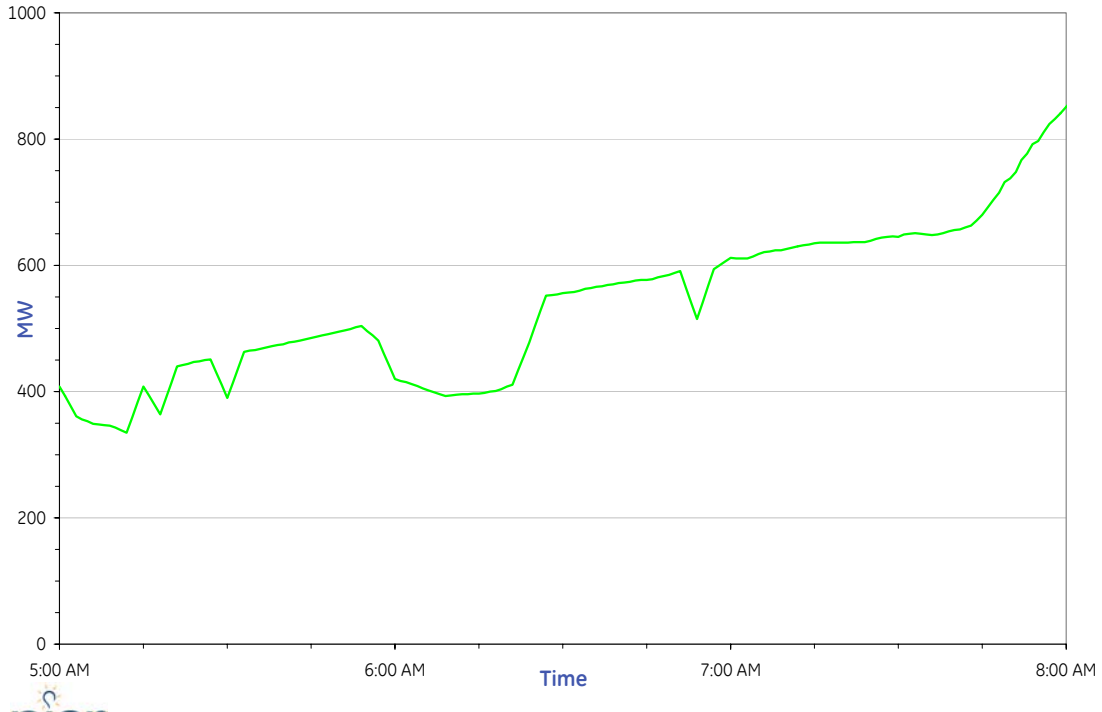
Largest 1-minute change in load is –300MW.

July Morning: Total CA Wind

Analysis of 3 Years of Hourly Data	
Maximum 3-hour Negative Wind Delta	-2,721 MW
# Times 3-hour Wind Deltas < -2,100 MW	17
Maximum 3-hour L-W-S Delta	11,000 MW
# Times 3-hour L-W-S Delta > 10,300 MW	7
# Times 3-hour Load Delta > 10,300 MW	1



July Morning: Total CA Solar



QSS Maneuverability Variables:

Variables describing important behavior of the generators participating in load following/economic dispatch (ED units):

PUP tot = Remaining range of ED units to increase output:

$\Sigma(P_{imax} - P_i)$ in MW

PDN tot = Remaining range of ED units to decrease output:

$\Sigma(P_{imin} - P_i)$ in MW

RUP tot = Remaining rate capability of ED units to ramp output up:

$\Sigma(Rate_i$, if $P_i<P_{imax})$ in MW/min

RDN tot = Remaining rate ability of ED units to ramp down output:

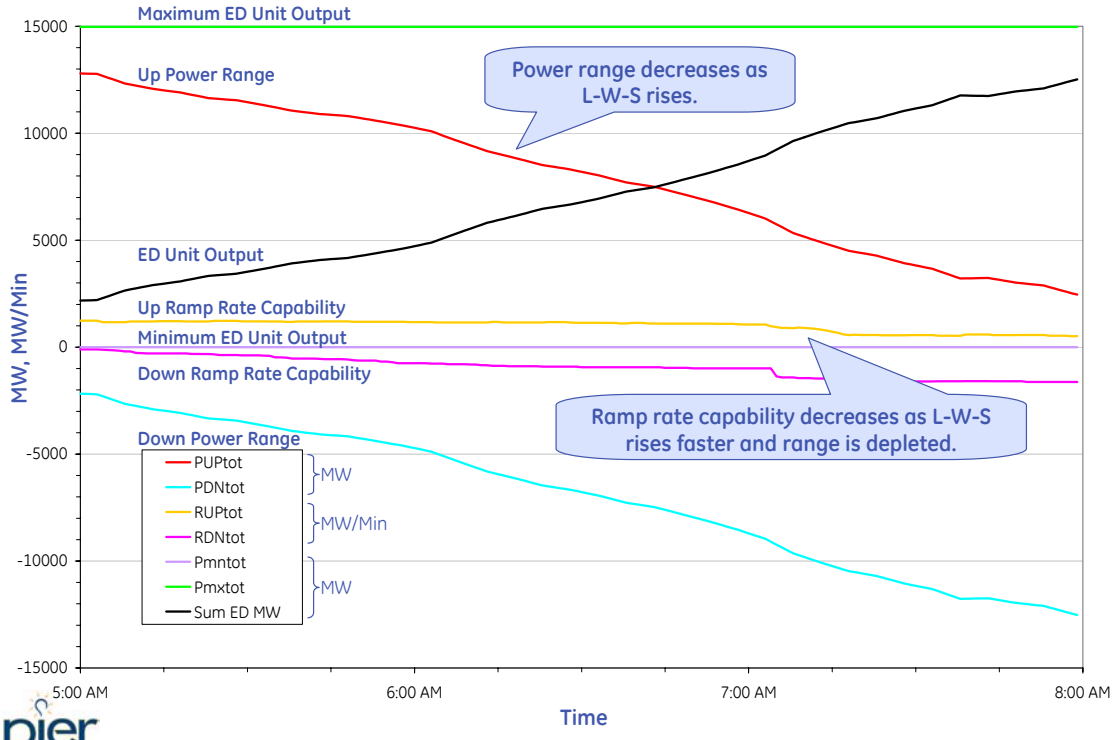
$\Sigma(-Rate_i$, if $P_i>P_{imin})$ in MW/min

Pmntot = Minimum power of ED units: ΣP_{imin} in MW

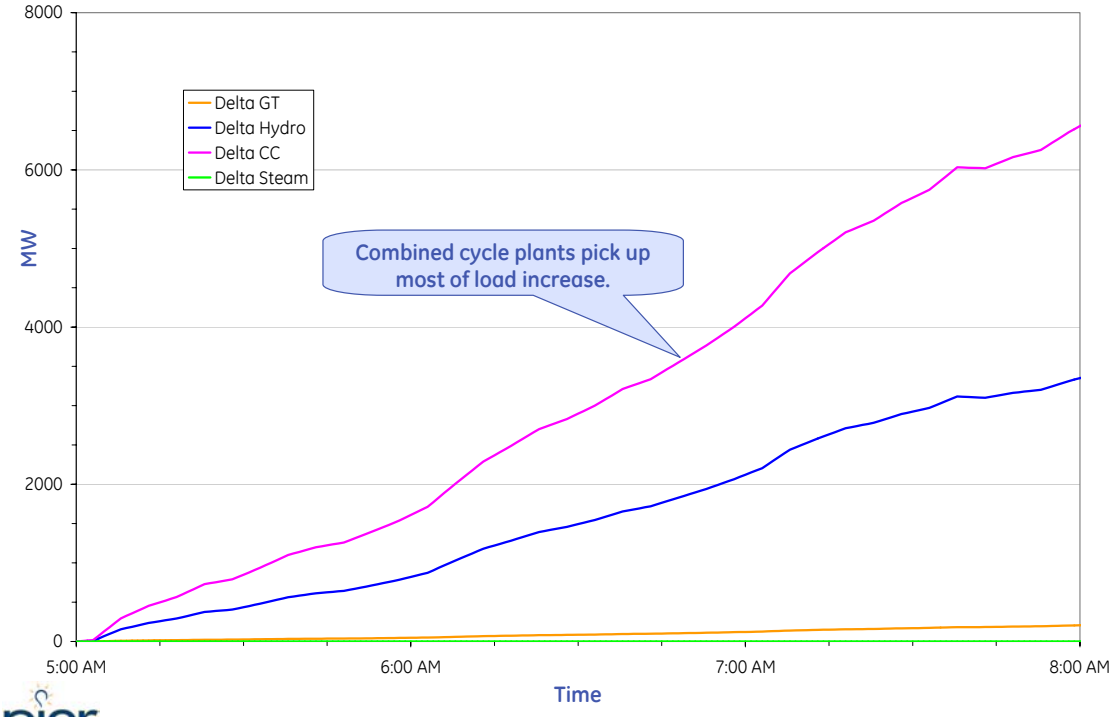
Pmxtot = Maximum power of ED units: ΣP_{imax} in MW

Sum ED MW = Output of ED units: ΣP_i in MW

July Morning: Maneuverability Variables



July Morning: Economic Dispatch Unit Change by Type



QSS Performance Variables:

