# Emission II Study of Advanced Storage used for Frequency Regulation

Department of Energy – Sandia National Labs

Project Number: Sandia Negotiation 96362

Prepared by KEMA, Inc.

December 31, 2012

Authors: Manuel Atanacio

Richard Fioravanti

Dr. Warren Katzenstein

Dr. Khoi Vu

# Table of Contents

# Table of Contents

## List of Exhibits

# Table of Contents

## Abbreviations

| | |
|---|---|
| AGC | area generation control |
| BESS | battery energy storage system |
| BMS | battery management system |
| CAISO | California ISO |
| DC | direct current |
| DoD | depth of discharge |
| DOE | U.S. Department of Energy |
| ES | energy storage |
| FERC | Federal Energy Regulatory Commission |
| GW | gigawatt |
| GWh | gigawatt-hour |
| HVAC | heating, ventilating, and air conditioning |
| IOU | investor-owned utility |
| ISO | independent system operator |
| IPP | independent power producer |
| LMP | locational marginal pricing |
| NERC | North American Electric Reliability Corporation |
| PCS | power conversion system |
| RPS | renewable portfolio standard |
| RTO | Regional Transmission Organization |
| SCADA | supervisory control and data acquisition |
| SOC | state of charge |
| T&D | transmission & distribution |
| VAR | volt-amperes reactive |

# 1. Executive Summary

In 2007, KEMA, Inc. (KEMA) was commissioned by the Depart of Energy (DOE), through Beacon Power Corporation and Sandia National Labs to investigate potential emission savings created by having advanced, fast response storage provide regulation vs. traditional power plants.

The project only provided a high level "snapshot" of the potential advantages that could be created by such a substitution. This snapshot essentially comprised of a comparison of a flywheel device vs. (1) A coal-fired plant and (2) a natural gas combustion turbine. Analysis focused on Baseloaded Generation (400 MW) and Peaker Plants (60 MW). In addition, a comparison was also made to a pumped hydro facility.

The results of this study showed significant advantages to using the fast response storage device in savings for $CO_2$ and advantages with NOx as well. The main driver to this was the fact that the storage device is charged by a "portfolio of generation" in the territory it was operating in and also by the perceived inefficiencies of operating power plants in regulation mode. These inefficiencies were assumed to be caused by "ramping" a generator in response to the regulation requirements.

The final report noted the high-level approach of the original model. Hence, in the 2007 report, recommendations were made for next steps. These recommendations included the following:

- All the data of this study was based on publicly available data from DOE, EPA and the different ISO sites. Some of the data may be dated in terms of the generation mix and generating efficiencies and heat rates. These results should be validated with direct ISO involvement in a future study.

- The assumed generation data is of a generic plant. It is thus limited in the details of specific frequency regulation plant efficiencies under different operating scenarios. It is proposed that a more in-depth analysis is performed based on specific coal or gas-fired generators. This should be done to calculate the specific emission savings that the flywheel installation can achieve at a specific installation in a certain ISO region.

- The frequency regulation control signal from a specific ISO could not be integrated into the current simplistic model. When a specific site is selected for frequency regulation, it is recommended to use specific generation data and integrate the relevant ISO frequency regulation control signal. This will be valuable to investigate the impact of partial discharge cycles on the lifetime emissions savings of the flywheel system compared to other generation technologies.

- The flywheel system has a much faster dynamic response compared to other frequency regulation generation technologies. The faster response or ramp-rate of the flywheel system may provide better frequency regulation results compared to conventional generation units. For comparison this improved performance could not be evaluated and needs to be investigated further.

Since the time of the original study, a number of advancements were made in the tools that could be used to evaluate this potential advantage. Hence, the original "concept" was re-evaluated using current evaluation tools as well as incorporating some of the recommendations from the original report. The results of this reevaluation are summarized in the next section.

## 1.1 Project Summary & Goals

Since the time of the original effort, there have been advancements in activities and modeling tools that could be utilized to update the original assessment and address the specific recommendations that were made in the original study. The advancements that have been made since the original study include:

- Actual Pilot demonstrations of both Lithium-ion and Flywheel devices for frequency regulation
- KEMA's creation of a real time simulation model to simulate the operation of the Frequency Regulation market for specific ISOs.

Hence, KEMA utilized its real time simulation modeling tool (named KERMIT) to produce power system simulations and studied the resulting behavior of conventional generation and fast acting storage devices. The new data resulting from the simulations served to update the approach used in the original assessment of potential emission benefits for storage technologies. Specifically, KEMA focused on two ISO/RTO territories for the study, PJM Territory and the California ISO (CAISO). Cooperating with these two areas, KEMA acquired actual power system and generation fleets data from each ISO, calibrated the KERMIT model for those power systems, ran a series of scenarios in a real time simulation of regulation services, and then calculated the emissions differences that resulted from the simulation using detailed dynamic emissions models for combined cycle and combustion turbine power plants.

The final goal of the effort was to look at the potential emission changes based on a simulation of an actual system rather than on a proxy snapshot of "generic" devices in static conditions.

## 1.2 Methodology

In order to study the effects on emissions from changes in frequency regulation service, KEMA used its proprietary KERMIT simulation modeling tool to examine the potential advantages of using fast acting storage when replacing conventional generation resources.

Hence, the tool was calibrated for two System Operators, PJM and CAISO (California Independent System Operator). Additional information on the KERMIT model is provided in the report. The study targeted the differences between fast response storage devices that could represent either a Flywheel based device or Lithium-ion based device and looked at the following scenarios:

1. Scenario 1: Base case – ISO system without any fast acting storage device providing frequency regulation

a. For CAISO the base case was the 2020 system with 2020 load, generation, renewable levels and hourly frequency regulation requirements for the ISO selected study days and conditions

b. For PJM the base case was the 2011 system with 2011 load, generation, renewable levels and hourly frequency regulation requirements for the ISO selected study days and conditions.

2. Scenario 2: Vary each ISO base case by replacing 10% of the frequency regulation service requirement supplied by conventional resources with an equivalent fast acting storage device capacity and re-run the simulations for the same cases.

3. Scenario 3: Vary each ISO base case by replacing 25% of the frequency regulation service requirement supplied by conventional resources with an equivalent fast acting storage device capacity and re-run the simulations for the same cases.

4. Scenario 4: Vary the PJM base case by replacing 50% of the frequency regulation service requirement supplied by conventional resources with an equivalent fast acting storage device capacity and re-run the simulations for the same cases.

5. Scenario 5: For a CAISO selected conventional power plant that provides frequency regulation for the selected dates, compare a one to one swap of a traditional, fossil-fuel power plant with fast acting storage device and re-run the simulations for the same cases.

Each KERMIT simulation produces second by second MW outputs for every on-line resource for the 24 hours of every day included in the simulation.

The results of each simulation run for all scenarios were then subjected to post processing calculations for emissions outputs for on-line fossil fuel resources using the emissions models created or applied for combined cycles, simple cycle combustion turbines and coal units.

The final step in the analysis was then to compare the calculated emissions for each on-line conventional (fossil fueled) resource between the base case and each scenario and aggregate the results at the requested levels. Comparisons were made at the following levels:

1. Total system emission levels per study day - base case vs. each fast acting storage scenario
2. Total emission levels from conventional resources providing frequency regulation service per study day - base case vs. each fast acting storage scenario (CAISO Only)
3. Total emissions levels from individual conventional resources providing frequency regulation service per study day - base case vs. each fast acting storage scenario (CAISO only)

## 1.3 Summary of Results

### 1.3.1 PJM Overall Observed Results

The detailed simulation results for the PJM cases show that overall, total system emissions differences between the base case (no storage providing frequency regulation) and the increasing penetrations levels of fast acting storage devices resulted in $CO_2$ emission savings in all days and some $NO_x$ emission savings in most days. Please refer to Section 4 and Attachments A and B for detailed data analysis.

Though the data shows emission reductions, the results show that the amount of emissions savings is small when compared to the total emissions of the entire PJM system for both $CO_2$ and $NO_x$ emissions. This is understandable as the amount of regulation used is typically approximately 1% of the total load. Hence, when energy schedules are held constant (as in the PJM cases) then introducing storage into regulation markets produces emission savings of 0.2% or less of total system emissions for both $CO_2$ and $NO_x$.

For PJM, the ISO hourly frequency regulation requirement in 2011 is calculated as 1% of on-peak load and off-peak valley. Energy-wise, the MWhs associated with regulation service can be no more than 1% of the total energy service at its operational extremes. For instance, at a peak load of 90,000MW, the equivalent PJM frequency regulation requirement for that peak load hour is 900MW. That represents a maximum MW range reserved to correct frequency deviations and Area Control Error for that hour. We know that MWh is what drives emissions production. That is, the input-output curve of fossil-fueled plants is monotonic: to produce more MWs a fossil fuel plant needs to burn more fuel, thus more emissions. In this study the scenarios replaced 10%, 25% and 50% of the base case conventional generation MWs assigned as part of the PJM frequency regulation requirements. For the 90,000MW peak load and 900MW frequency regulation reserve margin for that hour that means that the 10% scenario replaces 90MW of fossil generation with 90MW of storage, the 25% scenario replaced 225MWs and the 50% scenario replaced 450MW. In a 90,000 MW system for that hour, that represented a maximum MWh output reduction from fossil units of 0.1%, 0.25% and 0.5%. Furthermore consider these additional factors:

- Most hours the frequency regulation requirement is much lower than the requirement during the daily system peak hour.
- During a substantial number of AGC cycles over a 1 hour period the resources are *lowering* their output (and thus reducing emissions) rather than increasing their output to correct for over frequency and positive ACE deviations.
- Over a day, per NERC standards the number of ACE signal zero crossings are managed to be as close to a net zero to demonstrate acceptable control performance; thus the net amount of MWs spent to correct both over and under-frequency is managed to be small.
- The assigned frequency regulation participation factor for conventional units during each AGC cycle is typically distributed to favor faster responders (the more efficient units);
- Conventional fossil fueled resources have a limited range of operation for frequency regulation service – most fossil fueled resources cannot provide frequency regulation service through their entire operating range and thus are limited to 10% to 20% of their range for any given hour and finally,
- The mix of conventional resources actually providing frequency regulation in PJM favors combined cycles, rather than coal or combustion turbines.

Translate all of these factors into their impact on conventional resources outputs and the observed magnitudes of emissions reductions and the results of the study are congruent with these factors.

### 1.3.2 CAISO Overall Observed Results

The detailed simulation results for the CAISO cases are less conclusive showing overall that system emissions differences between the base case (no storage providing frequency regulation) and the increasing penetrations levels of fast acting storage devices resulted in some $CO_2$ emission savings in half of the study days and some NOx emission savings in less than half of the study days. Please refer to Section 4 and Attachments D and E for detailed data analysis. It is noted that for California, the portfolio mix of generation is much different than PJM, where there are far less emissions from coal plants to offset.

Differences in total emission levels from the *conventional resources* providing frequency regulation service between the base case (no storage providing frequency regulation) and the increasing penetrations levels of fast acting storage devices resulted in some $CO_2$ emission savings in half of the study days and some NOx emission savings in less than half of the study days. Please refer to Section 4 and Attachments D and E for detailed data analysis.

Differences in total emission levels from *individual conventional resources* providing frequency regulation service between the base case (no storage providing frequency regulation) and the increasing penetrations levels of fast acting storage devices resulted in $CO_2$ emission savings in one of the study days and NOx emission savings in one of the study days. Please refer to Section 4 and Attachments D and E for detailed data analysis.

When the real time energy dispatch of a system is influenced by its close interaction with its AGC control scheme, as observed with the CAISO results, then in only half of the study cases does introducing storage resources in regulation markets, produce emission savings.

## 1.4 Conclusions

1. In control areas where "coal" plants are part of the pool of resources contributing to regulation, storage devices appear to provide emission reductions. However, reductions are inconclusive in areas where clean generation has replaced coal or oil power production.

2. The interactions of the regulation market and the real time dispatch market complicates the analysis and makes it less straight forward to identify when emissions benefits are observed.

a. The simulation results show that power plants that are “bumped out” of the regulation queue typically do not stop producing, but rather continue to participate in the real time dispatching, thus minimizing the potential benefits of the storage device being introduced into the ancillary service

3. Once systems operators are able to quantify how much more efficiently storage resources can be in regulating their system frequency while maintaining system security, it will allow operators to procure reduced levels of frequency regulation capacity from conventional resources yielding some reductions in overall system emissions.

4. Additional emissions savings may be obtainable if emissions factors were to be included in the frequency regulation procurement and dispatch algorithms as an additional constraint in the control problem. That would require changes to current national and regional load balancing standards and frequency regulation market policies. Energy Storage devices represent a new factor to consider changes to those policies and regulations.

5. As regulation requirements make up a small percentage of the overall peak load, the frequency regulation margins in the studied cases are relatively small compared to total system power production and therefore the expected emissions totals associated exclusively with frequency regulation services from fossil fueled units is also relatively small compared with the total system emissions caused by production for energy supply.

# 2. Methodology

For the project, KEMA utilized its proprietary KEMA Renewable Model Integrating Technologies - KERMIT - simulation model to examine the potential advantages of using fast response storage. The tool is described in the next section in more detail. Specifically, KEMA focused on two ISO/RTO territories for the study, the California ISO (CAISO) and PJM Territory. Cooperating with these two areas, KEMA acquired actual ISO data and ran a series of advanced storage scenarios in a real time simulation of regulation services. The study teams then calibrated the KERMIT tool for the two System Operators to replicate the actual system operation data received from each entity. With the calibrated models the study teams then developed scenario analyses for each system.