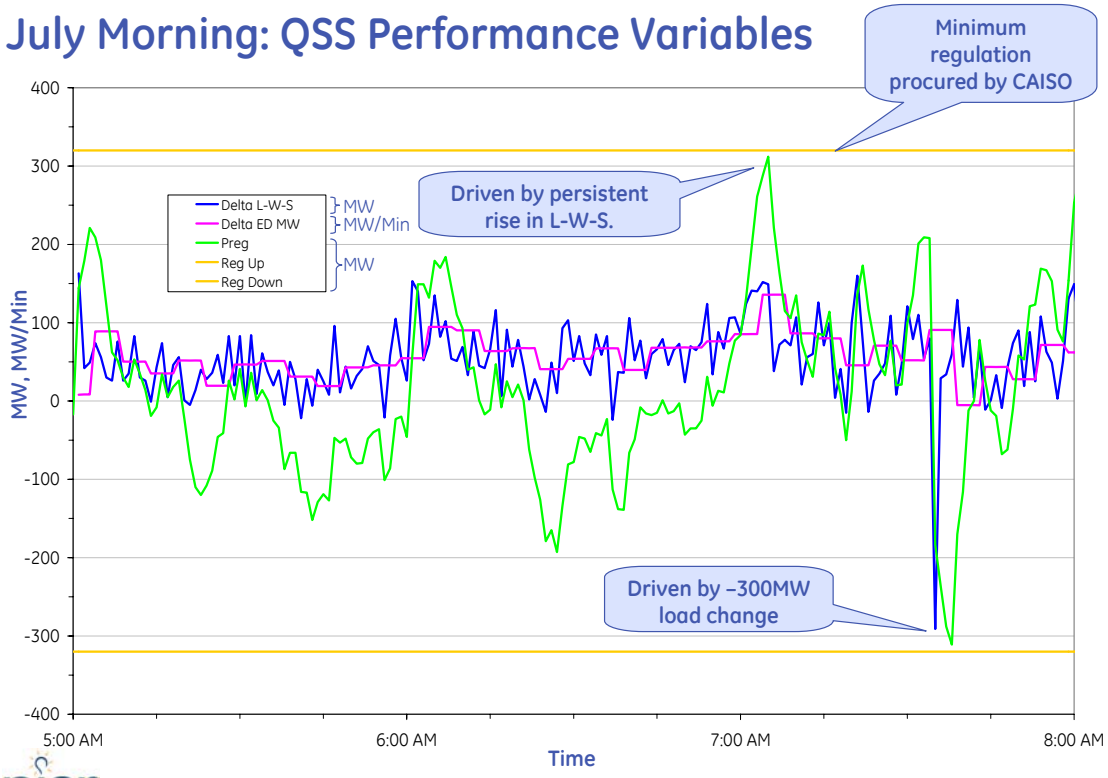
Variables describing important behavior of load variability, regulation and ED raise/lower signals:

Delta L-W-S = One-minute change in total load minus wind minus solar power in MW/min

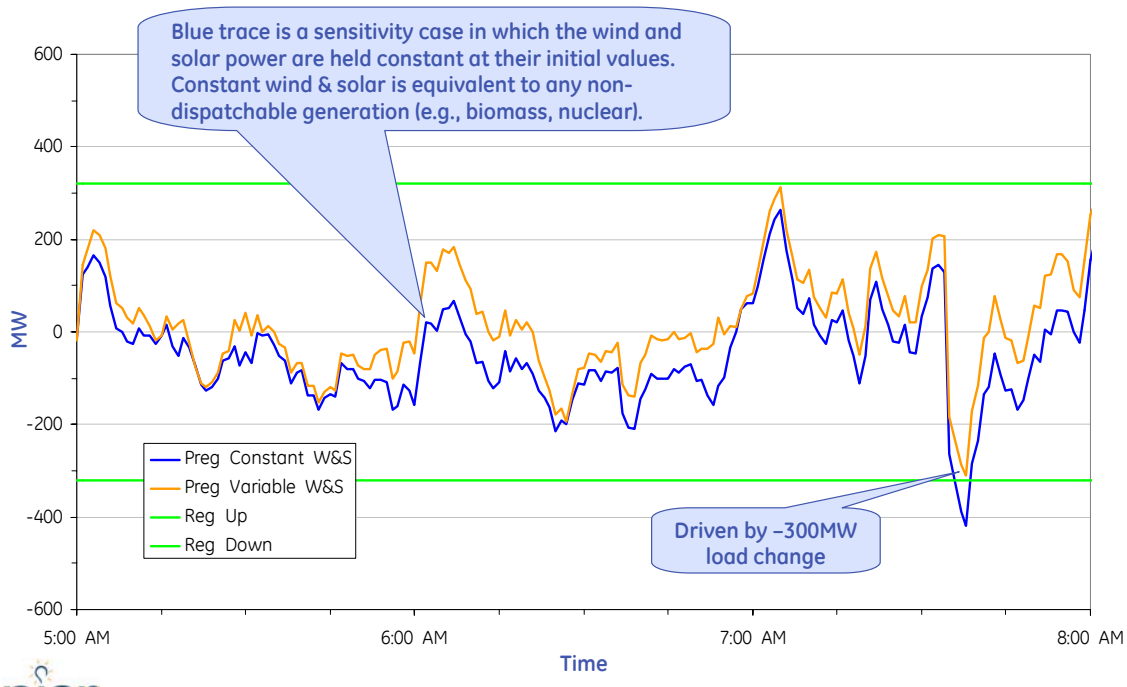
Delta ED MW = Sum of increment (or decrement) order to all ED units in MW/min (ED cycle is 5 minutes, so inc/dec is constant for each successive 5 minute period)

Preg = Total regulating power necessary to balance in MW

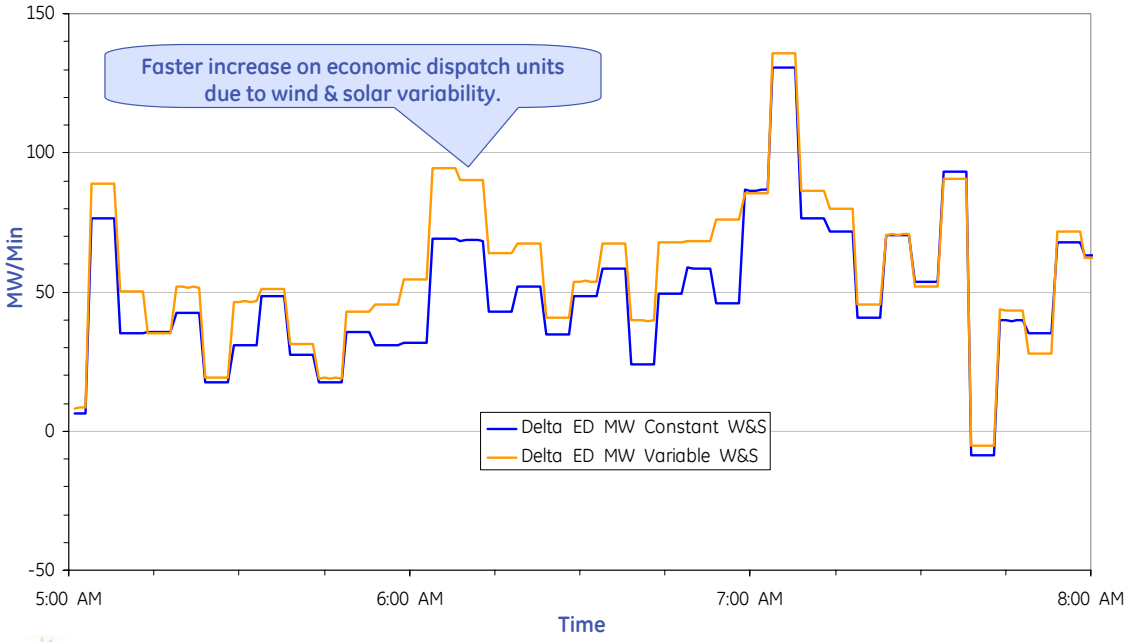
July Morning: QSS Performance Variables



July Morning: Impact of Wind & Solar Variability



July Morning: Impact of Wind & Solar Variability



July Morning Load Rise Case Illustrates:

- Most of the load-following is performed by combined-cycle plants
- Load following increases due to net decrease in renewable generation (from ~2,700mw/hr to ~3,300mw/hr)
- Regulation duty is due primarily to load variation, but is offset up by decrease in wind power
- An economically rational unit commitment and dispatch gives adequate load-following capability

May Night Case (2010X Mix)

~12,500MW Total CA Wind Capacity
142 Individual Wind Plants
~2,600MW Total CA Solar Capacity
42 Concentrating Solar Plants, 128 PV Sites
2003 Load Shape

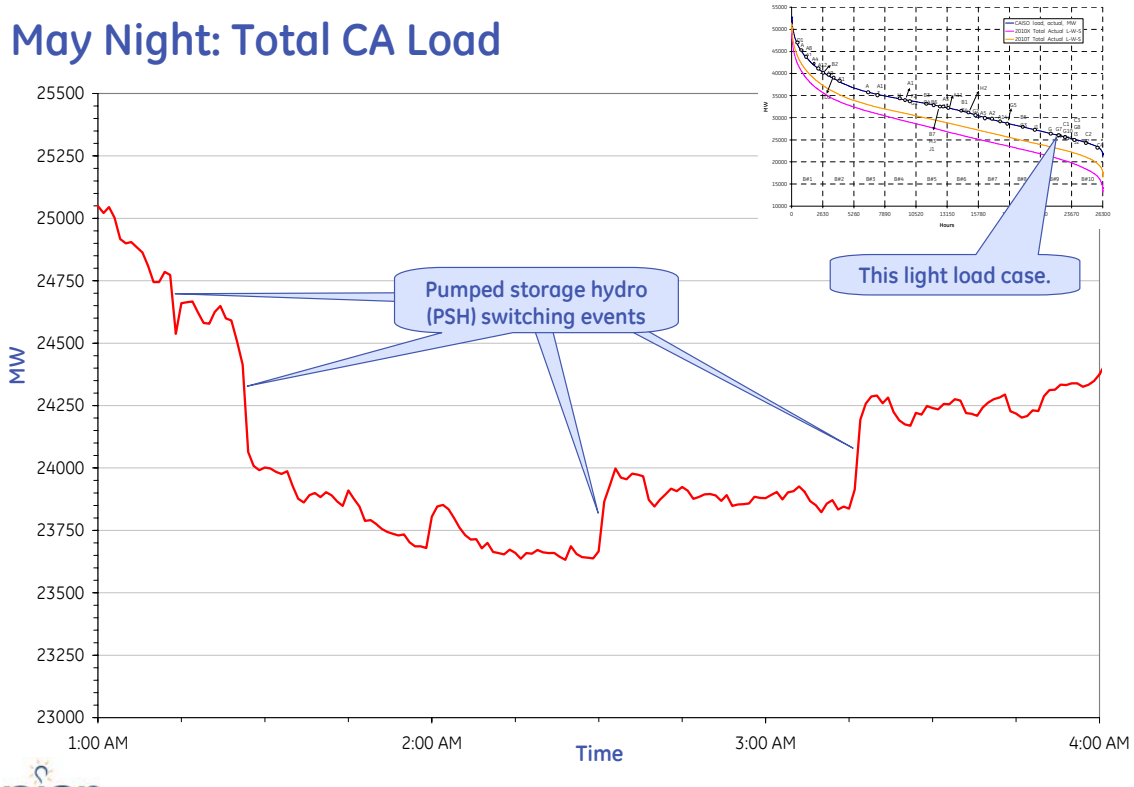
3hr Period of High Wind Power and Penetration

Total Load Decrease ~675 MW
Total Wind Decrease ~675 MW

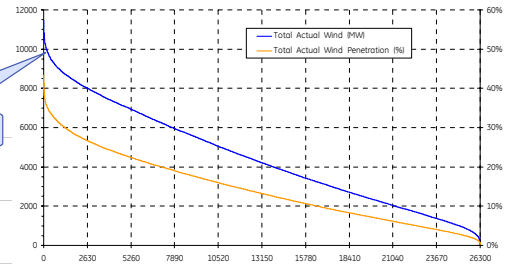
Case selected to examine potential for problems with high wind penetration during low, relatively steady load conditions.

Wind Penetration ~40% (~10GW Wind)

May Night: Total CA Load



May Night: Total CA Wind



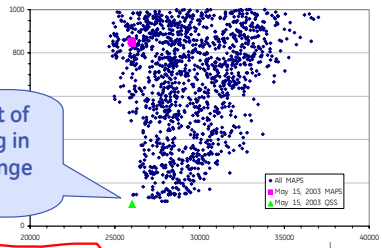
This high wind case.

MW

Time

Analysis of 3 Years of Hourly Data	
Maximum Total Wind	11,469 MW
% Hours with Total Wind > 10,000 MW	~1%
Average Intermittent Penetration at Light Load	29%
Peak Intermittent Penetration	39%

May Night: Maneuverability Variables



QSS ED units are subset of all MAPS units, resulting in lower ramp rate and range calculations.

Maximum ED Unit Output

Up Power Range

ED Unit Output

Minimum ED Unit Output

Up Ramp Rate Capability

Down Ramp Rate Capability

Down Power Range

PUPtot
PDNtot
RUPtot
RDNtot
Pmntot
Pmxtot
Sum ED MW

MW
MW/Min
MW

Down ramp rate capability exhausted

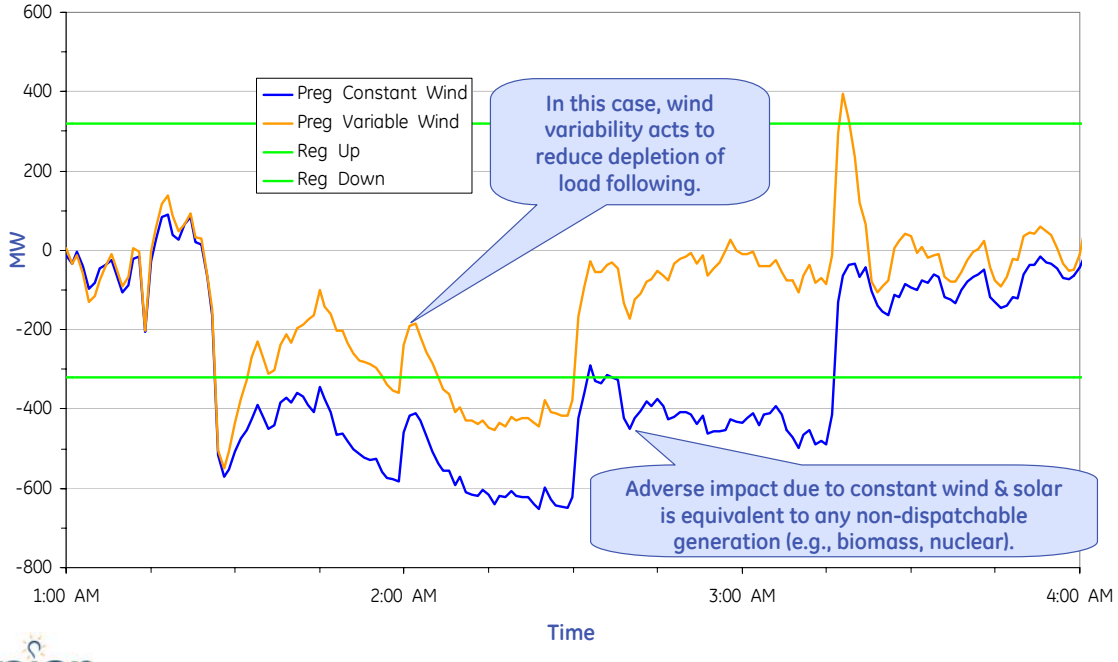
Down power range exhausted

MW, MW/Min

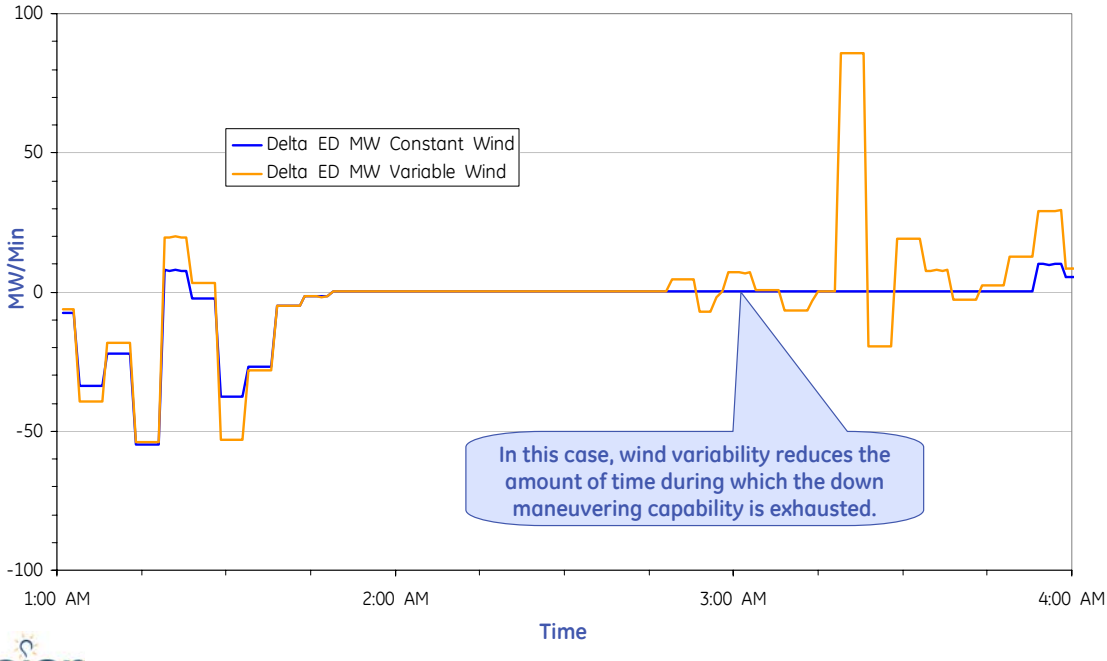
Time

May Night: Performance Variables

May Night: Impact of Wind Variability



May Night: Impact of Wind Variability



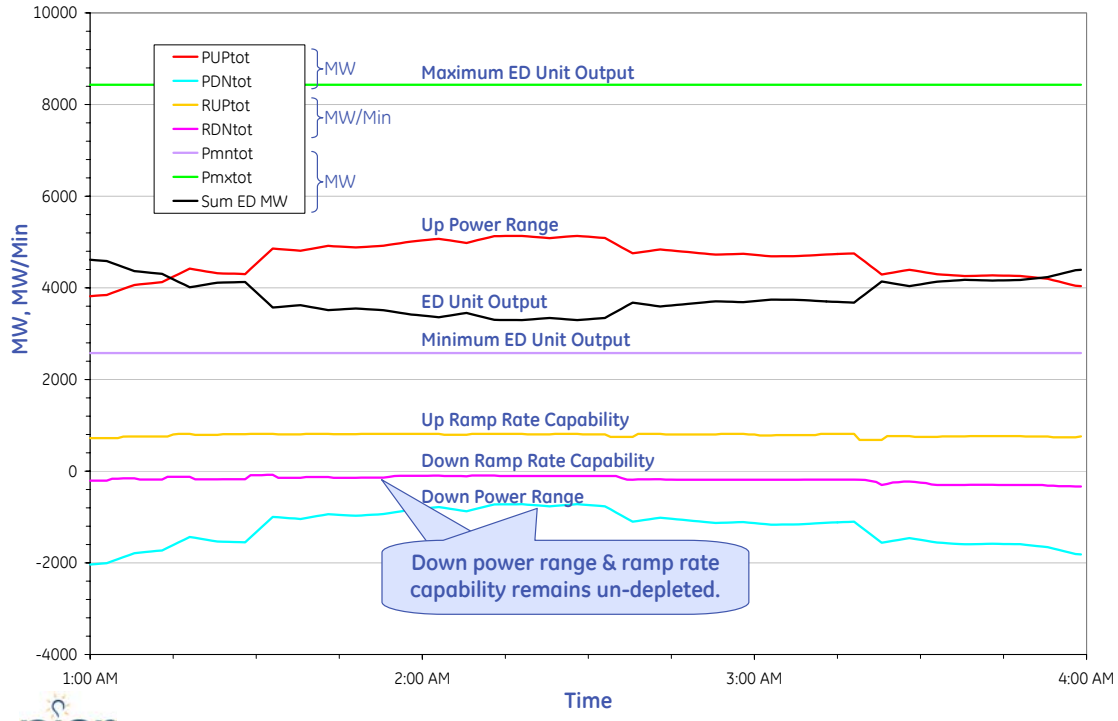
May Night Case (2010X Mix)

~12,500MW Total CA Wind Capacity
142 Individual Wind Plants
~2,600MW Total CA Solar Capacity
42 Concentrating Solar Plants, 128 PV Sites
2003 Load Shape