## 2.1 Description of KERMIT Model

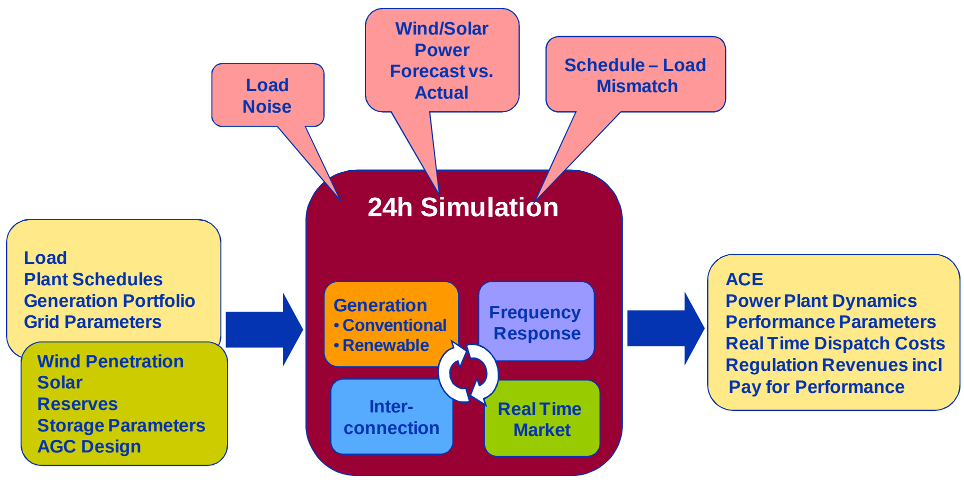
The KERMIT model is configured for studying power system frequency behavior over a time horizon of 24 hours. As such, it is well suited for analysis of pseudo steady-state conditions associated with Automatic Generation Control (AGC) response including non-fault events such as generator trips, sudden load rejection, and volatile renewable resources (e.g., wind) as well as time domain frequency response following short-time transients due to fault clearing events.

> **KERMIT:** "This is a software product used by KEMA to analyze the bulk power system for integrating renewable energy sources. This is not a commercial software product but an analysis tool for high level study where automatic generation control must be modeled; control area interconnections simulated and generator inertia can be modeled by balancing authority, not nodes. The time span for modeling is generally 1 second to 1 hour, so a 24-hour model simulation can be done in a balancing area for wind, congestion and regulation services in 15 to 30 minutes. Energy storage efficiency and response rates are included in the model."
>
> **Analysis Tools for Sizing and Placement of Energy Storage in Grid Applications - A Literature Review; Pacific Northwest National Lab, September 2010**

KERMIT model inputs include data on power plants, wind production, solar production, daily load, generation schedules, interchange schedules, system inertias and interconnection model, balancing and regulation participation. Parameters for electricity storage are also inputs – power ratings, energy capacity or "duration" of the storage at rated power, efficiencies, and rate limits on the change of power level. Model outputs include ACE, power plant output, area interchange and frequency deviation, real time dispatch requirements and results, storage power, energy, saturation, and numerous other dynamic variables. The KERMIT Model Overview graphic (Exhibit 2-1) depicts the model inputs and outputs graphically.

EXCEL-based dashboards allow the creation of comparative analyses of multiple simulations across control variables and the generation of time series plots of key dynamic variables with multiple simulation results co-plotted for easy comparison. Pivot table analysis allows the 3-D plotting of key metrics (such as maximum ACE) across multiple simulations and scenarios.

**Exhibit 2-1: KERMIT Model Overview**




The model has a number of useful features aimed at making it effective for analyzing specific conditions and different scenarios including:

- Spreadsheet based data to represent regional power plants.
- Use of actual interchange schedules and load forecasts from typical customer data.
- Analysis of dynamic performance of the power system, the AGC, the generation plants, storage devices:
  - Power spectral density analysis which allows comparison of hour to multi-hour time series (i.e. ACE, plant actual generation, frequency) by mathematical means
  - Computation of NERC CPS1 and CPS2 performance and statistics or other customer control standards
- Computation of useful statistics such as max over a time period, averages, and so on.

It is possible to make direct comparisons of different cases to highlight the results of changes from one scenario to the next, such as increased wind development, increased use of regulation for the same scenario, impact of varying levels of storage, impact of different control algorithms and tuning, and comparison of completely different strategies such as storage versus increased ancillaries. These are presented statistically and were turned into EXCEL pivot tables, or more typically, combined on MATLAB plots to show time series from different cases on the same plots.

## 2.2 Overall Approach to Measure Benefits

This study focuses on the total grid system and is an actual simulation. A couple key points need to be highlighted as ramifications to this approach

- Power plants ***typically do not dedicate all*** their capacity potential to regulation, but rather only bid a small percentage (ranging from 10% to 20% of their total capacity) to the regulation market

- Power plants that are bumped from the regulation "queue" are not necessarily taken off-line from the system, but remain available for energy in the real time dispatch market, thus continuing to provide real and reactive power to the system

For example, if a power plant is contributing to regulation, rarely does a power plant dedicate all of its resources to regulation. In the cases examined in this study, the traditional power plants would typically run on an 85% to 15% ratio, where roughly 85% of their total generation would be dedicated to producing energy and the remaining 15% would be dedicated to regulation. When another "regulation" device is added to the queue, the traditional power plant isn't really "bumped" out of other power generation services, rather the 15% that was dedicated to regulation typically enters the "real-time dispatch" market. In the cases simulated by KEMA, this additional potential is made available to the real time markets and selected for energy supply – meaning that the previous 15% of plant capacity is not being removed from the system, but rather is now being dedicated to another application such as simply producing energy.

Another ramification of the simulation is that emissions are examined in totality. Previous studies have shown a one to one comparison and a "snapshot" in time of emission comparisons of advanced vs. traditional suppliers of Regulation Services. However, in actuality, the amount of MWs required for regulation is relatively small compared to the overall energy requirements for the reliable and economic operation of the system. Hence, by examining the entire system when comparing the emissions differences, the savings will appear relatively small compared to the total emissions required for the operation of the system. The study attempted to filter out the total system results in order to see the impact of a "one to one" comparison, but though this solves one factor, the simulation does not "prevent" a traditional unit removed from regulation services from performing another service as would be the case in a real ISO operating scenario. Though it is acknowledged that this can be done, it is noted that the simulation does its best to reflect the realities what is happening during day-to-day operations.

## 2.3 One to One Case

Understanding that the approach of examining the system in totality could "overwhelm" the emissions savings that may occur in the smaller subset of regulation service providers, as a first step in the analysis, the study examined the emissions from units providing regulation only. The reason for this step is to attempt to filter out the impacts of units that are not participating to the regulation market and observe the potential emission benefits through a smaller subset of power plants. However, though examining a smaller subset, this approach did not prevent the power plant from re-entering the real time dispatch market.

## 2.4 ISO/RTO Cases

For each of the ISOs that were used in the study, cooperation was obtained from the specific ISOs to calibrate the model. Hence, the ISOs recommended the "year" they wanted to see assessed in the study and the study group complied with the recommendations.

The characteristics of the storage devices were kept constant between PJM and CAISO simulations. In addition, the study group assumed that the storage devices had enough stored energy capacity to meet any regulation obligations required during a simulated day. For each system we developed a Proportional plus Integral (PI) automatic generation control (AGC) that mimics the AGC algorithm each system has in place currently.

**Calibrating KERMIT model to PJM and CAISO Regulation**

There are two primary methods to incorporate storage into a regulation portfolio of assets. The first is to add storage devices to the list of regulating assets and keep the net capacity of regulation the same. This would result in decreasing the regulation capacity of each conventional resource by the penetration percentage of the fast acting storage devices. For example, for 100 MW of regulation capacity originally provided by generation portfolio X, a 10% penetration of storage would have 10 MW from storage devices and 90 MW from generation portfolio X. The net result is the AGC signal sent to each generator is reduced because of the proportional distribution. Thus potential emission savings can be realized by the set of generators being asked to provide a smaller amount of regulation capacity and being required to ramp up and down over a reduced range of outputs.

The second method to incorporate storage into a regulation portfolio of assets is to do a one for one replacement of conventional generation assets with equivalent storage devices. For example, say a regulation generation portfolio is comprised of four generators A, B, C, and D, and that each provides 25 MW of regulation for a total of 100 MW of regulating capacity. A 25% penetration of storage resources would replace one of the generators and the new regulation generation portfolio would be comprised of generators A, B, and C and 25 MW of storage resources leaving the shares of resources A, B and C unchanged. Potential emissions savings can be realized by avoiding having a subset of generators (generator D in our example) operate less efficiently as a result of their response to AGC requests. Since the CAISO and PJM frequency regulation markets procure regulation capacity at the MW level and not the unit level, the first methodology is a more realistic representation of those markets.

### 2.4.1 PJM Cases

For PJM, the study focused on examining the emissions benefits that fast acting storage devices can currently realize by participating in ***today's*** regulation market at PJM's request. As a result the study simulated fast acting storage devices operating in PJM's 2011 regulation market. KEMA used the following PJM datasets from the selected 2011 study days to build the KERMIT PJM model. Many such data were specific to the resources and have not been publicly available. The major datasets include:

1. Hourly schedules for all generation resources in the PJM footprint.
2. Hourly interchange profiles for interchanges with neighboring areas.
3. Pi-Historian records for frequency, ACE, etc. for the chosen days. PJM provided two-second resolution.
4. Key parameters of generation resources, such as nameplate capacity, fuel type, and ramp rates.
5. Disturbance records and resulting system-frequency behavior. (This was needed to calibrate the model so that its frequency behavior closely reflects what has been observed in practice.)

Model calibration was performed after the model was built. PJM provided KEMA with the Pi-Historical operational data (ACE, frequency, CPS1/2, load, etc.) as benchmark for model calibration. Based on the comparison of simulated results against Pi-Historical data, PJM and KEMA concluded that the KERMIT model developed for the study is a good representation of the PJM power system and well calibrated.

All simulation cases were based on the calibrated parameters of the model. Subsequent simulation cases were then variants of the base-case simulation where only two particular parameters are changed from case to case.

For PJM the study group developed four scenarios of 0%, 10%, 25%, and 50% penetration of fast acting storage devices in PJM's regulation market. PJM uses a proprietary AGC algorithm to keep their NERC regulation metrics in compliance. Their AGC algorithm generates a control signal to the generators providing regulation and distributes it proportionally based on capacity bid[1].

For our PJM scenarios, the study used the first method (described in section 2.4) to incorporate storage into a regulation portfolio of assets. Namely, the study group did not remove any generators from participating in the regulation market. For each scenario in our PJM simulations, the study group focused solely on the emissions benefits of fast acting storage devices in regulation markets by fixing the day ahead and real time energy schedules of each generator in KERMIT. To do so the study group used the historical day ahead and five minute generator energy schedules that PJM's security constrained economic dispatch software generated for each of the simulation days in 2011.

A total of twelve (12) representative days were chosen by PJM, one for each month of the year to represent PJM on-peak and off-peak days as the base cases of the simulation study. The selected days are listed in the Table 2-1: Twelve PJM days selected for the study

[1] Note that PJM uses a fleet based approach where if one company bids in a fleet of resources to provide regulation, PJM sends a control signal for the net capacity the company bid. The company is then allowed to assign participation factors and distribute the control signal to their fleet of resources as best they see fit.

. Since this study began in August 2011, the “most recent” month was July 2011.

**Table 2-1: Twelve PJM days selected for the study**

| Day # | Year | Month | Day | Characterized by | | | Comments |
|---|---|---|---|---|---|---|---|
| | | | | Conventional Gen | Interchange | Renewable/Total-Gen ratio | |
| 1 | 2010 | Aug | 15 | Low | Import | Low | |
| 2 | 2010 | Sep | 7 | Low | Import | Med | |
| 3 | 2010 | Oct | 28 | Low | Import | Hi & Ramp | |
| 4 | 2010 | Nov | 23 | Low | (neutral) | Hi & Ramp | |
| 5 | 2010 | Dec | 13 | Low | (neutral) | Med | |
| 6 | 2011 | Jan | 21 | Med | (neutral) | Low & ramp | |
| 7 | 2011 | Feb | 18 | Low | (neutral) | Hi | |
| 8 | 2011 | Mar | 20 | Low | Import | Hi | |
| 9 | 2011 | Apr | 11 | Low | (neutral) | Hi & ramps | Already picked by PJM |
| 10 | 2011 | May | 10 | Low | Import | Medium & ramp | |
| 11 | 2011 | Jun | 15 | Med | Import | Medium & ramp | |
| 12 | 2011 | Jul | 10 | High | Import | Low | Already picked by PJM |

NOTE: Data are downloaded from http://www.pjm.com/markets-and-operations/ops-analysis.aspx

Two input variables were selected to be changed independently for each of the 12 study dates:

- The PJM Regulation Requirement per hour, and
- The Percent of Energy Storage as fast-following resources represented in the study by different combinations of Energy-Storage technologies.

Normally, the PJM Regulation Requirement for any of the 12 days is set to be 1% of the peak load for on-peak hours and 1% of the minimum load for the off-peak hours. In KERMIT a simplified approach was used as follows: For each day, the Regulation Requirement is set to 1% of minimum load from hour 00:00 to 05:00, and to 1% of maximum load between 05:00 and 24:00.

The two variables that were manipulated in the combinations:

1. Vary the Regulation Requirement from 1.00% of peak load (or minimum load) down to 0.50% in 0.25% decrements yielding 3possible regulation requirements conditions[2].

[2] The variations in reserve requirements were a specific requirement of PJM in order to study other operational impacts and were not a requirement of the Sandia study. However, they resulted in a much richer number of simulations results to include in the emissions study.

2. Vary the Percentage of Energy Storage from 0% to 10%, 25% and 50% yielding four (4) possible levels of energy storage replacement conditions.

Therefore, for each of the 12 days, the simulations studied 12 scenarios. Since the study covers 12 days, the resulting number of scenarios studied was 144.

### 2.4.2 CAISO Cases

For CAISO, the study focused on examining the emissions benefits that fast acting storage devices can realize when significant penetrations of renewable energy are present. As a result, at CAISO's request to understand the potential implications of their 2020 renewable scenario, the study focused on fast acting storage devices participating in CAISO's 2020 regulation market when they expect to have 33% penetration of renewable energy.

A similar process was used to build and calibrate the CAISO KERMIT model as with the PJM KERMIT model. KEMA received the same type of major datasets from CAISO for selected 2009 and 2011 study days. The KERMIT model was then calibrated to replicate the observed Pi-Historian data for the selected study days. To simulate a set of 2020 days, KEMA utilized load and renewable generation profiles CAISO developed for their 33% renewables integration study.

Two scenarios of 0% and 25% penetration of fast acting storage devices in CAISO's 2020 regulation market were created. The study group used the second method to develop a regulation portfolio with 25% storage by capacity, namely for each simulation day the study group replaced enough combined cycle or combustion turbine power plants from the regulation market with storage devices to equal 25% of the total regulation capacity.

For the CAISO KERMIT model, a real time market was implemented to mimic CAISO's real-time dispatch. This is a different approach from the PJM simulations that were conducted. This is because the five minute dispatch schedules to use in the CAISO KERMIT model were not available. The result is that the RTD schedules in KERMIT are not fixed and change from scenario to scenario because there is interplay between the RTD and regulation markets.