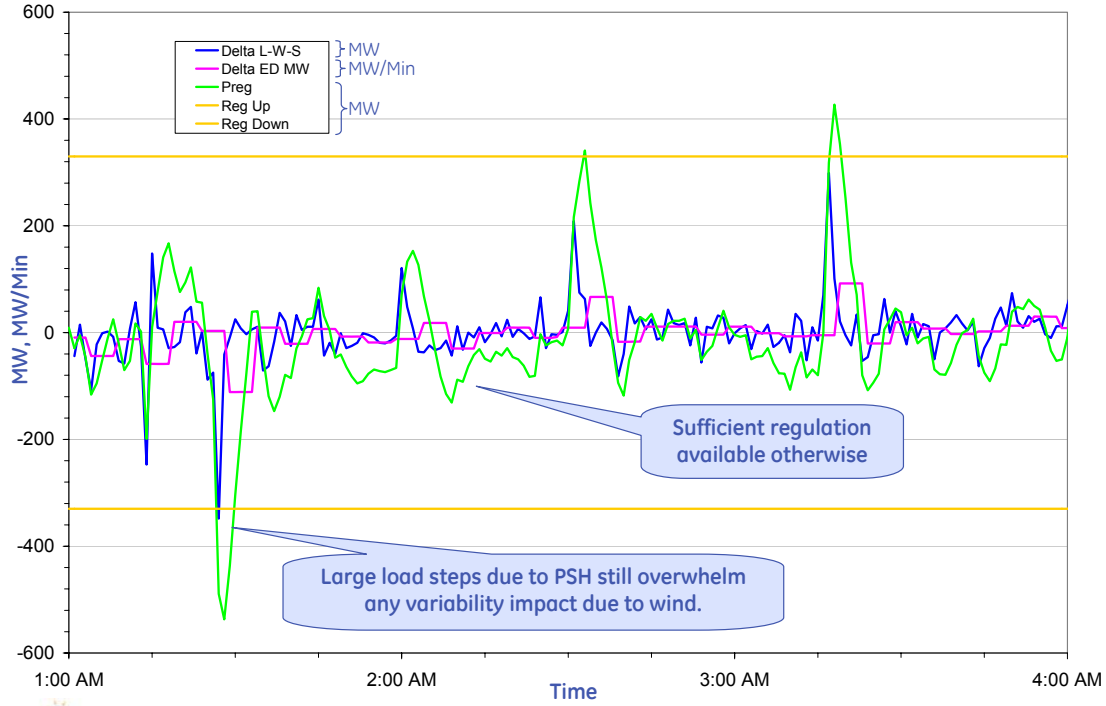
Change Generation Commitment, such that Maneuvering Capability is Increased by Replacing 2,200MW of Base Load Generation with 2,200MW of Combined-Cycle Generation

Sensitivity case designed to show impact of replacing un-maneuverable generation with maneuverable generation.

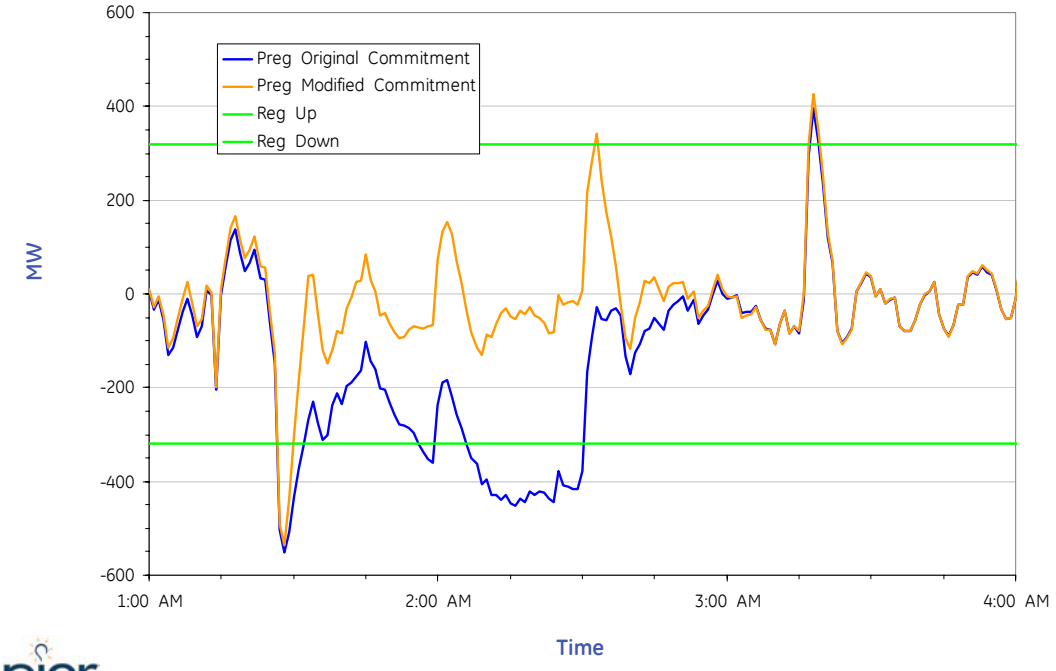
May Night: Maneuverability Variables with More CC



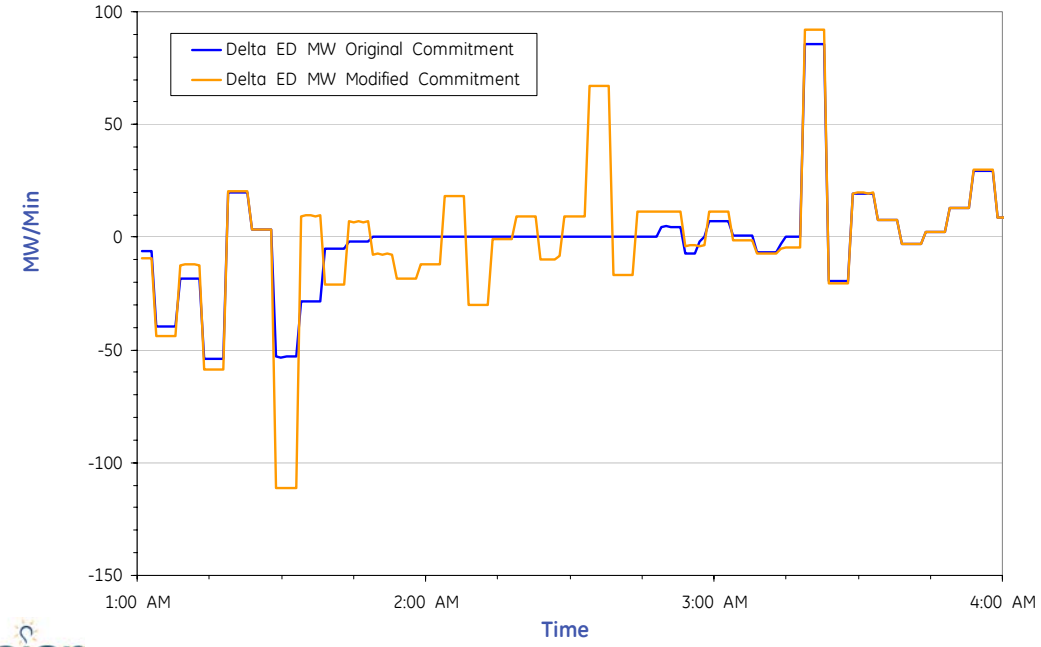
May Night: Performance Variables with More CC



May Night: Impact of Additional Maneuverable Units



May Night: Impact of Additional Maneuverable Units



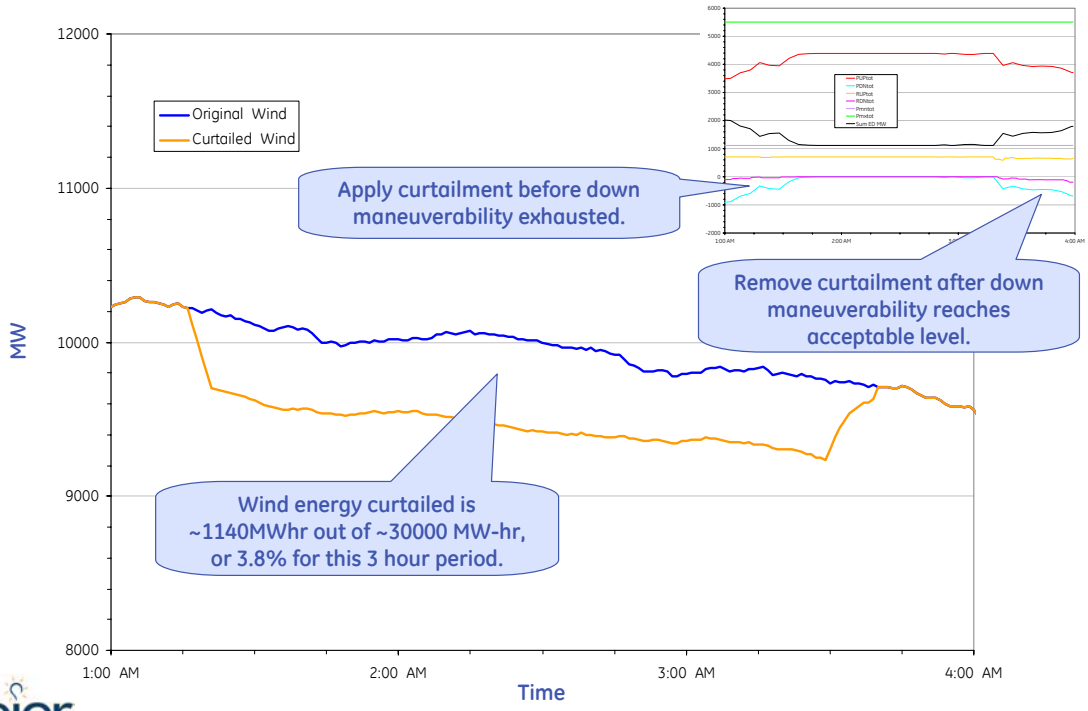
May Night Case (2010X Mix)

~12,500MW Total CA Wind Capacity
142 Individual Wind Plants
~2,600MW Total CA Solar Capacity
42 Concentrating Solar Plants, 128 PV Sites
2003 Load Shape

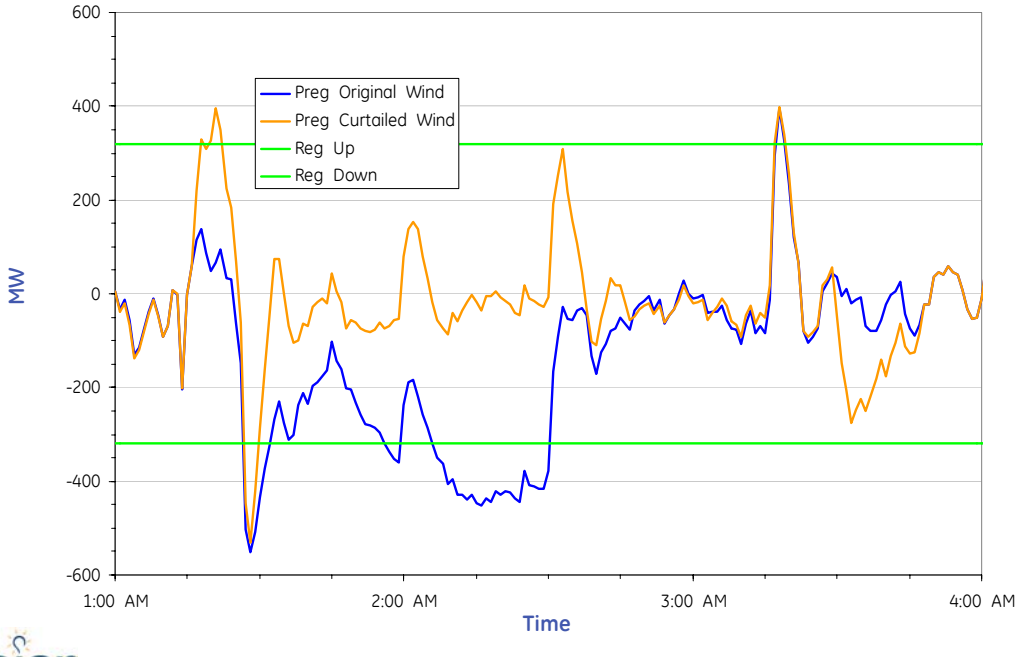
Improve System Maneuverability
Temporary Curtailment of Wind Generation

Sensitivity case designed to illustrate use of a mitigation scheme under extreme circumstances.

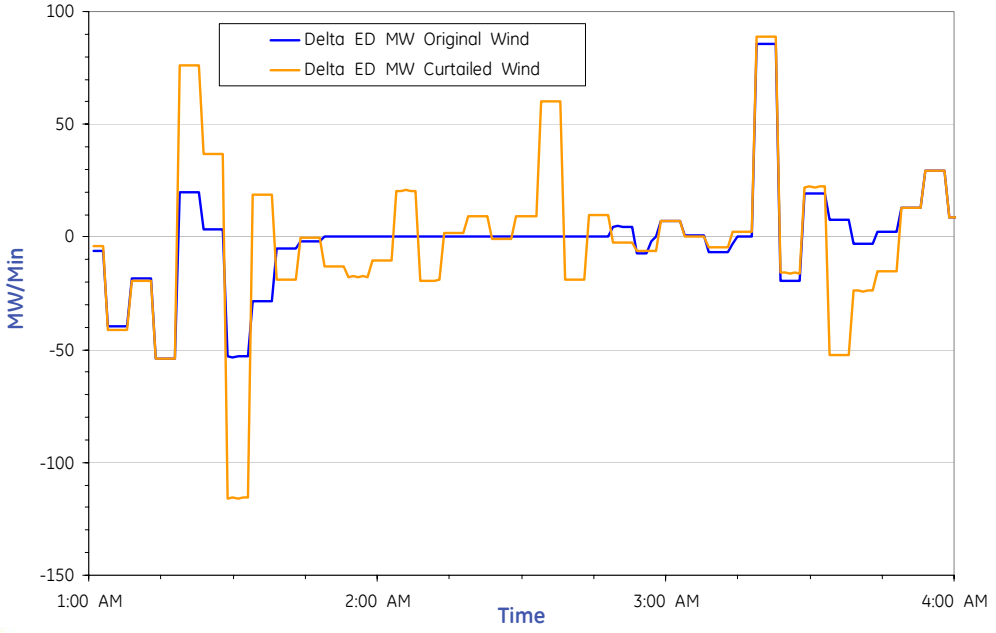
May Night: Temporary Wind Generation Curtailment



May Night: Temporary Wind Generation Curtailment



May Night: Temporary Wind Generation Curtailment



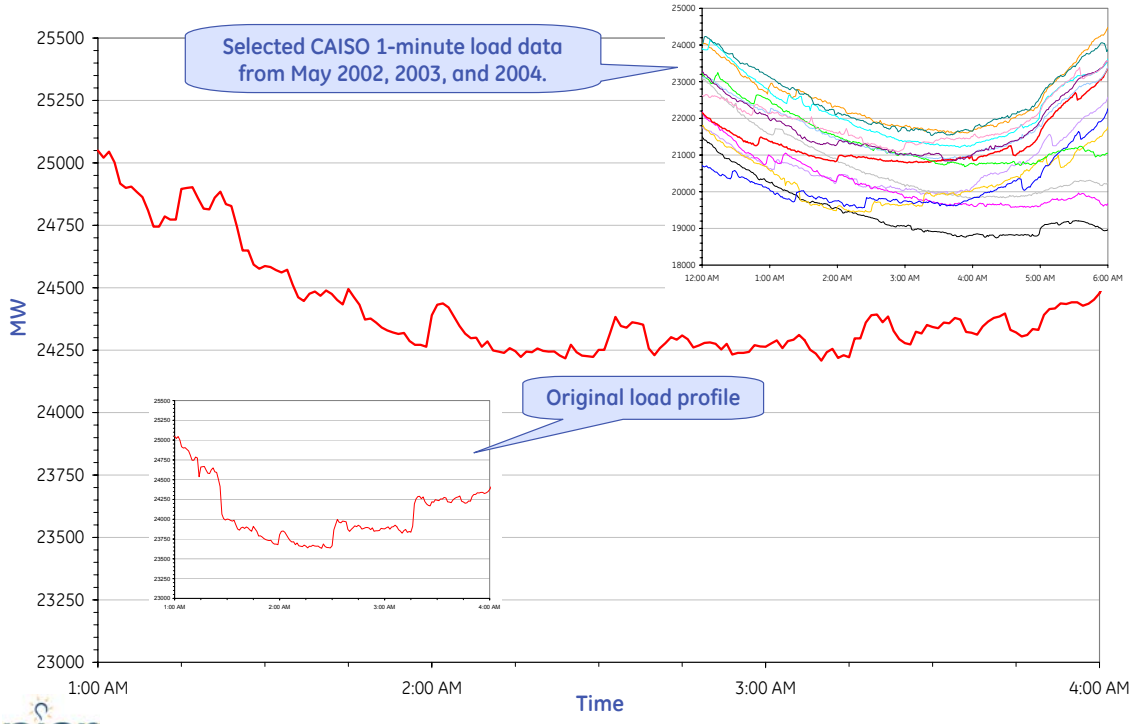
May Night Case (2010X Mix)

~12,500MW Total CA Wind Capacity
142 Individual Wind Plants
~2,600MW Total CA Solar Capacity
42 Concentrating Solar Plants, 128 PV Sites
2003 Load Shape

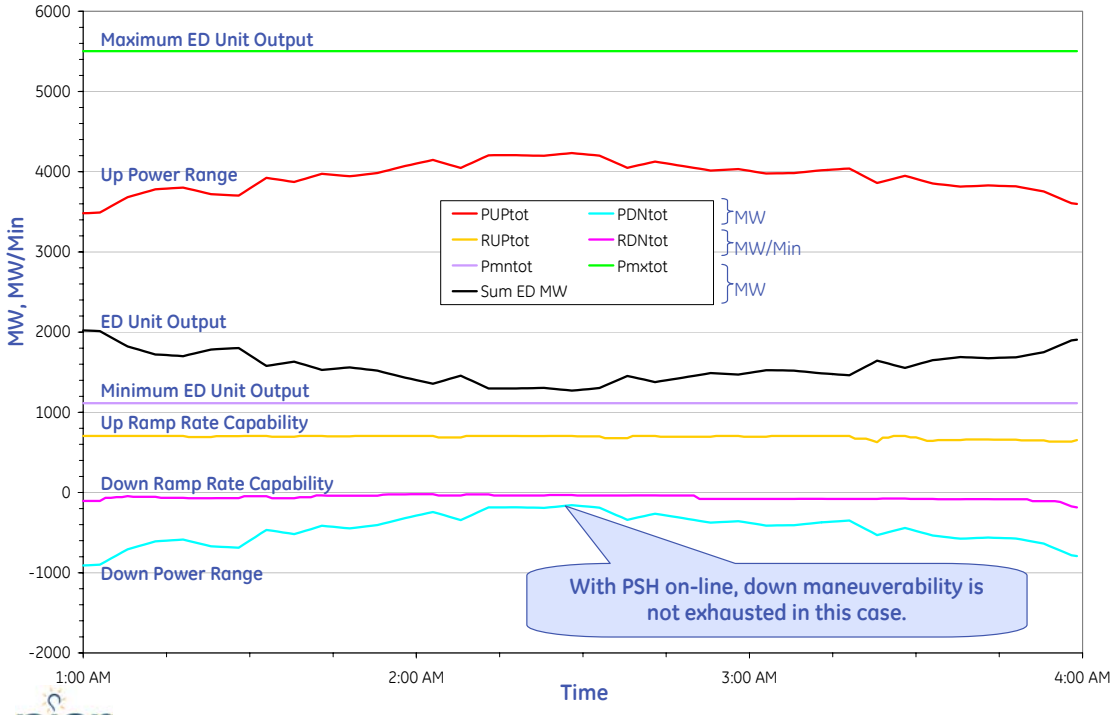
Remove Pumped Storage Hydro Steps from Load Profile

Sensitivity case designed to examine interaction of load and wind variability by isolating disruption from pumped storage hydro switching events.

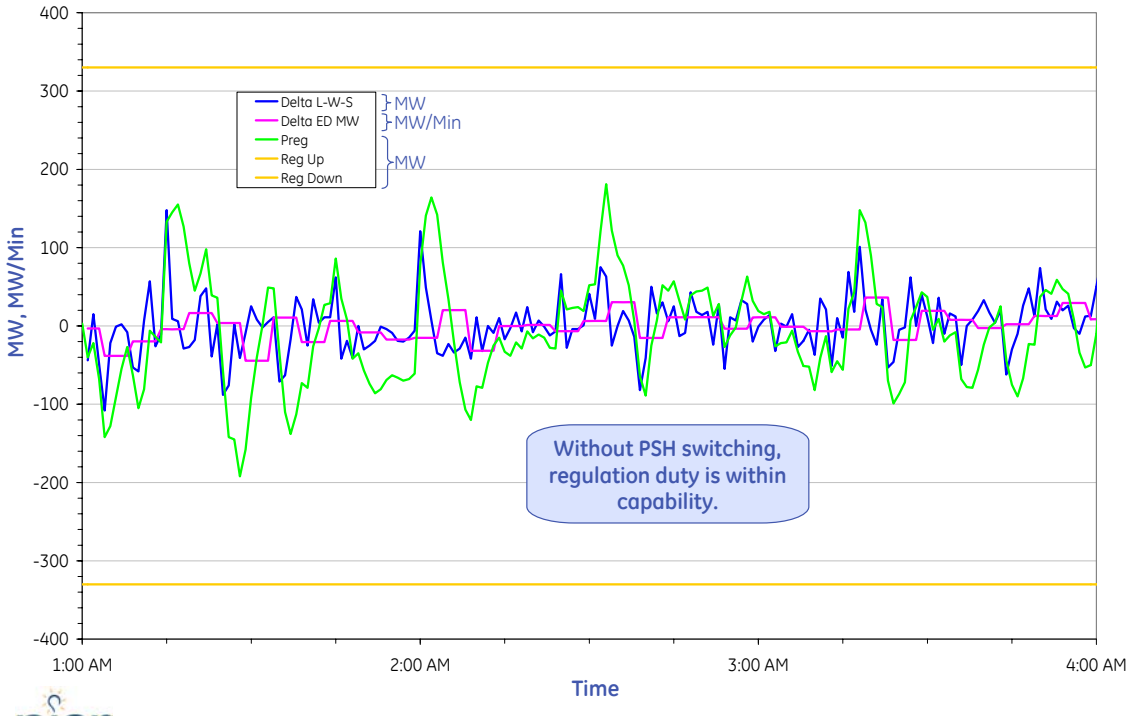
May Night: Total CA Load Without PSH Steps