For the CAISO simulations, six 2020 study days were selected. The criteria for selection were days with significant renewable events. Currently CAISO procures 480 MW of regulation capacity as their frequency regulation reserve requirement. Based on recent estimates of future ancillary service capacity requirements to adequately integrate 33% renewable resources provided by the ISO, the study group used 1000 MW of regulation capacity in the CAISO simulations. This resulted in the percent of energy storage as fast following resources as the only independent variable changed from scenario to scenario. The two possible values the input variable could take are 0% and 25%. As a result, the number of scenarios simulated for CAISO was 2 x 6 = 12 scenarios.

## 2.5 Post processing calculations for emissions output

The study group used dynamic emissions models to estimate emissions from combined cycle and combustion turbine generators. To develop the dynamic emission models, the KEMA team used the regression models Katzenstein and Apt (2008) developed for analysis of measured emissions and heat rate data taken at one minute resolution from two types of gas turbines to model emissions and heat rate as a function of power and ramp rate. Katzenstein and Apt obtained 1-minute resolution emissions data for seven General Electric LM6000 natural gas combustion turbines and two Siemens-Westinghouse 501FDs natural gas combined-cycle turbines. The LM6000 CTs had a nameplate power limit of 45 MW and utilize steam injection to mitigate $NO_x$ emissions. A total of 145 days of LM6000 emissions data was used in their regression analysis. The Siemens-Westinghouse 501FD NGCC turbines have a nameplate power limit of 200 MW with GE's Dry Low $NO_x$ system (lean premixed burn) and an ammonia selective catalytic reduction system for $NO_x$ control. Emissions data for 11 days were obtained for the 501FD NGCC. Each emissions data set contained six variables: date, time, power generated, heat rate, $NO_x$ mass emission, and a calibration flag.

Available $NO_x$ combustion control technologies are water (liquid or steam) injection systems and dry low-$NO_x$ combustion designs (EPA, 1993). The LM6000 data were obtained from 45 MW turbines that injected steam into the combustion chambers, lowering flame temperatures to reduce $NO_x$. The 200 MW 501FD turbines used General Electric's Dry-Low $NO_x$ (DLN) system of lean premixed combustion. The median nameplate size for all US natural gas turbines using Dry Low $NO_x$ control is 170 MW; using steam injection it is 80 MW. Thus, the turbines for which Katzenstein and Apt have data are moderately representative of the US fleet.

In GE's Dry-Low NOx systems, fuel is premixed with air to create a fuel-lean mixture that is burned in a two-stage process to reduce flame temperatures and residence times. At full generator output, GE's DLN operates at a mixture just richer than the flame blowout point of natural gas. As the generator load is reduced, less fuel is fed to the combustion chamber resulting in lower flame temperatures. As load is reduced further the flame blowout point is reached and GE's DLN system can no longer employ the fuel-lean premixed firing mode, and shifts to a diffusion flame where high flame temperatures are present. As a result, low NOx emission rates are achieved in the power range of approximately 50% to 100% of nameplate capacity and NOx emission rates an order of magnitude greater are observed in the power range of 0% to 50% (Davis and Black, 2000).

Katzenstein and Apt modeled $CO_2$ and NOx emission rates as a function of power level and ramp rate. We paired their emissions models with the power output from the combined cycle and combustion turbine generators in our KERMIT model to estimate $CO_2$ and NOx emissions for natural gas power plants.

For coal plants, KEMA used an emissions factor approach as no public dynamic emissions models are currently available. We used $CO_2$ and NOx emissions factors obtained from EPA's AP-42 database for a pulverized coal, dry bottom, wall-fired, medium-volatile bituminous coal plant.

# 3. Results

The study first examined the single plants to provide a one to one comparison of power plants that were "bumped" from the regulation queue and assessed the emission impact of the units being replaced by an advanced storage technology. The study then focused on the entire system in PJM and CAISO cases. As the study focused on simulations of grid operations, whether the examination is at a "single unit" level or the grid in totality, the issue encountered in each methodology is that when units are "bumped" from regulation, they are not "bumped" from production or grid operations. Typically, once bumped, the units begin to produce energy and may offset potential emission savings generated by the replacement.

This section examines each of the cases in detail.

## 3.1 One to one comparison of advanced storage vs. traditional power plants

The one-to-one comparison was conducted in the California ISO cases in order to provide a basis for the "system" calculations. Hence, if the analysis is restricted to examine only the emissions from the generators that were removed from the regulation market and replaced with storage devices, as seen in Table 3-1, five of the six study days showed an increase in the $CO_2$ and $NO_x$ emissions of the generators that were removed from participating in the CAISO's simulated 2020 regulation market. The increased emissions are a result of the generators being asked to provide more energy due to a change in their real time energy schedules. This highlights the complexity of estimating emission benefits any one technology can achieve. For example, CAISO relies on a significant amount of imported energy and freeing up generators from providing regulation enables them to provide more firm energy and allow CAISO to import slightly less energy. The changes in imports produce a net effect on the energy dispatch that causes the overall changes in resource outputs and therefore emissions.

**Table 3-1: Change in emissions between 25% storage penetration scenario and 0% storage penetration scenario for six CAISO 2020 study days.**

| CAISO 2020 Simulation Days | Difference (tonnes) | |
|---|---|---|
| | $CO_2$ | $NO_x$ |
| **12-Jan-20** | -0.01 | 5.77E-05 |
| **1-Feb-20** | 0.03 | -1.75E-03 |
| **9-Mar-20** | 0.08 | 6.13E-04 |
| **6-Apr-20** | 3.11 | 5.30E-02 |
| **1-Sep-20** | 0.16 | 2.06E-04 |
| **12-Dec-20** | 0.34 | 2.78E-03 |

## 3.2 Before and after of the total "regulation only" providers

The results presented for CAISO were estimated for an entire system and can be influenced by the energy production of units that are removed from providing regulation (Section 3.1). The emissions results in Table 3-2 were computed only for the generators that provided regulation for a given study day. Again we see the results are mixed. $CO_2$ emissions decreased for four of the six study days but on average increased by 0.7 tones because the emission decreases were small compared to the increases observed for April 6 and December 12 study days.

**Table 3-2: Emission results for generators providing regulation in CAISO system for 6 simulated 2020 days.**

| CAISO 2020 Simulation Days | No Storage | | 25% Storage | | Difference (Storage - No Storage) | | Percent Difference | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ (tonnes) | $NO_x$ (lbs) | $CO_2$ (tonnes) | $NO_x$ (lbs) | $CO_2$ (tonnes) | $NO_x$ (lbs) | $CO_2$ (tonnes) | $NO_x$ (lbs) |
| **12-Jan-20** | 1329 | 10111 | 1329 | 10099 | -0.5 | -11.3 | -0.03% | -0.11% |
| **1-Feb-20** | 1067 | 9010 | 1066 | 9003 | -0.8 | -6.9 | -0.08% | -0.08% |
| **9-Mar-20** | 1094 | 9186 | 1093 | 9184 | -1.5 | -2.8 | -0.14% | -0.03% |
| **6-Apr-20** | 822 | 6385 | 825 | 6508 | 3.0 | 122.7 | 0.37% | 1.92% |
| **1-Sep-20** | 1521 | 12522 | 1521 | 12527 | -0.1 | 5.3 | -0.01% | 0.04% |
| **12-Dec-20** | 1119 | 8347 | 1124 | 8352 | 4.3 | 5.8 | 0.38% | 0.07% |

Comparing the change in emissions in Table 3-2 (regulation only) with the change in emissions in Table 3-8 (total emissions for all units), only two of the six days showed a decrease in both calculations and only one day showed an increase in $CO_2$ emissions in both calculations. For the NOx emissions, only the September 1 study day showed the same direction of change in NOx emissions from both a systems point of view and a “regulation only” provider’s point of view. The remaining five study days differed in results when shifting the perspective from the system to the regulation only providers. This is indicative that changes in the real time dispatch of the CAISO generating assets in response to system performance complicates the emission benefits a system can realize by deploying storage and not changing their regulation procurement procedures.

## 3.3 Total PJM and CAISO Results

Based on the simulations results for PJM and CAISO system, incorporating advanced storage into regulation markets appears to provide a reduction on the total emissions attributable to frequency regulation services for PJM systems and is inconclusive for CAISO. For both PJM and CAISO, the largest percent reduction observed was 0.1% for $CO_2$ emissions and 0.2% for NOx emissions for the 25% storage penetration case of the December 12, 2020 CAISO simulation day. In terms of tones emitted, the largest emissions benefits observed was for the August 7, 2011 PJM study day where 63.9 tones of $CO_2$ and 470 lbs of NOx were avoided. Emissions benefits were observed for all scenarios and all study days for PJM. The CAISO scenarios showed mixed results with half the study days showing decreased system emissions while half showed increased system emissions.

The difference in results between CAISO and PJM is due primarily to the difference between using a fixed RTD schedule (our PJM simulations) and a dynamic RTD schedule (our CAISO simulations). An electricity system provides many interrelated services across multiple time scales which means that when changing one the others may also be affected. This dynamic is captured in the CAISO results and highlights the difficulty in realizing emissions benefits if emissions are not explicitly considered in dispatch decisions. In addition, the portfolio of generation technologies participating in regulation also plays a role in the analysis.

Tables 3-3 through 3-5 compare the results from all cases simulated for CAISO and PJM respectively. All cases exhibit a decrease in both $CO_2$ and NOx emissions and the emissions benefits increase as the penetration percentage of storage increases. From a system emission savings point of view, the emissions reductions are negligible in all but the 50% scenarios where average system emission savings of 0.01% are observed. The nonlinear production of NOx emissions and the linear production of $CO_2$ emissions results in greater NOx emission benefits (on a percentage basis of system emissions) than $CO_2$.

**Table 3-3: Summary of total estimated emissions for PJM coal, combined cycle, and combustion turbine plants for 12 2011 study days for cases with 0% and 10% penetration of storage in PJM regulation markets.**

| PJM 2011 Simulation Days | No Storage | | 10% Storage | | Difference | | Percent Difference | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ |
| **21-Jan-20** | 887359 | 3589598 | 887355 | 3589572 | -4.1 | -26.4 | 0.00% | 0.00% |
| **18-Feb-20** | 639117 | 2676095 | 639117 | 2676078 | -0.3 | -16.8 | 0.00% | 0.00% |
| **20-Mar-20** | 544915 | 2290840 | 544908 | 2290786 | -6.5 | -54.3 | 0.00% | 0.00% |
| **11-Apr-20** | 665802 | 2753881 | 665795 | 2753753 | -7.2 | -127.9 | 0.00% | 0.00% |
| **10-May-20** | 658456 | 2724044 | 658450 | 2724030 | -5.7 | -14.7 | 0.00% | 0.00% |
| **15-Jun-20** | 999290 | 4209819 | 999288 | 4209808 | -1.5 | -11.6 | 0.00% | 0.00% |
| **10-Jul-20** | 944278 | 3964203 | 944274 | 3964115 | -3.9 | -88.3 | 0.00% | 0.00% |
| **15-Sep-20** | 848813 | 3584259 | 848806 | 3584213 | -6.5 | -45.7 | 0.00% | 0.00% |
| **7-Aug-20** | 842677 | 3501504 | 842667 | 3501435 | -10.1 | -69.1 | 0.00% | 0.00% |
| **28-Oct-20** | 675138 | 2783817 | 675132 | 2783746 | -5.7 | -70.3 | 0.00% | 0.00% |
| **23-Nov-20** | 667589 | 2786632 | 667588 | 2786628 | -0.5 | -3.6 | 0.00% | 0.00% |
| **13-Dec-20** | 961636 | 3882956 | 961632 | 3882931 | -3.9 | -25.7 | 0.00% | 0.00% |

**Table 3-4: Summary of total estimated emissions for PJM coal, combined cycle, and combustion turbine plants for 12 2011 study days for cases with 0% and 25% penetration of storage in PJM regulation markets.**

| PJM 2011 Simulation Days | No Storage | | 25% Storage | | Difference | | Percent Difference | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ |
| **21-Jan-20** | 887359 | 3589598 | 887351 | 3589587 | -8.3 | -10.9 | 0.00% | 0.00% |
| **18-Feb-20** | 639117 | 2676095 | 639112 | 2676057 | -4.7 | -38.3 | 0.00% | 0.00% |
| **20-Mar-20** | 544915 | 2290840 | 544901 | 2290702 | -13.9 | -138.2 | 0.00% | -0.01% |
| **11-Apr-20** | 665802 | 2753881 | 665787 | 2753643 | -15.3 | -238.6 | 0.00% | -0.01% |
| **10-May-20** | 658456 | 2724044 | 658441 | 2723976 | -14.8 | -68.2 | 0.00% | 0.00% |
| **15-Jun-20** | 999290 | 4209819 | 999265 | 4209760 | -24.2 | -59.1 | 0.00% | 0.00% |
| **10-Jul-20** | 944278 | 3964203 | 944271 | 3963967 | -7.4 | -235.8 | 0.00% | -0.01% |
| **15-Sep-20** | 848813 | 3584259 | 848798 | 3584086 | -14.5 | -172.6 | 0.00% | 0.00% |
| **7-Aug-20** | 842677 | 3501504 | 842640 | 3501286 | -36.8 | -218.3 | 0.00% | -0.01% |
| **28-Oct-20** | 675138 | 2783817 | 675123 | 2783674 | -14.6 | -142.8 | 0.00% | -0.01% |
| **23-Nov-20** | 667589 | 2786632 | 667585 | 2786619 | -4.0 | -12.4 | 0.00% | 0.00% |
| **13-Dec-20** | 961636 | 3882956 | 961631 | 3882900 | -4.6 | -56.7 | 0.00% | 0.00% |