May Night: Maneuverability Variables w/o PSH Steps



May Night: Performance Variables w/o PSH Steps



May Night Light Load, High Wind Case Illustrates:

- Large steps in load have more significant impact on regulation than wind variability
- Insufficient down capability (both range and ramp rate) shifts load following duty to regulation, which may then become exhausted
- Variability of wind increases the ED unit duty
  - MW/min increases about 20%
  - Frequency of sign changes increases
- The importance of using available maneuverability, and avoiding non-technical constraints
- Change in commitment or curtailment of wind effectively mitigates loss of maneuverability

June Evening Case (2010X Mix)

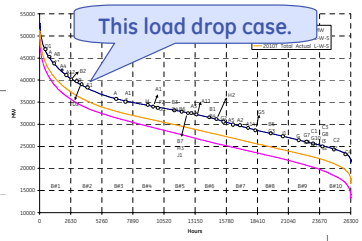
~12,500MW Total CA Wind Capacity
142 Individual Wind Plants
~2,600MW Total CA Solar Capacity
42 Concentrating Solar Plants, 128 PV Sites
2004 Load Shape

3hr Period of Load Decrease and Wind Increase

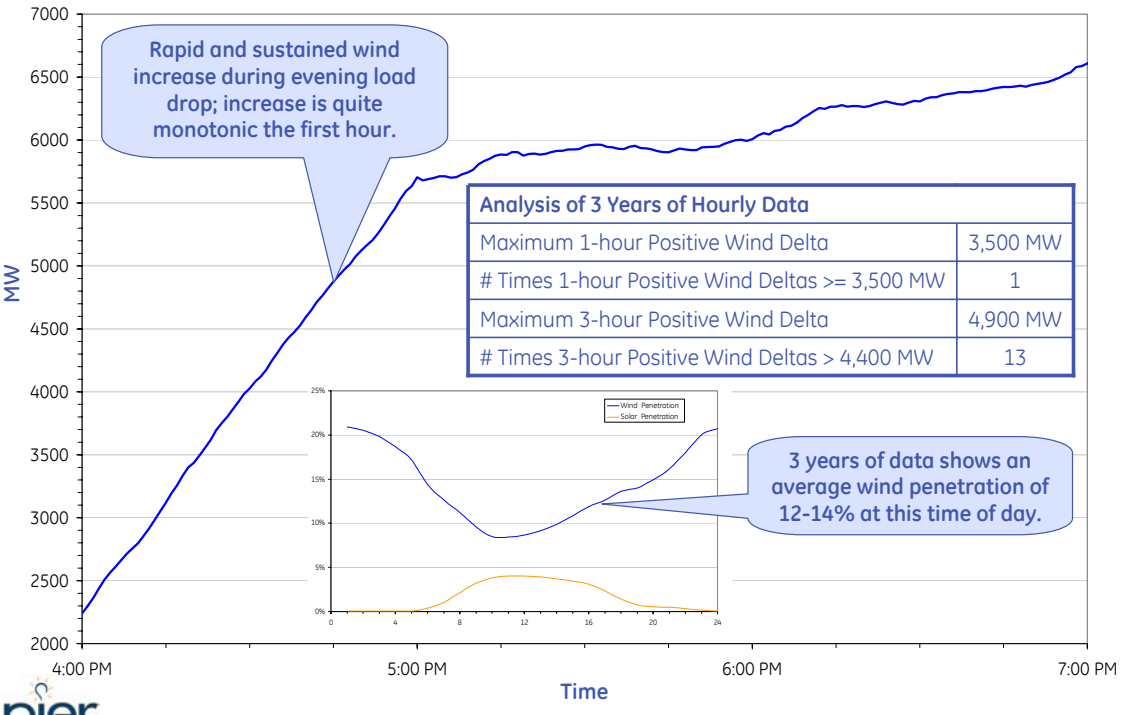
Total Load Decrease ~2,700 MW
Total Wind Increase ~4,400 MW
Total Solar Decrease ~900 MW
Wind & Solar Penetration 9% -> 18%

Case selected to examine potential for problems with rapid wind power increase during periods of load decrease

June Evening: Total CA Load

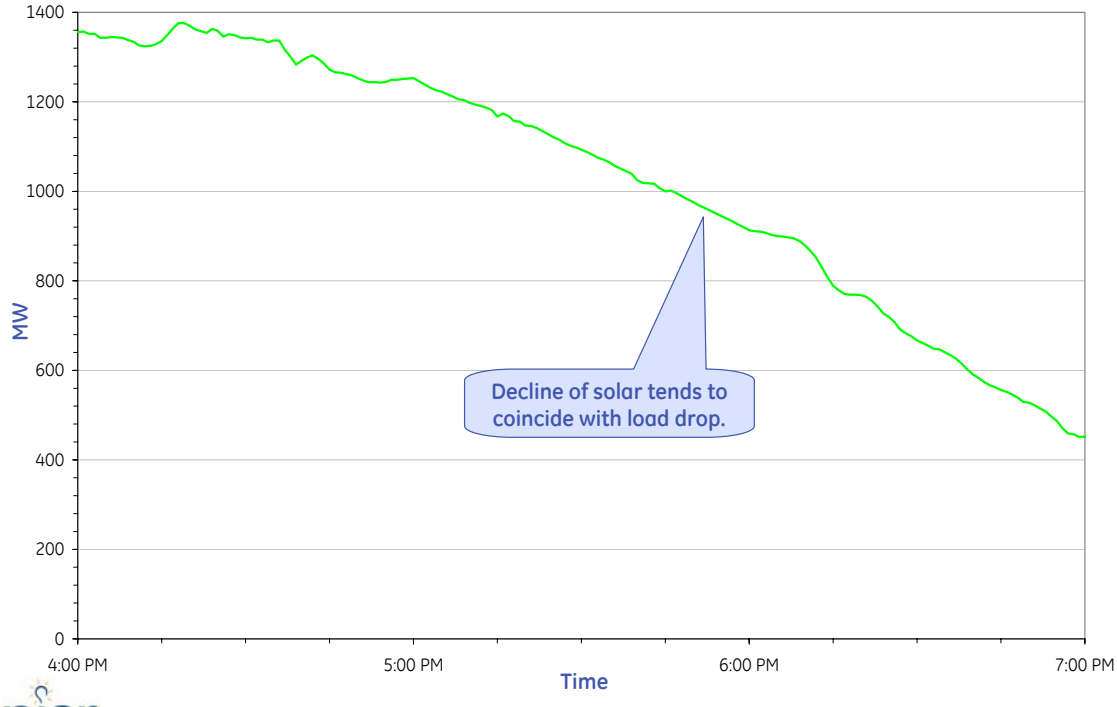


June Evening: Total CA Wind

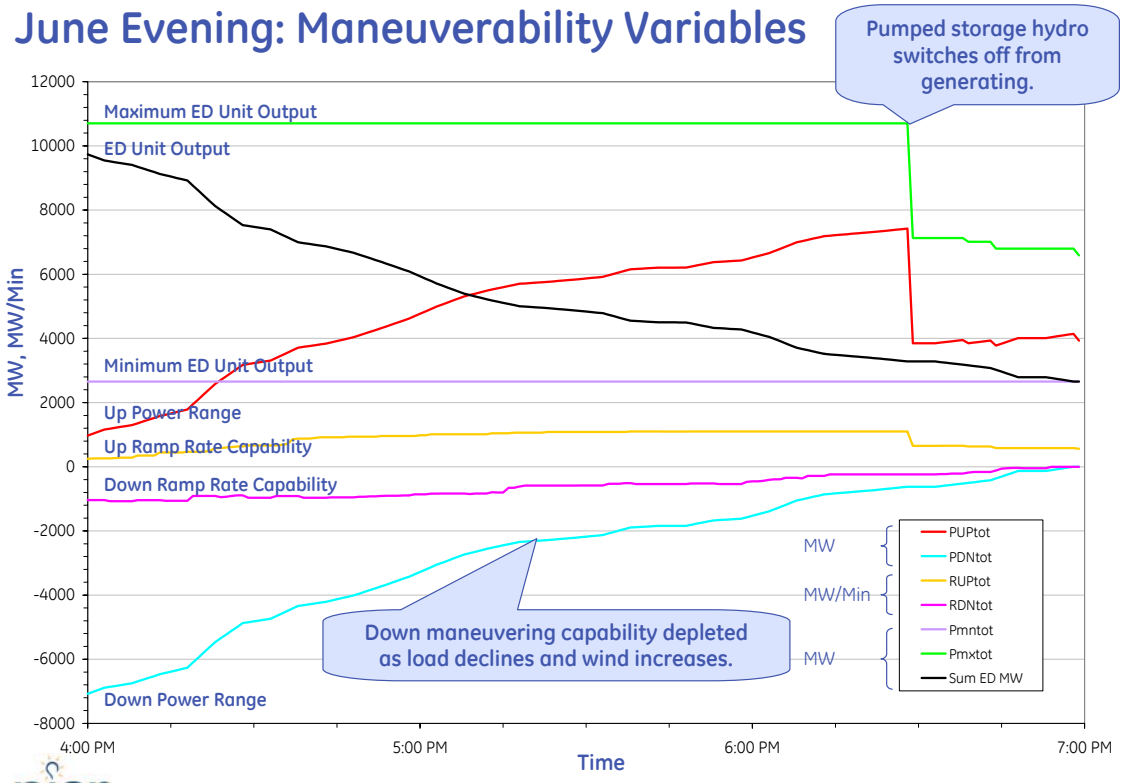


Analysis of 3 Years of Hourly Data	
Maximum 1-hour Positive Wind Delta	3,500 MW
# Times 1-hour Positive Wind Deltas >= 3,500 MW	1
Maximum 3-hour Positive Wind Delta	4,900 MW
# Times 3-hour Positive Wind Deltas > 4,400 MW	13

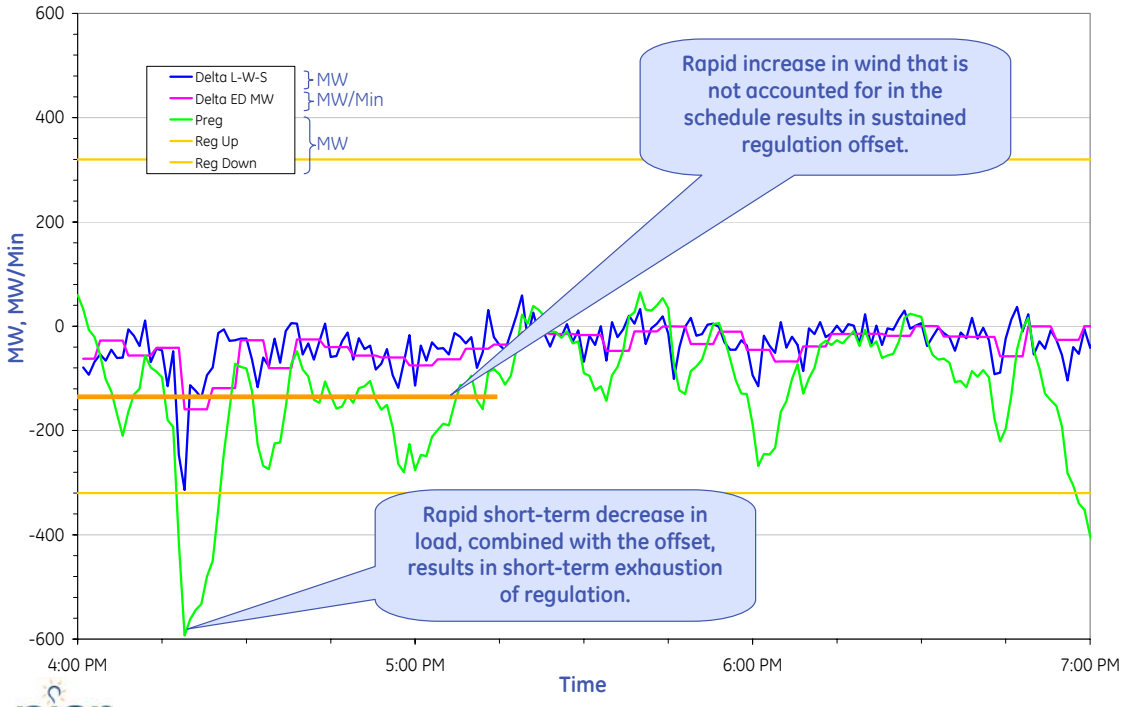
June Evening: Total CA Solar



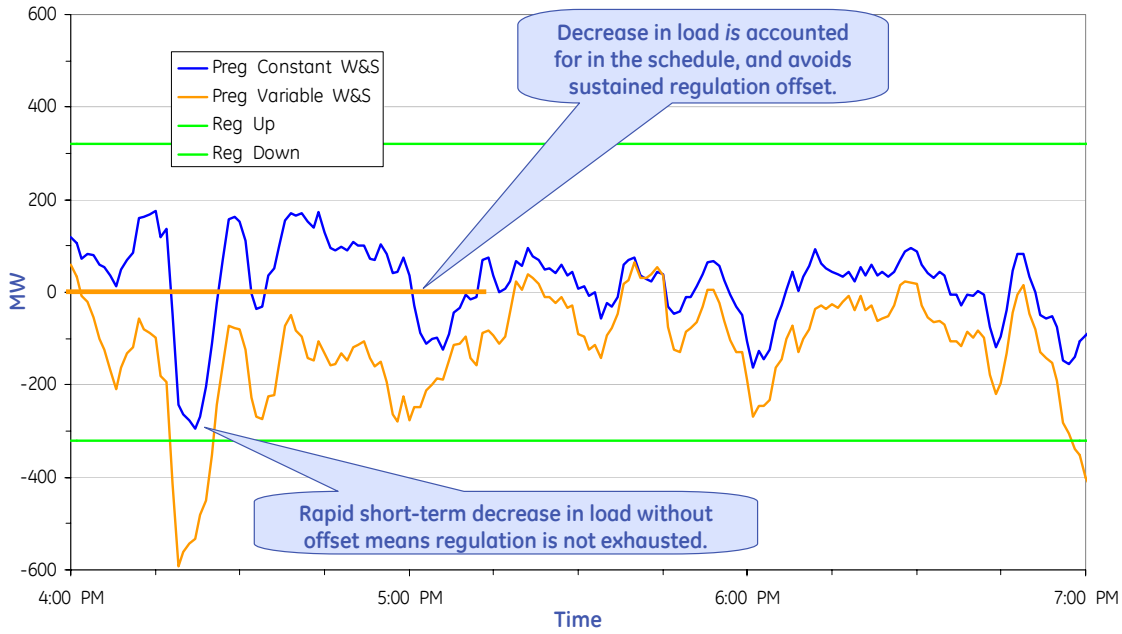
June Evening: Maneuverability Variables



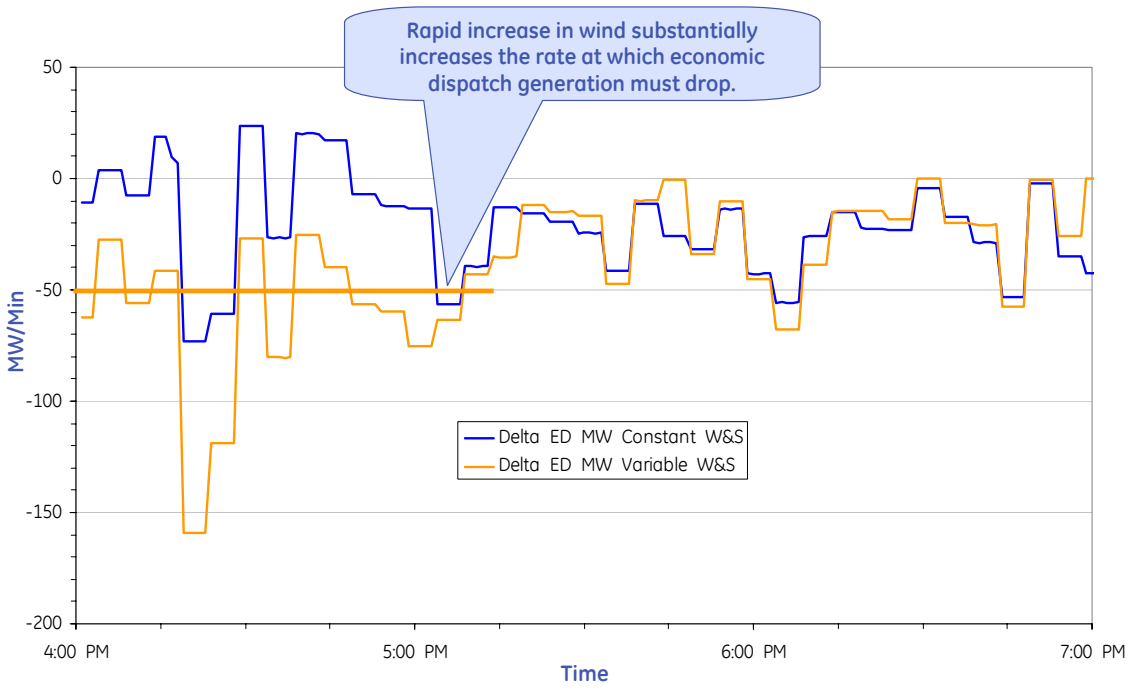
June Evening: Performance Variables



June Evening: Impact of Wind & Solar Variability



June Evening: Impact of Wind & Solar Variability



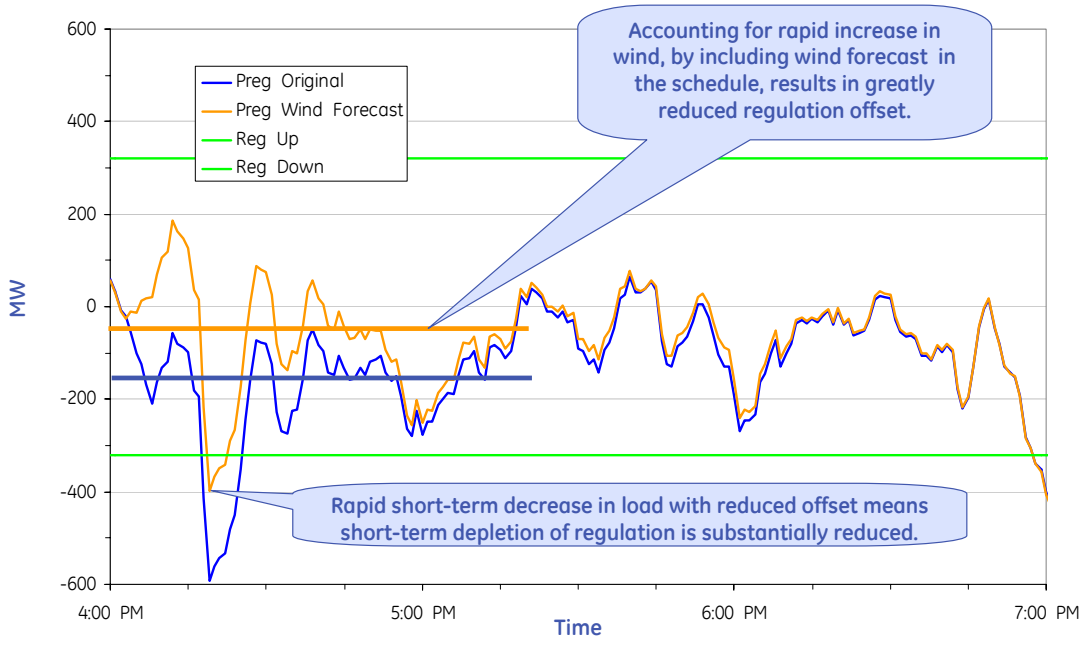
June Evening Case (2010X Mix)

~12,500MW Total CA Wind Capacity
142 Individual Wind Plants
~2,600MW Total CA Solar Capacity
42 Concentrating Solar Plants, 128 PV Sites
2004 Load Shape