**Table 3-5: Summary of total estimated emissions for PJM coal, combined cycle, and combustion turbine plants for 12 2011 study days for cases with 0% and 50% penetration of storage in PJM regulation markets.**

| PJM 2011 Simulation Days | No Storage | | 50% Storage | | Difference | | Percent Difference | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ |
| **21-Jan-20** | 887359 | 3589598 | 887314 | 3589354 | -44.7 | -244.7 | -0.01% | -0.01% |
| **18-Feb-20** | 639117 | 2676095 | 639081 | 2675932 | -35.7 | -163.1 | -0.01% | -0.01% |
| **20-Mar-20** | 544915 | 2290840 | 544881 | 2290486 | -34.1 | -354.1 | -0.01% | -0.02% |
| **11-Apr-20** | 665802 | 2753881 | 665765 | 2753150 | -36.8 | -731.3 | -0.01% | -0.03% |
| **10-May-20** | 658456 | 2724044 | 658406 | 2723649 | -50.3 | -395.0 | -0.01% | -0.01% |
| **15-Jun-20** | 999290 | 4209819 | 999230 | 4209665 | -60.1 | -153.9 | -0.01% | 0.00% |
| **10-Jul-20** | 944278 | 3964203 | 944250 | 3963855 | -28.3 | -348.0 | 0.00% | -0.01% |
| **15-Sep-20** | 848813 | 3584259 | 848763 | 3583842 | -49.6 | -416.2 | -0.01% | -0.01% |
| **7-Aug-20** | 842677 | 3501504 | 842613 | 3501034 | -63.9 | -469.6 | -0.01% | -0.01% |
| **28-Oct-20** | 675138 | 2783817 | 675097 | 2783441 | -40.7 | -376.1 | -0.01% | -0.01% |
| **23-Nov-20** | 667589 | 2786632 | 667553 | 2786475 | -35.5 | -156.9 | -0.01% | -0.01% |
| **13-Dec-20** | 961636 | 3882956 | 961605 | 3882704 | -30.9 | -252.5 | 0.00% | -0.01% |

**Table 3-6: Cumulative total of $CO_2$ tones for the 50% case for PJM coal, combined cycle, and combustion turbine plans for 12 2011 study days for cases with 0% and 50% penetration of storage in PJM regulation markets**

| Selected Day | CO2 Tons Base Case | CO2 Tons 50% Storage | Difference | Estimated Month Total |
|---|---|---|---|---|
| 21-Jan | 887359 | 887314 | 45 | 1395 |
| 18-Feb | 639117 | 639081 | 36 | 1008 |
| 20-Mar | 544915 | 544881 | 34 | 1054 |
| 11-Apr | 665802 | 665765 | 37 | 1110 |
| 10-May | 658456 | 658406 | 50 | 1550 |
| 15-Jun | 999290 | 999230 | 60 | 1800 |
| 10-Jul | 944278 | 944250 | 28 | 868 |
| 15-Aug | 848813 | 848763 | 50 | 1550 |
| 7-Sep | 842677 | 842613 | 64 | 1920 |
| 28-Oct | 675138 | 675097 | 41 | 1271 |
| 11-Nov | 667589 | 667553 | 36 | 1080 |
| 13-Dec | 961636 | 961605 | 31 | 961 |
| | | Total Year | | 15567 |

The data in Table 3-6 shows that though on a relative "percentage" basis, the difference between the changes and emissions output are small when compared to the entire grid operation, on a cumulative basis and projected out for an entire year, an impactful total yearly reduction in the amount of tones emitted was seen.

Tables 3-7 and 3-8 list the estimated emissions by conventional fossil fueled plant types participating in frequency regulation services during the simulated days. For $CO_2$ emissions, the largest emissions savings are from coal plants though on a percent basis all three types of power plants have similar $CO_2$ emissions reductions. For NOx emissions, the largest emissions savings are from Combined Cycle plants both by weight and percent basis. This is due to the combustion behavior of the dry low NOx systems installed on combined cycle plants where NOx emissions are an order of magnitude greater when the plants are operating at 50% or below their nameplate capacity than when they are operating at 50% or above their nameplate capacity.

**Table 3-7: Summary of estimated emissions by power plant type for twelve 2011 days for cases with no penetration of storage and 25% penetration of storage in PJM regulation markets.**

| PJM 2011 Simulation Days (tonnes) | Coal | | Combined Cycle | | Combustion Turbine | | Total | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ |
| **No Storage** | | | | | | | | |
| *21-Jan-20* | 767,197 | 1524 | 118,737 | 100 | 1,424 | 4 | 887,359 | 1628.2 |
| *18-Feb-20* | 569,874 | 1132 | 67,748 | 78 | 1,495 | 4 | 639,117 | 1213.9 |
| *20-Mar-20* | 473,112 | 940 | 69,474 | 93 | 2,328 | 6 | 544,915 | 1039.1 |
| *11-Apr-20* | 577,895 | 1148 | 83,048 | 87 | 4,860 | 14 | 665,802 | 1249.1 |
| *10-May-20* | 571,214 | 1135 | 86,381 | 99 | 862 | 2 | 658,456 | 1235.6 |
| *15-Jun-20* | 891,835 | 1772 | 104,980 | 131 | 2,475 | 7 | 999,290 | 1909.5 |
| *10-Jul-20* | 809,318 | 1608 | 125,530 | 161 | 9,430 | 29 | 944,278 | 1798.1 |
| *15-Sep-20* | 728,933 | 1448 | 116,714 | 168 | 3,165 | 9 | 848,813 | 1625.8 |
| *7-Aug-20* | 715,365 | 1421 | 120,310 | 146 | 7,002 | 21 | 842,677 | 1588.3 |
| *28-Oct-20* | 585,259 | 1163 | 84,888 | 87 | 4,992 | 13 | 675,138 | 1262.7 |
| *23-Nov-20* | 586,408 | 1165 | 79,779 | 95 | 1,402 | 4 | 667,589 | 1264.0 |
| *13-Dec-20* | 820,265 | 1630 | 134,060 | 108 | 7,311 | 23 | 961,636 | 1761.3 |
| **25% Storage** | | | | | | | | |
| *21-Jan-20* | 767,190 | 1524 | 118,737 | 100 | 1,424 | 4 | 887,351 | 1628.2 |
| *18-Feb-20* | 569,870 | 1132 | 67,747 | 78 | 1,495 | 4 | 639,112 | 1213.8 |
| *20-Mar-20* | 473,100 | 940 | 69,473 | 93 | 2,328 | 6 | 544,901 | 1039.0 |
| *11-Apr-20* | 577,880 | 1148 | 83,047 | 86 | 4,860 | 14 | 665,787 | 1249.0 |
| *10-May-20* | 571,199 | 1135 | 86,380 | 99 | 862 | 2 | 658,441 | 1235.6 |
| *15-Jun-20* | 891,812 | 1772 | 104,979 | 131 | 2,475 | 7 | 999,265 | 1909.5 |
| *10-Jul-20* | 809,311 | 1608 | 125,530 | 161 | 9,430 | 29 | 944,271 | 1798.0 |
| *15-Sep-20* | 728,920 | 1448 | 116,713 | 168 | 3,165 | 9 | 848,798 | 1625.7 |
| *7-Aug-20* | 715,331 | 1421 | 120,307 | 146 | 7,002 | 21 | 842,640 | 1588.2 |
| *28-Oct-20* | 585,245 | 1163 | 84,887 | 87 | 4,992 | 13 | 675,123 | 1262.7 |
| *23-Nov-20* | 586,404 | 1165 | 79,779 | 95 | 1,402 | 4 | 667,585 | 1264.0 |
| *13-Dec-20* | 820,260 | 1630 | 134,060 | 108 | 7,311 | 23 | 961,631 | 1761.3 |

**Table 3-8: Comparison of 0% and 25% penetration of storage cases in PJM regulation markets by power plant type for twelve 2011 study days.**

| PJM 2011 Simulation Days | Coal | | Combined Cycle | | Combustion Turbine | | Total | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ |
| **Difference** | | | | | | | | |
| *21-Jan-20* | -7.68 | -0.02 | -0.60 | 0.01 | 0.01 | -1.30E-04 | -8 | 0.00 |
| *18-Feb-20* | -4.45 | -0.01 | -0.29 | -0.01 | 0.01 | -1.81E-04 | -5 | -0.02 |
| *20-Mar-20* | -12.66 | -0.03 | -1.21 | -0.04 | -0.04 | -4.83E-06 | -14 | -0.06 |
| *11-Apr-20* | -14.84 | -0.03 | -0.56 | -0.08 | 0.12 | 4.90E-04 | -15 | -0.11 |
| *10-May-20* | -14.27 | -0.03 | -0.49 | 0.00 | -0.01 | -1.15E-06 | -15 | -0.03 |
| *15-Jun-20* | -23.21 | -0.05 | -1.06 | 0.02 | 0.05 | -1.99E-04 | -24 | -0.03 |
| *10-Jul-20* | -7.54 | -0.01 | 0.02 | -0.09 | 0.11 | -7.30E-04 | -7 | -0.11 |
| *15-Sep-20* | -13.47 | -0.03 | -1.07 | -0.05 | 0.01 | -2.12E-04 | -15 | -0.08 |
| *7-Aug-20* | -34.19 | -0.07 | -2.66 | -0.03 | 0.01 | -4.34E-04 | -37 | -0.10 |
| *28-Oct-20* | -13.66 | -0.03 | -1.05 | -0.04 | 0.13 | -2.58E-04 | -15 | -0.06 |
| *23-Nov-20* | -3.85 | -0.01 | -0.16 | 0.00 | 0.02 | -9.99E-05 | -4 | -0.01 |
| *13-Dec-20* | -4.47 | -0.01 | -0.30 | -0.02 | 0.14 | -1.62E-03 | -5 | -0.03 |
| **Percent Difference** | | | | | | | | |
| *21-Jan-20* | -0.001% | -0.001% | -0.001% | 0.010% | 0.001% | -0.003% | -0.001% | 0.006% |
| *18-Feb-20* | -0.001% | -0.001% | 0.000% | -0.011% | 0.001% | -0.005% | 0.000% | -0.016% |
| *20-Mar-20* | -0.003% | -0.003% | -0.002% | -0.040% | -0.002% | 0.000% | -0.006% | -0.043% |
| *11-Apr-20* | -0.003% | -0.003% | -0.001% | -0.091% | 0.002% | 0.003% | -0.001% | -0.091% |
| *10-May-20* | -0.002% | -0.002% | -0.001% | -0.003% | -0.001% | 0.000% | -0.004% | -0.005% |
| *15-Jun-20* | -0.003% | -0.003% | -0.001% | 0.015% | 0.002% | -0.003% | -0.001% | 0.009% |
| *10-Jul-20* | -0.001% | -0.001% | 0.000% | -0.057% | 0.001% | -0.002% | 0.000% | -0.060% |
| *15-Sep-20* | -0.002% | -0.002% | -0.001% | -0.031% | 0.000% | -0.002% | -0.003% | -0.035% |
| *7-Aug-20* | -0.005% | -0.005% | -0.002% | -0.021% | 0.000% | -0.002% | -0.007% | -0.028% |
| *28-Oct-20* | -0.002% | -0.002% | -0.001% | -0.043% | 0.003% | -0.002% | -0.001% | -0.047% |
| *23-Nov-20* | -0.001% | -0.001% | 0.000% | 0.002% | 0.001% | -0.002% | 0.000% | -0.001% |
| *13-Dec-20* | -0.001% | -0.001% | 0.000% | -0.014% | 0.002% | -0.007% | 0.001% | -0.022% |

Table 3-9 shows the total $CO_2$ and $NO_x$ emissions for each CAISO study day. The total $CO_2$ emissions for CAISO decrease in half of the study days (January 12, September 1, December 12) and increase in the remaining study days (February 1, March 9, and April 6). The December 12 study day had the largest decrease in $CO_2$ emissions with a reduction of 60 tones of $CO_2$. The average change in carbon dioxide emissions for the six study days is 11.7 tones indicating that incorporating 25% of storage resources into CAISO's regulation market has inconclusive results due to the differences observed in the sample set that was utilized for the study. We believe this is attributable to the dynamic interplay between the regulation market and the real time energy dispatch market and we examine this in more detail in the next subsection.

The NOx results show similar results although only two of the six days exhibit a decrease in NOx emissions when storage is incorporated in the regulation market. The remaining four days see an increase in NOx emissions. The April 6 study day had the largest decrease in NOx emissions with a reduction of 2 tones of NOx. The average change in NOx emissions for the six study days is a decrease of .3 tones indicating that adding storage to CAISO's regulation market can decrease NOx emissions but the inconsistency in the results indicate that there is no real definitive trend increasing or decreasing emissions. Again, we believe the dynamic interplay between the regulation market and the real time energy dispatch market plays a role in the inconsistency of the results.

**Table 3-9: Summary of total estimated emissions for CAISO coal, combined cycle, and combustion turbine plants for six simulated 2020 days for cases with no penetration of storage and 25% penetration of storage in CAISO regulation markets.**

| CAISO 2020 Simulation Days (tones) | No Storage | | 25% Storage | | Difference | | Percent Difference | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ |
| **12-Jan-20** | 61430 | 186 | 61428 | 186 | -2 | 0.0 | 0.00% | 0.00% |
| **1-Feb-20** | 60347 | 194 | 60397 | 194 | 50 | 0.2 | 0.08% | 0.09% |
| **9-Mar-20** | 58226 | 200 | 58252 | 200 | 26 | 0.4 | 0.04% | 0.21% |
| **6-Apr-20** | 56582 | 199 | 56639 | 197 | 57 | -1.9 | 0.10% | -0.93% |
| **1-Sep-20** | 61527 | 189 | 61526 | 189 | -1 | 0.1 | 0.00% | 0.04% |
| **12-Dec-20** | 63005 | 186 | 62946 | 185 | -60 | -0.4 | -0.10% | -0.20% |

Similar results are also evident if we examine the CAISO simulation results by looking at the emissions factor of the system (Table 3-10). For $CO_2$, half of the study days show decreases in $CO_2$ emissions factors and the other half of the study days show increases in $CO_2$ emissions. Interestingly, the subset of 3 days with decreases in CAISO's system $CO_2$ emissions factor is the subset of 3 days where total $CO_2$ emissions increased for CAISO. The converse is also true. This indicates a counter-intuitive result for the original reductions in emissions reported in Table 4-6. CAISO's system was more efficient on a $CO_2$ emissions basis for the February, March, and April study days even though total emissions increased.

The results for the NOx emissions factor differ from the $CO_2$ results. Of the two study days that showed a decrease in the total NOx emissions for the CAISO simulations, the April 6 study day was the only one to also show a decrease in the system NOx emission factor. The December 12 study day shows an increase in the system NOx emission factor when total NOx emissions decreased. The NOx emission factor for the February 1 study day decreased indicating the system was more efficient on a NOx emissions basis even though total NOx emissions were estimated to have increased. The NOx emission factor for the remaining three days increased.