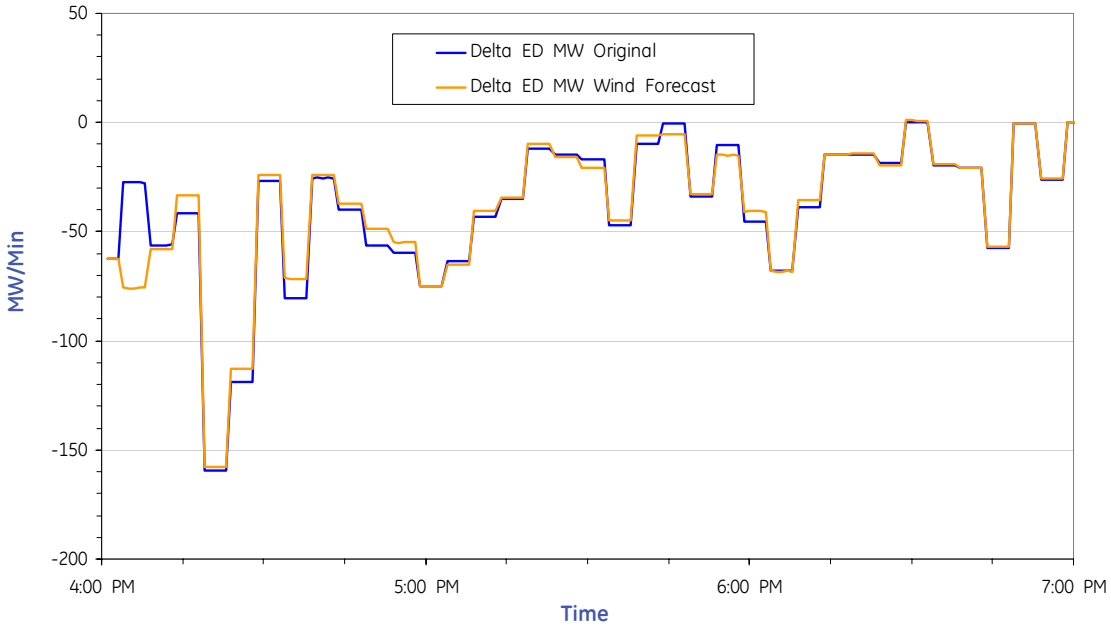
Mitigate High Regulation Need
Incorporate Hourly Wind Forecast into ED

Mitigation case designed to examine potential benefit for short-term forecasting to reduce high regulation need and avoid schedule violations (CPS2).

June Evening: Impact of Including Hourly Wind Forecast



June Evening: Impact of Including Hourly Wind Forecast



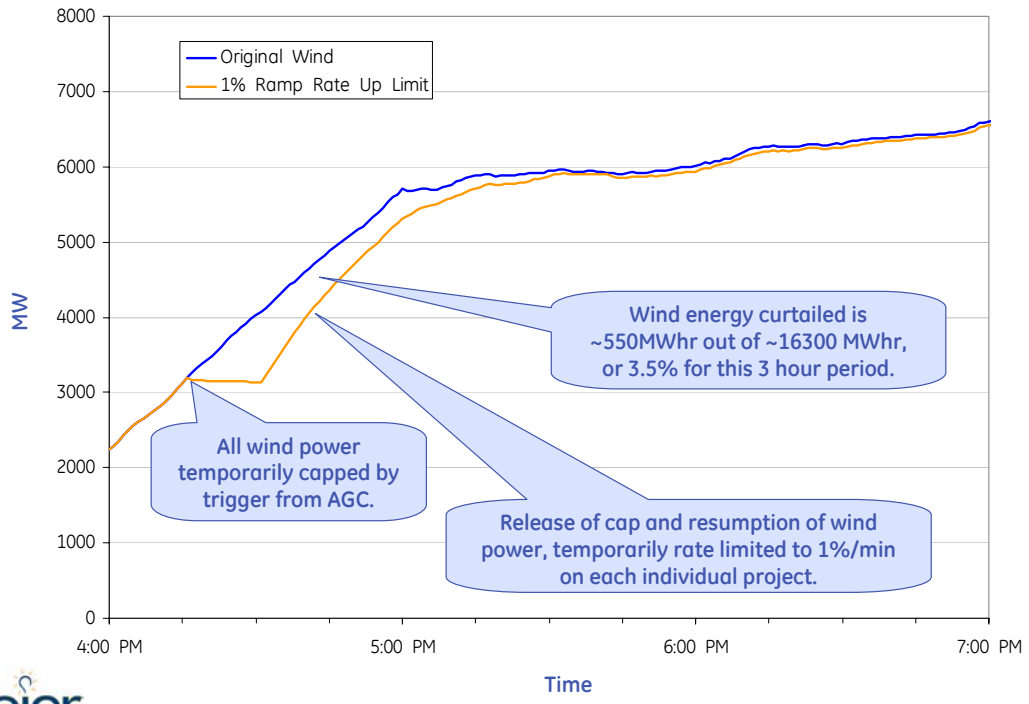
June Evening Case (2010X Mix)

~12,500MW Total CA Wind Capacity
142 Individual Wind Plants
~2,600MW Total CA Solar Capacity
42 Concentrating Solar Plants, 128 PV Sites
2004 Load Shape

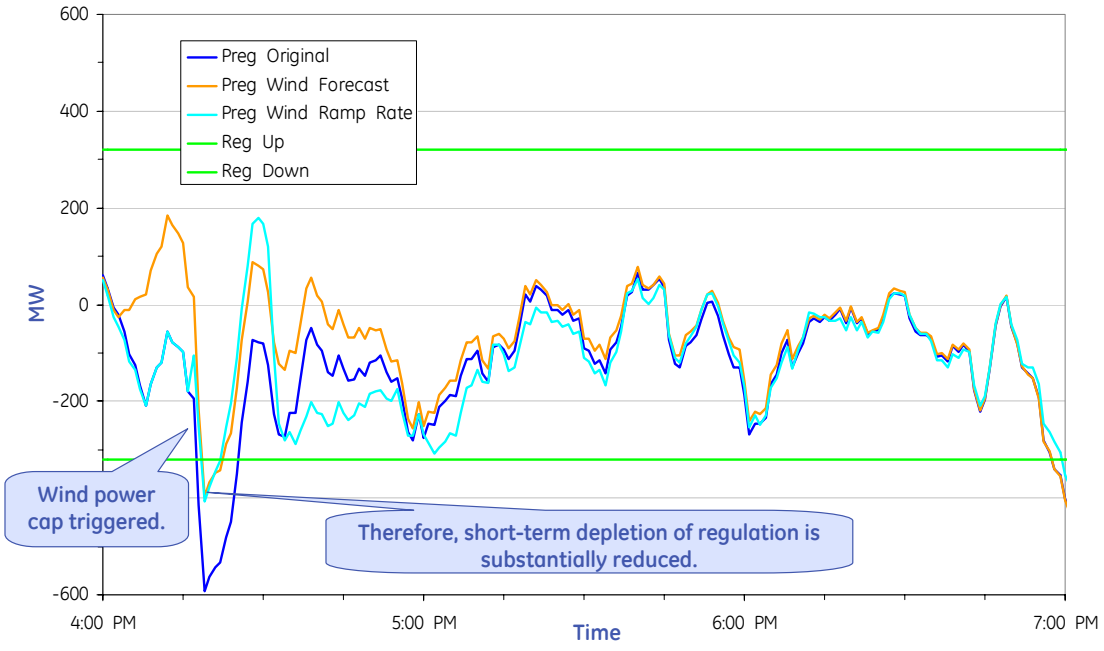
Mitigate High Regulation Need
Triggered Wind Generation Cap with 1%/Minute Ramp Up Rate Limit After Release

Mitigation case designed to examine potential benefit for one type of wind plant active power control to reduce high regulation need and avoid schedule violations (CPS2).

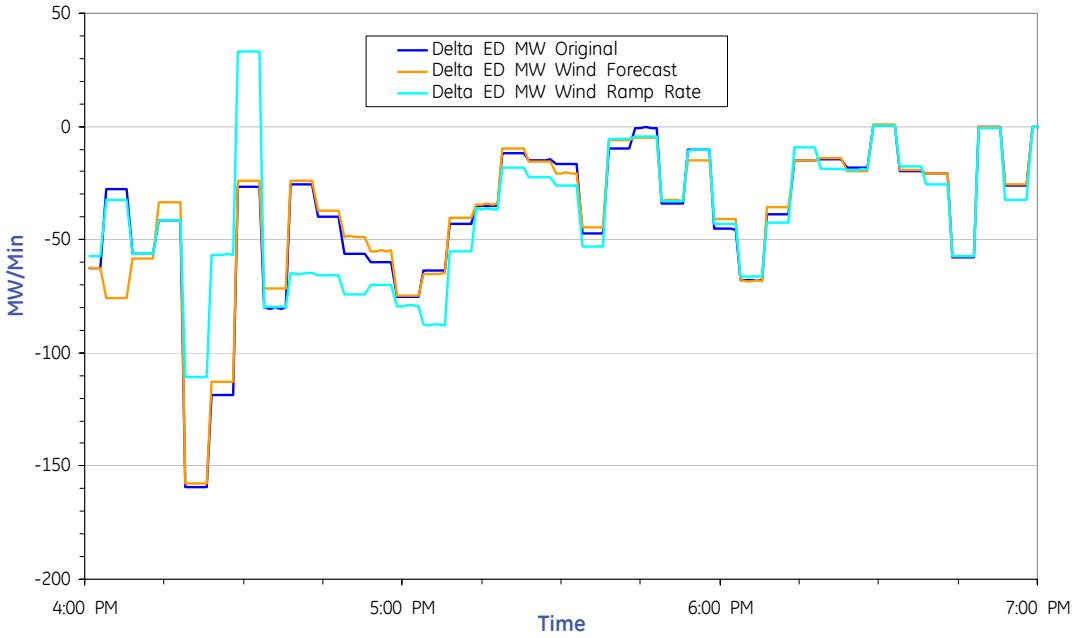
June Evening: Temporary Wind Ramp Rate Up Limit



June Evening: Impact of Wind Ramp Rate Up Limit



June Evening: Impact of Wind Ramp Rate Up Limit



June Evening Load Drop, Wind Rise Case Illustrates:

- Regulation picks up sustained changes in wind power unless short-term forecasted changes are included in the schedule
- This increases the likelihood that regulation will be exhausted, and less able to respond to rapid changes in load
  - Shows incremental risk of CPS2 violations
- Short-term curtailment of wind (with a ramp-rate limitation after release) can reduce the severity of regulation duty due to rapid changes in load or intermittent renewable generation
  - Some wind energy production is lost to achieve this benefit
  - Occurred < 0.1% of the hours in 3 years of data