**Table 3-10: Summary of total emissions factors for CAISO coal, combined cycle, and combustion turbine plants for six simulated 2020 days for cases with no penetration of storage and 25% penetration of storage in CAISO regulation markets.**

| CAISO 2020 Simulation Days (tones/MWh) | No Storage | | 25% Storage | | Difference | | Percent Difference | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ |
| **12-Jan-20** | 0.33 | 0.0010 | 0.33 | 0.0010 | 2.85E-05 | 7.83E-08 | 0.01% | 0.01% |
| **1-Feb-20** | 0.35 | 0.0011 | 0.35 | 0.0011 | -5.88E-04 | -1.75E-06 | -0.17% | -0.16% |
| **9-Mar-20** | 0.36 | 0.0012 | 0.36 | 0.0012 | -3.45E-04 | 9.19E-07 | -0.09% | 0.07% |
| **6-Apr-20** | 0.39 | 0.0014 | 0.39 | 0.0013 | -1.00E-03 | -1.75E-05 | -0.26% | -1.29% |
| **1-Sep-20** | 0.33 | 0.0010 | 0.33 | 0.0010 | 2.08E-05 | 4.88E-07 | 0.01% | 0.05% |
| **12-Dec-20** | 0.31 | 0.0009 | 0.31 | 0.0009 | 5.89E-04 | 8.24E-07 | 0.19% | 0.09% |

Table 3-11 displays the emissions for the six CAISO study days by plant type and Table 3-12 examines the difference in emissions from the two scenarios. As seen in Table 3-12, the determining factor in whether total system $CO_2$ emissions increased or decreased were the combined cycle power plants. The large increase in $CO_2$ emissions from the combined cycle generating assets was greater than the decrease in $CO_2$ emissions from the combustion turbine assets. Coal emissions have little impact due to the low penetration of coal power within CAISO's system. The combined cycle assets play a similarly important role in determining the change in total system NOx emissions. When NOx emissions for the combined cycle power plants decrease then the total NOx emissions for the system also decrease.

**Table 3-11: Summary of estimated emissions by power plant type for six simulated 2020 days for cases with no penetration of storage and 25% penetration of storage in CAISO regulation markets.**

| CAISO 2020 Simulation Days (tones) | Coal | | Combined Cycle | | Combustion Turbine | |
|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ | $CO_2$ | $NO_x$ |
| **No Storage** | | | | | | |
| *12-Jan-20* | 808 | 1.61 | 52659 | 157 | 7963 | 27.5 |
| *1-Feb-20* | 796 | 1.58 | 51453 | 164 | 8098 | 28.5 |
| *9-Mar-20* | 620 | 1.23 | 50390 | 171 | 7216 | 27.1 |
| *6-Apr-20* | 679 | 1.35 | 49346 | 172 | 6556 | 25.6 |
| *1-Sep-20* | 810 | 1.61 | 52236 | 158 | 8481 | 29.3 |
| *12-Dec-20* | 899 | 1.79 | 53085 | 155 | 9021 | 28.4 |
| **25% Storage** | | | | | | |
| *12-Jan-20* | 808 | 1.61 | 52657 | 157 | 7962 | 27.5 |
| *1-Feb-20* | 796 | 1.58 | 51504 | 164 | 8096 | 28.5 |
| *9-Mar-20* | 620 | 1.23 | 50429 | 172 | 7203 | 27.1 |
| *6-Apr-20* | 678 | 1.35 | 49420 | 170 | 6541 | 25.7 |
| *1-Sep-20* | 810 | 1.61 | 52234 | 158 | 8481 | 29.3 |
| *12-Dec-20* | 902 | 1.79 | 53011 | 155 | 9032 | 28.4 |

**Table 3-12: Comparison of 0% and 25% penetration of storage cases in CAISO regulation markets by power plant type for six simulated 2020 days.**

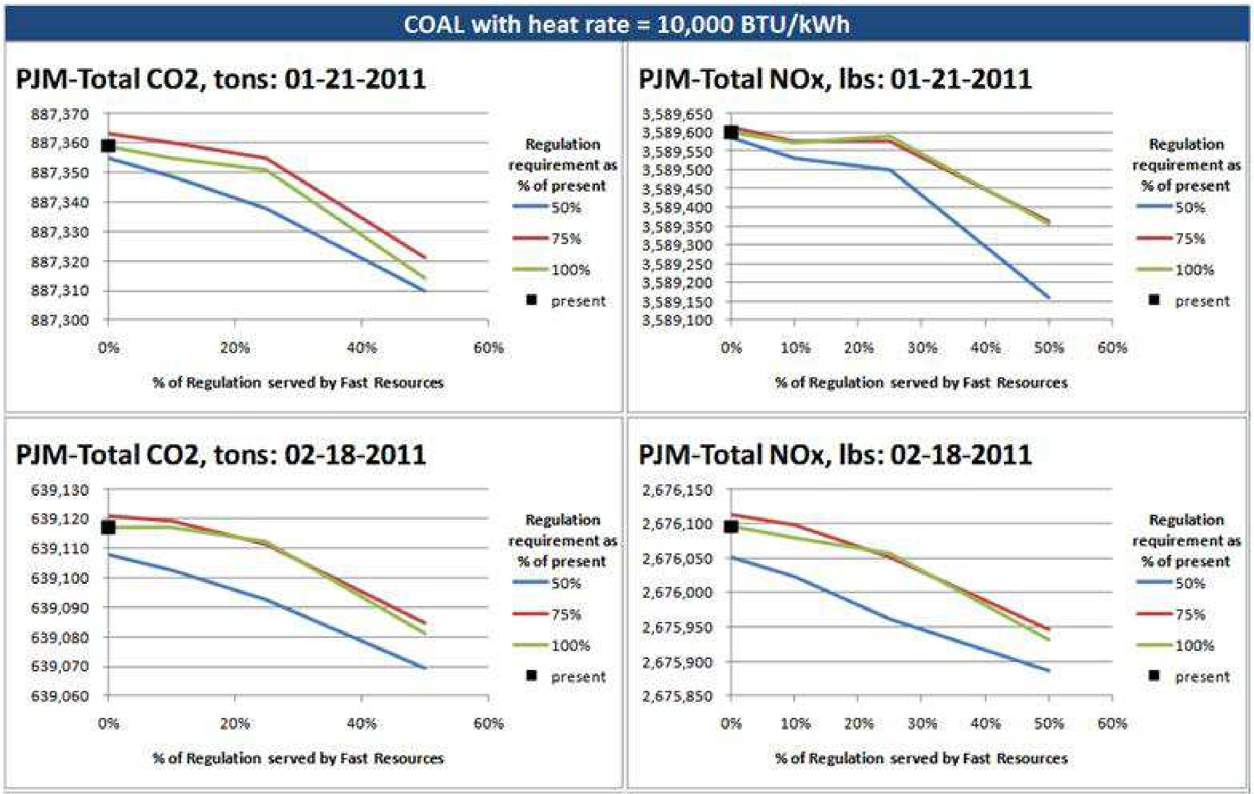
| CAISO 2020 Simulation Days | Coal | | Combined Cycle | | Combustion Turbine | |
|---|---|---|---|---|---|---|
| | *$CO_2$* | *$NO_x$* | *$CO_2$* | *$NO_x$* | *$CO_2$* | *$NO_x$* |
| **Difference** | | | | | | |
| *12-Jan-20* | 0.00 | 0.000 | -1 | -0.02 | -1.2 | 0.01 |
| *1-Feb-20* | 0.26 | 0.001 | 51 | 0.23 | -1.6 | -0.05 |
| *9-Mar-20* | 0.01 | 0.000 | 39 | 0.48 | -13.4 | -0.05 |
| *6-Apr-20* | -1.55 | -0.003 | 74 | -1.89 | -15.4 | 0.04 |
| *1-Sep-20* | 0.00 | 0.000 | -2 | 0.06 | 0.7 | 0.01 |
| *12-Dec-20* | 2.55 | 0.005 | -74 | -0.38 | 11.5 | 0.01 |
| **Percent Difference** | | | | | | |
| *12-Jan-20* | 0.00% | 0.00% | 0.00% | -0.01% | -0.02% | 0.03% |
| *1-Feb-20* | 0.03% | 0.03% | 0.10% | 0.14% | -0.02% | -0.17% |
| *9-Mar-20* | 0.00% | 0.00% | 0.08% | 0.28% | -0.18% | -0.20% |
| *6-Apr-20* | -0.23% | -0.23% | 0.15% | -1.10% | -0.23% | 0.15% |
| *1-Sep-20* | 0.00% | 0.00% | 0.00% | 0.04% | 0.01% | 0.04% |
| *12-Dec-20* | 0.28% | 0.28% | -0.14% | -0.24% | 0.13% | 0.03% |

## 3.4 Assessment of diminishing returns of storage benefits

As seen in Table 3-13, the emission savings for PJM is generally linear as the penetration of storage resources increases. Plots for the rest of the days can be found in the appendices to this report. Again, the maximum emissions reductions for both $CO_2$ and NOx are small (less than 1% of total system emissions).

We also examined what effect decreasing the regulation capacity requirement for PJM would have on system $CO_2$ and NOx emissions. In most cases no emissions savings were evident if the regulation requirement was reduced to 75% of the current regulation capacity requirements. If the regulation requirement is reduced to 50% of the current requirements then emission reductions are observed although they savings are minor (a decrease of less than 0.05% over the 100% cases).

**Table 3-13: Sample results for PJM Emissions**



## 3.5 Alternative Approaches to Reducing Emissions with Storage

Below are alternative approaches that could be utilized in order to increase the emission reduction advantages from a technology such as storage. These solutions are theoretical and most likely would policy initiatives in order to achieve, but are listed as potential outcomes.

### 3.5.1 Modifying Regulation Selection to maximize Emission Reduction

It is noted from studying some of the markets that of Regulation participants that there is a mix of Natural Gas, Coal, Oil, and zero emission resources participating in the regulation market. Though our study looked at replacing devices that participate in the market, this section examines the potential of taking a closer look at the impacts of regulation "up" and regulation "down" impacts.

Table 3-14 shows how a typical regulation service is handled by different generation groups in a control area. Conceivably, the percentages change on an hourly basis, but for this example, a single day is examined.

**Table 3-14: Potential Regulation Participation Mix for an ISO**

| Hypothetical Regulation Mix | Contribution to Regulation Up | Contribution to Regulation Down |
|---|---|---|
| Natural Gas | 13.9% | 0.0% |
| Coal | 75.2% | 85.3% |
| Oil | 0.0% | 0.0% |
| Emission-free power plants | 10.9% | 14.7% |

The meaning of the percentages in the table is as follows:

- If at a given time instant, the regulation signal is +100MW, i.e., Regulation Up, then the Natural Gas units are asked to increase their output by 13.9MW, Coal units by 75.2MW, Oil units by 0MW (or unchanged), and all other units by 10.9MW.
- If the regulation signal is -100MW, i.e., Regulation Down, then the Natural Gas units are asked to reduce their outputs by 0MW (unchanged), Coal units by 85.3MW, Oil units by 0MW, and all other units by 14.7MW.
- Note the asymmetry in the Up-versus-Down percentages. For the example day, those Natural Gas units that participate in Regulation were at their minimum power output, and thus cannot provide Regulation Down.

- The Up-versus-Down asymmetry implies that the emission is biased in one direction. To see why, we look at the $CO_2$ emission associated with a +1MW regulation signal and that with a -1MW regulation signal.
  - With **+1MW** signal, the Natural Gas plants will be asked to increase output by 0.139MW, and Coal by 0.752MW. (See Column 2 of table.) Using the emission factors of Table 3, the $CO_2$ emission will be added at a rate of +0.139*1,278 + 0.752*2,200 = **+1,832 lb/hr**.
  - With **-1MW** signal, the Coal plants will be asked to decrease output by 0.853MW, where as Natural Gas plants keep output unchanged. (See Column 3 of table.) Using the emission factors, the $CO_2$ emission will drop at a rate of - 0*1,278 - 0.853*2,200 = **-1,877 lb/hr**.

The take-away from this section is the following principle: In an emission-minded design for Frequency Regulation:

- Resources that are least polluted get highest priority during Regulation Up.
- Resources that are most polluted get highest priority during Regulation Down.

### 3.5.2 Using Storage for Spinning Reserve

Another potential emission reduction area is to examine the use of storage for spinning reserve. For this concept, the DNV KEMA study team examined four (4) areas in order to compare the emissions savings of using storage assets to provide spinning reserve for the grid.

The four (4) cases area described below:

1. Before: A 100 MW generator is providing spinning reserve for an hour by reserving 20% of its capacity (it is operating at 80% nameplate capacity or 80 MW). After: A 20MWh battery is provides spinning reserve and an 80 MW generator is running at 100% (80 MW). We compare the emissions from the before case to the after case.
2. Before: A 20 MW generator is providing spinning reserve for an hour by being on but not producing power (it is operating at 0% capacity or some small fraction). After: A 20MWh battery provides spinning reserve. We compare the emissions from the before case to the after case.
3. Same as case 1 except that an event happens during the given hour to where the spinning reserve is deployed (for both the before and after case).
4. Same as case 2 except that an event happens during the given hour to where the spinning reserve is deployed (for both the before and after case).

To run the cases, generator profiles were created. Then the generator profiles were run through the emissions code already utilized in the project for either a hypothetical 501D or LM 6000 device. The same simulated profile can be used in the after case. What will change is the nameplate capacity fed into the emissions code.

For all cases we assume a fully charged 20 MWh device. However, for most days when spinning reserves aren't deployed, the 20 MWh charge will last until there is appreciable decay in its charge that it needs to be recharged. As a result, some thought needs to be given to how to translate the emission savings from an hour's estimate to daily or annual estimates.

Below is an example of the daily potential savings that could be achieved though storage being utilized for spinning reserve.

**Table 3-15: Potential $CO_2$ Reductions achieve by utilizing storage for spinning reserve**

| Case | CO2 (ton) | | NOx (lb) | |
|---|---|---|---|---|
| | Before | After | Before | After |
| 1 | 12.06 | 11.8 | 70.81 | 56.65 |
| 2 | 0.62 | 0 | 5.67 | 0 |
| 3 | 14.75 | 11.8 | 70.81 | 56.65 |
| 4 | 2.95 | 0 | 14.16 | 0 |

# 4. Final Conclusions

1. In control areas where “coal” plants are part of the pool of resources contributing to regulation, storage devices appear to provide emission reductions. However, reductions are inconclusive in areas where clean generation has replaced coal or oil power production.

2. The interactions of the regulation market and the real time dispatch market complicates the analysis and makes it less straight forward to identify when emissions benefits are observed.

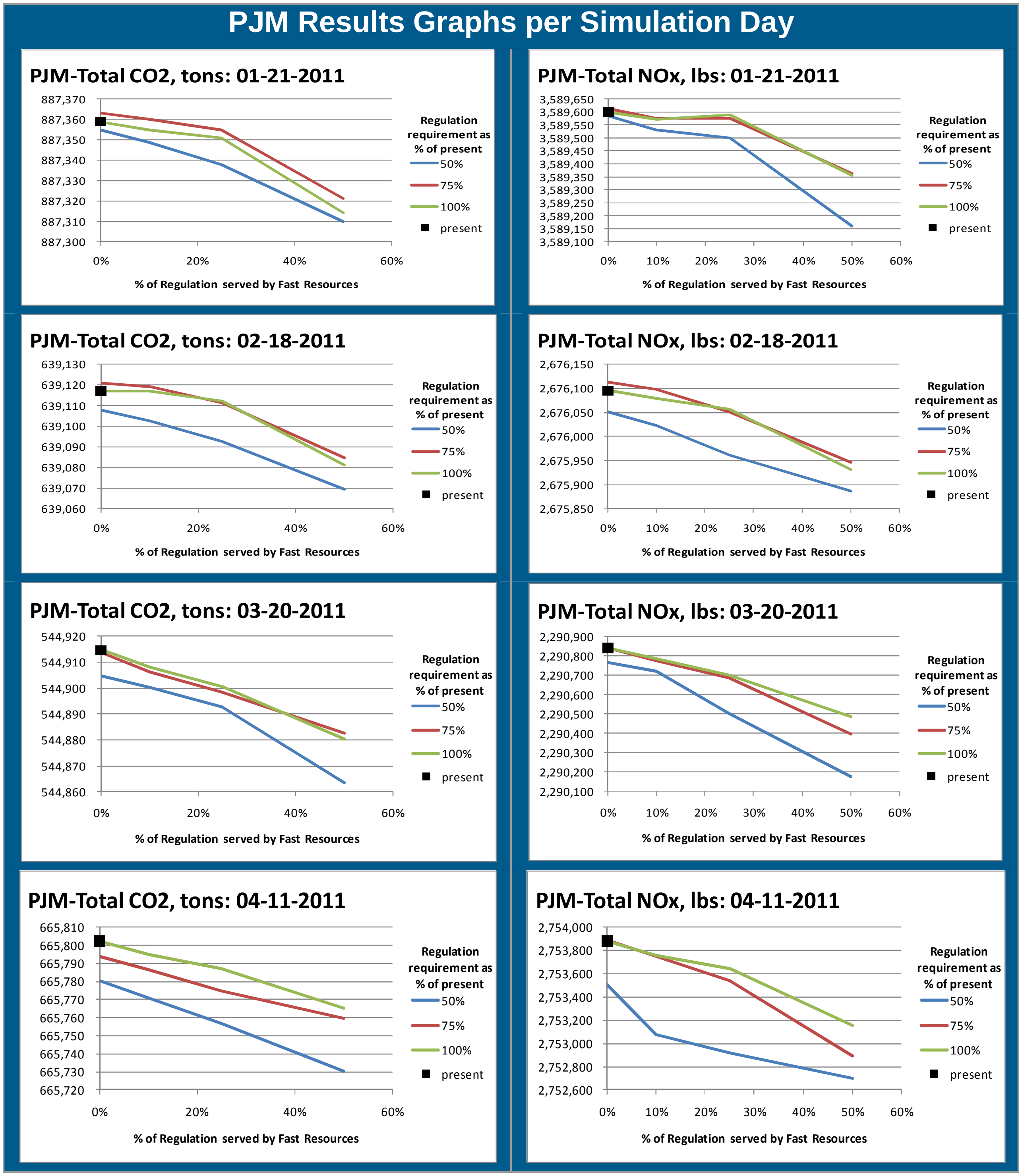
    a. The simulation results show that power plants that are “bumped out” of the regulation queue typically do not stop producing, but rather continue to participate in the real time dispatching, thus minimizing the potential benefits of the storage device being introduced into the ancillary service.

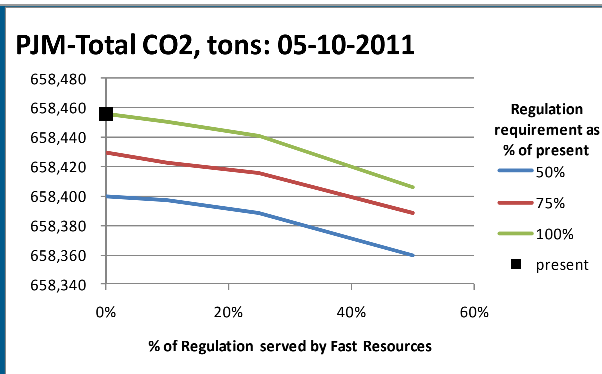
3. Once systems operators are able to quantify how much more efficiently storage resources can be in regulating their system frequency while maintaining system security, it will allow operators to procure reduced levels of frequency regulation capacity from conventional resources yielding some reductions in overall system emissions.

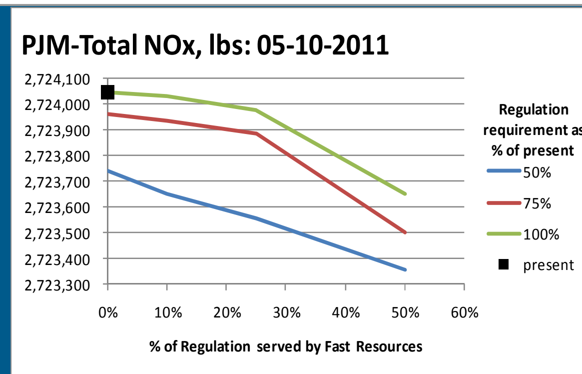
4. Additional emissions savings may be obtainable if emissions factors were to be included in the frequency regulation procurement and dispatch algorithms as an additional constraint in the control problem. That would require changes to current national and regional load balancing standards and frequency regulation market policies. Energy Storage devices represent a new factor to consider changes to those policies and regulations.

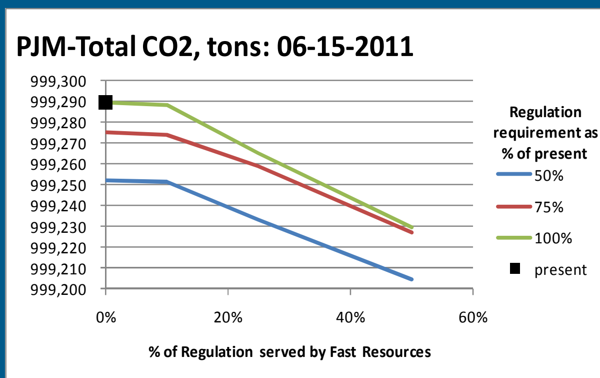
5. As regulation requirements make up a small percentage of the overall peak load, the frequency regulation margins in the studied cases are relatively small compared to total system power production and therefore the expected emissions totals associated exclusively with frequency regulation services from fossil fueled units is also relatively small compared with the total system emissions caused by production for energy supply.

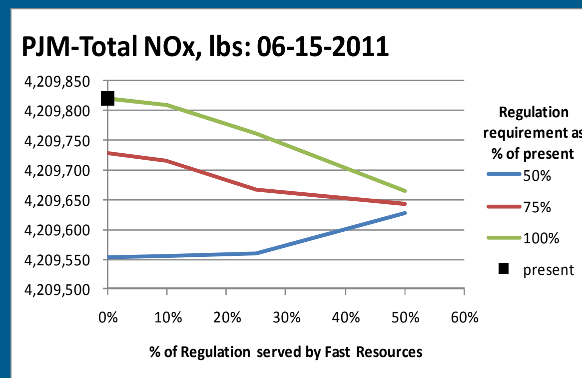
# A. PJM Results Graph

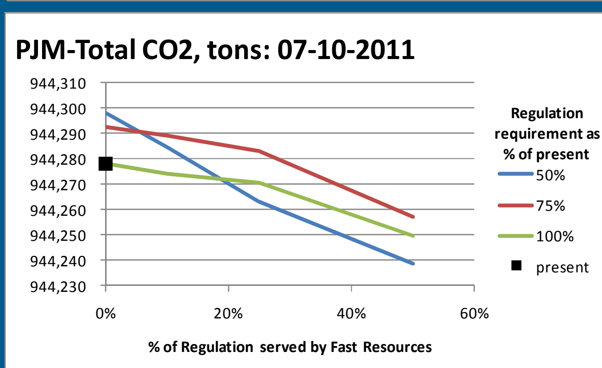


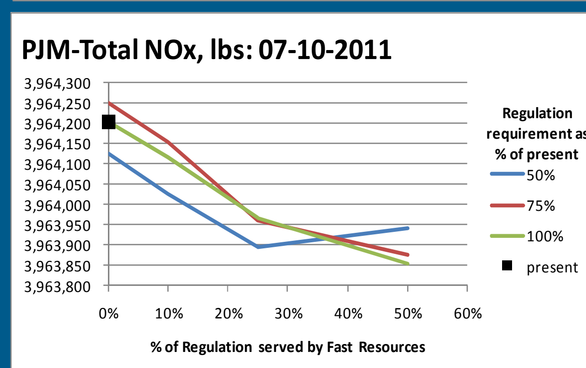

PJM-Total CO2, tons: 05-10-2011
Regulation requirement as % of present
50%
75%
100%
present
% of Regulation served by Fast Resources

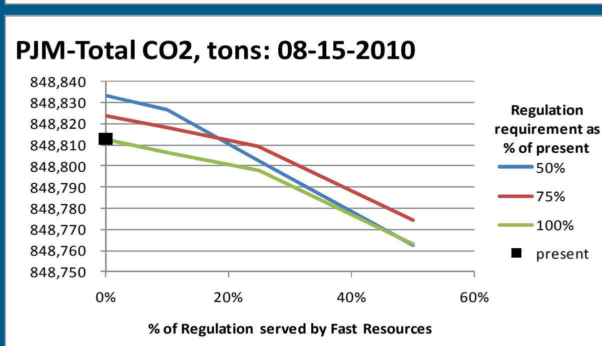

PJM-Total NOx, lbs: 05-10-2011
Regulation requirement as % of present
50%
75%
100%
present
% of Regulation served by Fast Resources

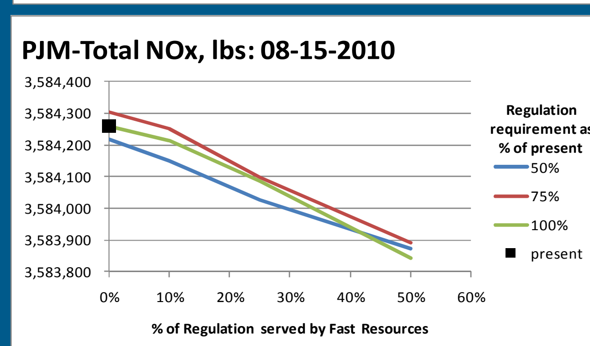

PJM-Total CO2, tons: 06-15-2011
Regulation requirement as % of present
50%
75%
100%
present
% of Regulation served by Fast Resources

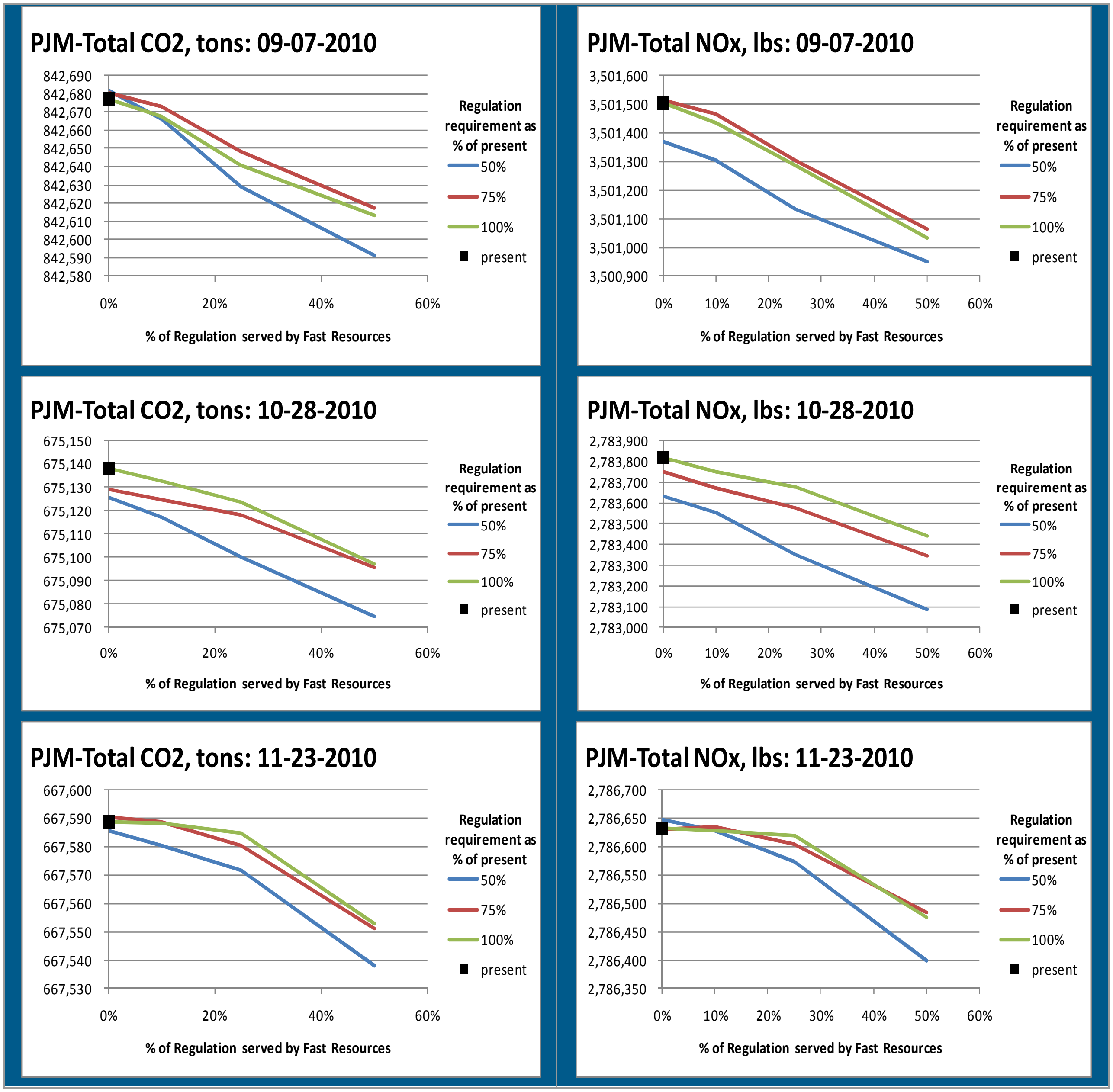

PJM-Total NOx, lbs: 06-15-2011
Regulation requirement as % of present
50%
75%
100%
present
% of Regulation served by Fast Resources

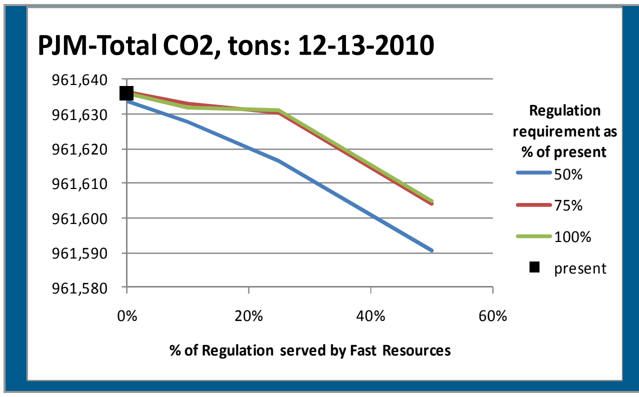

PJM-Total CO2, tons: 07-10-2011
Regulation requirement as % of present
50%
75%
100%
present
% of Regulation served by Fast Resources

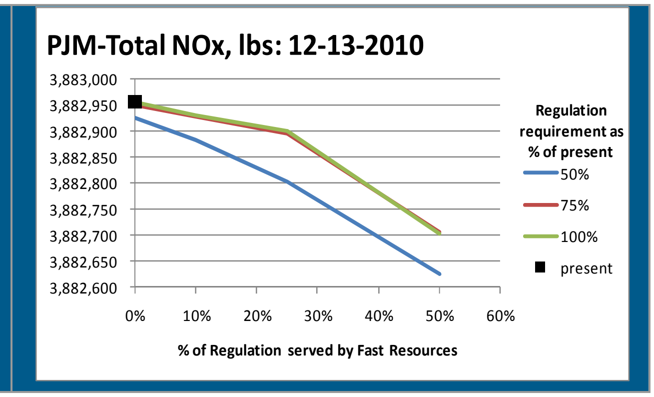

PJM-Total NOx, lbs: 07-10-2011
Regulation requirement as % of present
50%
75%
100%
present
% of Regulation served by Fast Resources


PJM-Total CO2, tons: 08-15-2010
Regulation requirement as % of present
50%
75%
100%
present
% of Regulation served by Fast Resources


PJM-Total NOx, lbs: 08-15-2010
Regulation requirement as % of present
50%
75%
100%
present
% of Regulation served by Fast Resources


PJM-Total CO2, tons: 09-07-2010
842,690
842,680
842,670
842,660
842,650
842,640
842,630
842,620
842,610
842,600
842,590
842,580
0%
20%
40%
60%
% of Regulation served by Fast Resources
Regulation requirement as % of present
50%
75%
100%
present
PJM-Total NOx, lbs: 09-07-2010
3,501,600
3,501,500
3,501,400
3,501,300
3,501,200
3,501,100
3,501,000
3,500,900
0%
10%
20%
30%
40%
50%
60%
% of Regulation served by Fast Resources
Regulation requirement as % of present
50%
75%
100%
present
PJM-Total CO2, tons: 10-28-2010
675,150
675,140
675,130
675,120
675,110
675,100
675,090
675,080
675,070
0%
20%
40%
60%
% of Regulation served by Fast Resources
Regulation requirement as % of present
50%
75%
100%
present
PJM-Total NOx, lbs: 10-28-2010
2,783,900
2,783,800
2,783,700
2,783,600
2,783,500
2,783,400
2,783,300
2,783,200
2,783,100
2,783,000
0%
10%
20%
30%
40%
50%
60%
% of Regulation served by Fast Resources
Regulation requirement as % of present
50%
75%
100%
present
PJM-Total CO2, tons: 11-23-2010
667,600
667,590
667,580
667,570
667,560
667,550
667,540
667,530
0%
20%
40%
60%
% of Regulation served by Fast Resources
Regulation requirement as % of present
50%
75%
100%
present
PJM-Total NOx, lbs: 11-23-2010
2,786,700
2,786,650
2,786,600
2,786,550
2,786,500
2,786,450
2,786,400
2,786,350
0%
10%
20%
30%
40%
50%
60%
% of Regulation served by Fast Resources
Regulation requirement as % of present
50%
75%
100%
present


PJM-Total CO2, tons: 12-13-2010
961,640
961,630
961,620
961,610
961,600
961,590
961,580
0%
20%
40%
60%
% of Regulation served by Fast Resources
Regulation requirement as % of present
50%
75%
100%
present


PJM-Total NOx, lbs: 12-13-2010
3,883,000
3,882,950
3,882,900
3,882,850
3,882,800
3,882,750
3,882,700
3,882,650
3,882,600
0%
10%
20%
30%
40%
50%
60%
% of Regulation served by Fast Resources
Regulation requirement as % of present
50%
75%
100%
present

# B. Sandia PJM Emission Data – Detailed Results

## PJM Simulations Detailed Results

| | Cases | Date | CO2_COAL | CO2_COMBINEDCYCLE | CO2_COMBUSTIONTURBINE | NOx_COAL | NOx_COMBINEDCYCLE | NOx_COMBUSTIONTURBINE | MWh_COAL | MWh_COMBINEDCYCLE | MWh_COMBUSTIONTURBINE | Total CO2 | Total NOx | PctReg | PctStor |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 1-21-2011_10PctStor_100PctReg | 1-21-2011 | 767193.46 | 118737.04 | 1424.26 | 3360341.82 | 220026.81 | 9203.25 | 712672.50 | 742118.31 | 7455.45 | 887355 | 3589572 | 100% | 10% |
| 4 | 2-18-2011_10PctStor_100PctReg | 2-18-2011 | 569873.78 | 67747.64 | 1495.33 | 2496072.76 | 171444.47 | 8561.09 | 529375.43 | 415524.34 | 9387.44 | 639117 | 2676078 | 100% | 10% |
| 5 | 3-20-2011_10PctStor_100PctReg | 3-20-2011 | 473106.62 | 69473.70 | 2327.80 | 2072228.25 | 205721.84 | 12835.75 | 439485.08 | 417700.07 | 14926.05 | 544908 | 2290786 | 100% | 10% |
| 6 | 4-11-2011_10PctStor_100PctReg | 4-11-2011 | 577887.80 | 83047.25 | 4859.89 | 2531174.56 | 190773.27 | 31805.64 | 536819.94 | 504244.30 | 23442.07 | 665795 | 2753753 | 100% | 10% |
| 7 | 5-10-2011_10PctStor_100PctReg | 5-10-2011 | 571208.24 | 86380.25 | 861.69 | 2501917.77 | 217274.33 | 4837.48 | 530615.06 | 520223.82 | 5698.36 | 658450 | 2724030 | 100% | 10% |
| 8 | 6-15-2011_10PctStor_100PctReg | 6-15-2011 | 891833.18 | 104980.11 | 2474.82 | 3906269.41 | 288853.74 | 14684.58 | 828454.64 | 627741.16 | 15076.70 | 999288 | 4209808 | 100% | 10% |
| 9 | 7-10-2011_10PctStor_100PctReg | 7-10-2011 | 809314.43 | 125530.20 | 9429.62 | 3544833.57 | 354784.12 | 64497.26 | 751800.12 | 743072.62 | 41769.90 | 944274 | 3964115 | 100% | 10% |
| 10 | 8-15-2010_10PctStor_100PctReg | 8-15-2010 | 728927.15 | 116713.74 | 3165.39 | 3192733.66 | 371059.26 | 20420.10 | 677125.60 | 681237.54 | 16800.06 | 848806 | 3584213 | 100% | 10% |
| 11 | 9-7-2010_10PctStor_100PctReg | 9-7-2010 | 715355.75 | 120308.92 | 7002.49 | 3133290.33 | 321823.88 | 46320.71 | 664518.66 | 702341.46 | 34052.55 | 842667 | 3501435 | 100% | 10% |
| 12 | 10-28-2010_10PctStor_100PctReg | 10-28-2010 | 585253.32 | 84887.52 | 4991.57 | 2563435.86 | 191247.05 | 29063.42 | 543662.02 | 523516.39 | 30002.66 | 675132 | 2783746 | 100% | 10% |
| 13 | 11-23-2010_10PctStor_100PctReg | 11-23-2010 | 586407.19 | 79779.01 | 1401.86 | 2568489.85 | 209317.25 | 8820.82 | 544733.89 | 481755.69 | 7547.28 | 667588 | 2786628 | 100% | 10% |
| 14 | 12-13-2010_10PctStor_100PctReg | 12-13-2010 | 820261.05 | 134059.84 | 7311.00 | 3592780.25 | 238554.96 | 51595.51 | 761968.81 | 841705.13 | 29705.98 | 961632 | 3882931 | 100% | 10% |
| 15 | 1-21-2011_25PctStor_100PctReg | 1-21-2011 | 767189.63 | 118736.73 | 1424.27 | 3360325.07 | 220059.25 | 9203.07 | 712668.94 | 742115.48 | 7455.47 | 887351 | 3589587 | 100% | 25% |
| 16 | 2-18-2011_25PctStor_100PctReg | 2-18-2011 | 569869.56 | 67747.37 | 1495.34 | 2496054.29 | 171441.80 | 8560.77 | 529371.51 | 415521.93 | 9387.47 | 639112 | 2676057 | 100% | 25% |
| 17 | 3-20-2011_25PctStor_100PctReg | 3-20-2011 | 473099.83 | 69473.12 | 2327.79 | 2072198.53 | 205667.62 | 12835.76 | 439478.77 | 417694.82 | 14925.93 | 544901 | 2290702 | 100% | 25% |
| 18 | 4-11-2011_25PctStor_100PctReg | 4-11-2011 | 577879.81 | 83047.07 | 4859.97 | 2531139.54 | 190696.50 | 31806.76 | 536812.51 | 504242.67 | 23442.76 | 665787 | 2753643 | 100% | 25% |
| 19 | 5-10-2011_25PctStor_100PctReg | 5-10-2011 | 571199.36 | 86380.03 | 861.68 | 2501878.89 | 217259.75 | 4837.48 | 530606.81 | 520221.97 | 5698.33 | 658441 | 2723976 | 100% | 25% |
| 20 | 6-15-2011_25PctStor_100PctReg | 6-15-2011 | 891811.65 | 104978.88 | 2474.84 | 3906175.09 | 288900.83 | 14684.29 | 828434.63 | 627730.01 | 15076.86 | 999265 | 4209760 | 100% | 25% |
| 21 | 7-10-2011_25PctStor_100PctReg | 7-10-2011 | 809310.67 | 125530.33 | 9429.71 | 3544817.12 | 354654.16 | 64496.17 | 751796.63 | 743073.79 | 41770.56 | 944271 | 3963967 | 100% | 25% |
| 22 | 8-15-2010_25PctStor_100PctReg | 8-15-2010 | 728919.67 | 116713.15 | 3165.39 | 3192700.91 | 370965.33 | 20419.80 | 677118.65 | 681232.21 | 16800.10 | 848798 | 3584086 | 100% | 25% |
| 23 | 9-7-2010_25PctStor_100PctReg | 9-7-2010 | 715330.92 | 120307.00 | 7002.49 | 3133181.57 | 321784.17 | 46320.05 | 664495.59 | 702324.10 | 34052.54 | 842640 | 3501286 | 100% | 25% |
| 24 | 10-28-2010_25PctStor_100PctReg | 10-28-2010 | 585244.95 | 84886.88 | 4991.65 | 2563399.20 | 191211.74 | 29062.91 | 543654.25 | 523510.61 | 30003.22 | 675123 | 2783674 | 100% | 25% |
| 25 | 11-23-2010_25PctStor_100PctReg | 11-23-2010 | 586403.94 | 79778.78 | 1401.87 | 2568475.60 | 209322.91 | 8820.64 | 544730.87 | 481753.60 | 7547.31 | 667585 | 2786619 | 100% | 25% |
| 26 | 12-13-2010_25PctStor_100PctReg | 12-13-2010 | 820260.24 | 134059.86 | 7311.08 | 3592776.73 | 238529.93 | 51593.07 | 761968.07 | 841705.27 | 29706.41 | 961631 | 3882900 | 100% | 25% |
| 27 | 1-21-2011_50PctStor_100PctReg | 1-21-2011 | 767156.91 | 118733.07 | 1424.25 | 3360181.73 | 219969.44 | 9202.49 | 712638.54 | 742082.34 | 7455.32 | 887314 | 3589354 | 100% | 50% |
| 28 | 2-18-2011_50PctStor_100PctReg | 2-18-2011 | 569840.83 | 67745.11 | 1495.32 | 2495928.45 | 171443.32 | 8560.30 | 529344.83 | 415501.48 | 9387.25 | 639081 | 2675932 | 100% | 50% |
| 29 | 3-20-2011_50PctStor_100PctReg | 3-20-2011 | 473081.43 | 69471.37 | 2327.71 | 2072117.93 | 205532.30 | 12835.78 | 439461.68 | 417679.01 | 14925.37 | 544881 | 2290486 | 100% | 50% |
| 30 | 4-11-2011_50PctStor_100PctReg | 4-11-2011 | 577859.06 | 83046.18 | 4860.14 | 2531048.67 | 190295.02 | 31806.35 | 536793.24 | 504234.58 | 23444.11 | 665765 | 2753150 | 100% | 50% |
| 31 | 5-10-2011_50PctStor_100PctReg | 5-10-2011 | 571166.08 | 86377.80 | 861.67 | 2501733.09 | 217078.73 | 4837.48 | 530575.89 | 520201.72 | 5698.22 | 658406 | 2723649 | 100% | 50% |
| 32 | 6-15-2011_50PctStor_100PctReg | 6-15-2011 | 891777.60 | 104977.00 | 2474.91 | 3906025.97 | 288955.88 | 14683.49 | 828403.01 | 627713.07 | 15077.24 | 999230 | 4209665 | 100% | 50% |
| 33 | 7-10-2011_50PctStor_100PctReg | 7-10-2011 | 809291.17 | 125528.88 | 9429.77 | 3544731.68 | 354632.15 | 64491.45 | 751778.51 | 743060.62 | 41770.65 | 944250 | 3963855 | 100% | 50% |
| 34 | 8-15-2010_50PctStor_100PctReg | 8-15-2010 | 728887.75 | 116710.08 | 3165.36 | 3192561.09 | 370862.52 | 20418.83 | 677089.00 | 681204.39 | 16799.82 | 848763 | 3583842 | 100% | 50% |
| 35 | 9-7-2010_50PctStor_100PctReg | 9-7-2010 | 715305.08 | 120305.68 | 7002.58 | 3133068.41 | 321649.17 | 46316.92 | 664471.59 | 702312.17 | 34052.96 | 842613 | 3501034 | 100% | 50% |
| 36 | 10-28-2010_50PctStor_100PctReg | 10-28-2010 | 585220.71 | 84884.86 | 4991.77 | 2563293.01 | 191086.52 | 29061.07 | 543631.72 | 523492.36 | 30003.88 | 675097 | 2783441 | 100% | 50% |
| 37 | 11-23-2010_50PctStor_100PctReg | 11-23-2010 | 586375.07 | 79776.17 | 1401.85 | 2568349.16 | 209305.38 | 8820.10 | 544704.05 | 481729.97 | 7547.15 | 667553 | 2786475 | 100% | 50% |
| 38 | 12-13-2010_50PctStor_100PctReg | 12-13-2010 | 820236.32 | 134057.38 | 7311.18 | 3592671.96 | 238444.11 | 51587.93 | 761945.84 | 841682.88 | 29706.68 | 961605 | 3882704 | 100% | 50% |
| 39 | 1-21-2011_10PctStor_75PctReg | 1-21-2011 | 767198.24 | 118737.58 | 1424.26 | 3360362.76 | 220010.17 | 9203.25 | 712676.93 | 742123.21 | 7455.46 | 887360 | 3589576 | 75% | 10% |
| 40 | 2-18-2011_10PctStor_75PctReg | 2-18-2011 | 569875.96 | 67747.86 | 1495.33 | 2496082.34 | 171453.97 | 8560.78 | 529377.46 | 415526.37 | 9387.41 | 639119 | 2676097 | 75% | 10% |
| 41 | 3-20-2011_10PctStor_75PctReg | 3-20-2011 | 473104.71 | 69473.61 | 2327.78 | 2072219.89 | 205718.88 | 12835.76 | 439483.30 | 417699.29 | 14925.85 | 544906 | 2290775 | 75% | 10% |
| 42 | 4-11-2011_10PctStor_75PctReg | 4-11-2011 | 577879.38 | 83046.97 | 4859.95 | 2531137.65 | 190801.94 | 31806.58 | 536812.11 | 504241.71 | 23442.55 | 665786 | 2753746 | 75% | 10% |
| 43 | 5-10-2011_10PctStor_75PctReg | 5-10-2011 | 571182.62 | 86378.12 | 861.68 | 2501805.56 | 217293.88 | 4837.48 | 530591.26 | 520204.59 | 5698.28 | 658422 | 2723937 | 75% | 10% |
| 44 | 6-15-2011_10PctStor_75PctReg | 6-15-2011 | 891819.90 | 104979.21 | 2474.84 | 3906211.25 | 288820.51 | 14684.15 | 828442.30 | 627733.07 | 15076.78 | 999274 | 4209716 | 75% | 10% |
| 45 | 7-10-2011_10PctStor_75PctReg | 7-10-2011 | 809328.23 | 125531.37 | 9429.61 | 3544894.00 | 354763.68 | 64497.24 | 751812.94 | 743083.21 | 41769.81 | 944289 | 3964155 | 75% | 10% |
| 46 | 8-15-2010_10PctStor_75PctReg | 8-15-2010 | 728938.04 | 116714.69 | 3165.38 | 3192781.38 | 371048.14 | 20420.04 | 677135.72 | 681246.16 | 16800.06 | 848818 | 3584250 | 75% | 10% |
| 47 | 9-7-2010_10PctStor_75PctReg | 9-7-2010 | 715361.43 | 120309.32 | 7002.49 | 3133315.21 | 321827.31 | 46320.62 | 664523.93 | 702345.15 | 34052.53 | 842673 | 3501463 | 75% | 10% |
| 48 | 10-28-2010_10PctStor_75PctReg | 10-28-2010 | 585245.84 | 84886.99 | 4991.67 | 2563403.08 | 191203.18 | 29062.81 | 543655.07 | 523511.59 | 30003.40 | 675124 | 2783669 | 75% | 10% |
| 49 | 11-23-2010_10PctStor_75PctReg | 11-23-2010 | 586407.87 | 79779.06 | 1401.86 | 2568492.84 | 209321.89 | 8820.74 | 544734.52 | 481756.11 | 7547.24 | 667589 | 2786635 | 75% | 10% |
| 50 | 12-13-2010_10PctStor_75PctReg | 12-13-2010 | 820262.01 | 134059.90 | 7310.99 | 3592784.49 | 238547.87 | 51595.31 | 761969.71 | 841705.70 | 29705.85 | 961633 | 3882928 | 75% | 10% |
| 51 | 1-21-2011_25PctStor_75PctReg | 1-21-2011 | 767193.33 | 118737.16 | 1424.27 | 3360341.29 | 220029.68 | 9203.02 | 712672.38 | 742119.42 | 7455.48 | 887355 | 3589574 | 75% | 25% |
| 52 | 2-18-2011_25PctStor_75PctReg | 2-18-2011 | 569868.53 | 67747.32 | 1495.33 | 2496049.79 | 171441.56 | 8560.51 | 529370.56 | 415521.50 | 9387.40 | 639111 | 2676052 | 75% | 25% |
| 53 | 3-20-2011_25PctStor_75PctReg | 3-20-2011 | 473097.47 | 69472.96 | 2327.75 | 2072188.16 | 205662.41 | 12835.76 | 439476.57 | 417693.38 | 14925.70 | 544898 | 2290686 | 75% | 25% |
| 54 | 4-11-2011_25PctStor_75PctReg | 4-11-2011 | 577868.33 | 83046.40 | 4860.01 | 2531089.24 | 190641.62 | 31806.70 | 536801.84 | 504236.58 | 23443.06 | 665775 | 2753538 | 75% | 25% |

# C. Sandia PJM Emission Data – Summary Statistics

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | PJM Emissions Calculations Summary Statistics | | | | | | | | | | | | | | | | |
| 2 | CO2 | | | | | | | | | | | | | | | | |
| 3 | Row Label: | 10-28-2010 | 11-23-2010 | 1-21-2011 | 12-13-2010 | 2-18-2011 | 3-20-2011 | 4-11-2011 | 5-10-2011 | 6-15-2011 | 7-10-2011 | 8-15-2010 | 9-7-2010 | Max | Min | Ave | Std Dev |
| 4 | 50% Regulation Requirement | | | | | | | | | | | | | | | | |
| 5 | 0% | -0.0018% | -0.0004% | -0.0005% | -0.0002% | -0.0015% | -0.0018% | -0.0033% | -0.0085% | -0.0038% | 0.0021% | 0.0024% | 0.0005% | 0.0024% | -0.0085% | -0.0014% | 0.0029% |
| 6 | 10% | -0.0031% | -0.0012% | -0.0012% | -0.0009% | -0.0023% | -0.0026% | -0.0047% | -0.0090% | -0.0038% | 0.0007% | 0.0017% | -0.0014% | 0.0017% | -0.0090% | -0.0023% | 0.0028% |
| 7 | 25% | -0.0056% | -0.0026% | -0.0024% | -0.0020% | -0.0039% | -0.0040% | -0.0068% | -0.0102% | -0.0056% | -0.0016% | -0.0012% | -0.0057% | -0.0012% | -0.0102% | -0.0043% | 0.0026% |
| 8 | 50% | -0.0094% | -0.0076% | -0.0056% | -0.0047% | -0.0075% | -0.0094% | -0.0108% | -0.0146% | -0.0085% | -0.0042% | -0.0059% | -0.0102% | -0.0042% | -0.0146% | -0.0082% | 0.0030% |
| 9 | 75% Regulation Requirement | | | | | | | | | | | | | | | | |
| 10 | 0% | -0.0013% | 0.0003% | 0.0005% | 0.0001% | 0.0006% | -0.0002% | -0.0012% | -0.0040% | -0.0015% | 0.0015% | 0.0013% | 0.0004% | 0.0015% | -0.0040% | -0.0003% | 0.0015% |
| 11 | 10% | -0.0020% | 0.0000% | 0.0001% | -0.0003% | 0.0003% | -0.0016% | -0.0024% | -0.0051% | -0.0016% | 0.0012% | 0.0006% | -0.0005% | 0.0012% | -0.0051% | -0.0009% | 0.0017% |
| 12 | 25% | -0.0029% | -0.0012% | -0.0005% | -0.0006% | -0.0009% | -0.0030% | -0.0041% | -0.0061% | -0.0031% | 0.0005% | -0.0004% | -0.0035% | 0.0005% | -0.0061% | -0.0021% | 0.0019% |
| 13 | 50% | -0.0063% | -0.0056% | -0.0043% | -0.0033% | -0.0050% | -0.0058% | -0.0064% | -0.0102% | -0.0062% | -0.0022% | -0.0045% | -0.0071% | -0.0022% | -0.0102% | -0.0056% | 0.0020% |
| 14 | 100% Regulation Requirement | | | | | | | | | | | | | | | | |
| 15 | | | | | | | | | | | | | | | | | |
| 16 | 10% | -0.0008% | -0.0001% | -0.0005% | -0.0004% | 0.0000% | -0.0012% | -0.0011% | -0.0009% | -0.0001% | -0.0004% | -0.0008% | -0.0012% | 0.0000% | -0.0012% | -0.0006% | 0.0004% |
| 17 | 25% | -0.0022% | -0.0006% | -0.0009% | -0.0005% | -0.0007% | -0.0026% | -0.0023% | -0.0022% | -0.0024% | -0.0008% | -0.0017% | -0.0044% | -0.0005% | -0.0044% | -0.0018% | 0.0011% |
| 18 | 50% | -0.0060% | -0.0053% | -0.0050% | -0.0032% | -0.0056% | -0.0063% | -0.0055% | -0.0076% | -0.0060% | -0.0030% | -0.0058% | -0.0076% | -0.0030% | -0.0076% | -0.0056% | 0.0014% |
| 19 | | | | | | | | | | | | | | | | | |
| 20 | | | | | | | | | | | | | | | | | |
| 21 | Nox | | | | | | | | | | | | | | | | |
| 22 | Row Label: | 10-28-2010 | 11-23-2010 | 1-21-2011 | 12-13-2010 | 2-18-2011 | 3-20-2011 | 4-11-2011 | 5-10-2011 | 6-15-2011 | 7-10-2011 | 8-15-2010 | 9-7-2010 | Max | Min | Ave | Std Dev |
| 23 | 50% Regulation Requirement | | | | | | | | | | | | | | | | |
| 24 | 0% | -0.0066% | 0.0006% | -0.0004% | -0.0008% | -0.0017% | -0.0032% | -0.0138% | -0.0112% | -0.0063% | -0.0020% | -0.0012% | -0.0038% | 0.0006% | -0.0138% | -0.0042% | 0.0045% |
| 25 | 10% | -0.0095% | -0.0001% | -0.0019% | -0.0019% | -0.0027% | -0.0053% | -0.0291% | -0.0144% | -0.0063% | -0.0045% | -0.0031% | -0.0057% | -0.0001% | -0.0291% | -0.0070% | 0.0080% |
| 26 | 25% | -0.0167% | -0.0021% | -0.0028% | -0.0039% | -0.0050% | -0.0148% | -0.0349% | -0.0179% | -0.0062% | -0.0078% | -0.0065% | -0.0106% | -0.0021% | -0.0349% | -0.0108% | 0.0093% |
| 27 | 50% | -0.0262% | -0.0084% | -0.0123% | -0.0085% | -0.0078% | -0.0289% | -0.0429% | -0.0253% | -0.0046% | -0.0066% | -0.0108% | -0.0158% | -0.0046% | -0.0429% | -0.0165% | 0.0118% |
| 28 | 75% Regulation Requirement | | | | | | | | | | | | | | | | |
| 29 | 0% | -0.0024% | 0.0000% | 0.0004% | -0.0002% | 0.0007% | 0.0000% | 0.0003% | -0.0030% | -0.0022% | 0.0012% | 0.0013% | 0.0003% | 0.0013% | -0.0030% | -0.0003% | 0.0014% |
| 30 | 10% | -0.0053% | 0.0001% | -0.0006% | -0.0007% | 0.0001% | -0.0029% | -0.0049% | -0.0039% | -0.0025% | -0.0012% | -0.0003% | -0.0012% | 0.0001% | -0.0053% | -0.0019% | 0.0019% |
| 31 | 25% | -0.0086% | -0.0010% | -0.0007% | -0.0016% | -0.0016% | -0.0067% | -0.0125% | -0.0059% | -0.0036% | -0.0061% | -0.0045% | -0.0057% | -0.0007% | -0.0125% | -0.0049% | 0.0035% |
| 32 | 50% | -0.0170% | -0.0053% | -0.0066% | -0.0065% | -0.0056% | -0.0193% | -0.0359% | -0.0200% | -0.0042% | -0.0082% | -0.0103% | -0.0126% | -0.0042% | -0.0359% | -0.0126% | 0.0092% |
| 33 | 100% Regulation Requirement | | | | | | | | | | | | | | | | |
| 34 | | | | | | | | | | | | | | | | | |
| 35 | 10% | -0.0025% | -0.0001% | -0.0007% | -0.0007% | -0.0006% | -0.0024% | -0.0046% | -0.0005% | -0.0003% | -0.0022% | -0.0013% | -0.0020% | -0.0001% | -0.0046% | -0.0015% | 0.0013% |
| 36 | 25% | -0.0051% | -0.0004% | -0.0003% | -0.0015% | -0.0014% | -0.0060% | -0.0087% | -0.0025% | -0.0014% | -0.0059% | -0.0048% | -0.0062% | -0.0003% | -0.0087% | -0.0037% | 0.0028% |
| 37 | 50% | -0.0135% | -0.0056% | -0.0068% | -0.0065% | -0.0061% | -0.0155% | -0.0266% | -0.0145% | -0.0037% | -0.0088% | -0.0116% | -0.0134% | -0.0037% | -0.0266% | -0.0110% | 0.0063% |

# D. CAISO Emissions Calculations Results by Regulating Unit for the six study days (25% Storage Case)

Please refer to attached workbook: Appendix D - CAISO Regulating Units Hourly Emissions Results at 25 percent storage.xlsx.

# E. CAISO emission by each plant on AGC

Please refer to attached workbook: Appendix E - CAISO emission by each plant on AGC_20120119.xlsx.