# Compensating for Wind Variability Using Co-Located Natural Gas Generation and Energy Storage

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## Abstract

Wind generation presents variability on every time scale, which must be accommodated by the electric grid. Limited quantities of wind power can be successfully integrated by the current generation and demand-side response mix but, as deployment of variable resources increases, the resulting variability becomes increasingly difficult and costly to mitigate. We model a co-located power generation/energy storage block which contains wind generation, a gas turbine, and fast-ramping energy storage. Conceptually, the system is designed with the goal of producing near-constant “baseload” power at a reasonable cost while still delivering a significant and environmentally meaningful fraction of that power from wind. The model is executed in 10 second time increments in order to correctly reflect the operational limitations of the natural gas turbine. A scenario analysis identifies system configurations that can generate power with 30% of energy from wind, a variability of less than 0.5% of the desired power level, and an average cost around $70/MWh. The systems described have the most utility for isolated grids, such as Hawaii or Ireland, but the study has implications for all electrical systems seeking to integrate wind energy and informs potential incentive policies.

# 1. Introduction

Wind power output is variable on every time scale [1]. Wind power variation on the scale of hours or days can be smoothed by traditional generators or by compressed air energy storage (CAES). Natural gas turbines in particular are able to quickly change their power output and are important for the integration of wind power, but are unable to respond in seconds to minutes, especially from a cold start. For example, the GE 7FA gas turbine, a common unit, has a fast start-up option which allows the turbine to dispatch in 10 minutes after a start signal [2, 3]. In addition to non-zero startup time, these generators have low operating limits, limited ramp rates, inefficiency at low output, and other characteristics that are sometimes neglected when they are modeled as wind-smoothing devices. For this reason, if a wind farm is coupled with a gas generator (or gas-fired CAES), the power output can be smooth on an hourly scale, but can still become quite noisy on shorter time scales. In most contemporary electrical systems, this high frequency variation is mitigated by distributing the response over a large number of traditional generation resources or hydropower resources providing regulation service [4, 5]. At higher wind penetration levels significant ancillary services, in the form of quick-ramping regulation, are likely to be required. This can lead to increased emissions, as it has been shown that fast and frequent ramping of gas generators decreases their average efficiency, increases their average $CO_2$ emissions, and greatly increases their $NO_x$ emissions for some types of gas generators [6]. Energy storage may mitigate variability in renewable generation, but most energy storage technologies are still prohibitively expensive for bulk storage applications and typically have limited round-trip efficiencies [7–9].

The goal of this work is to determine whether adding a small amount of fast-ramping energy storage to wind+natural gas turbine systems can reduce the costs and emissions of smoothing the output from wind generators by providing a small amount of short time scale smoothing. Conceptually, gas generators and storage are used complementarily to smooth wind – energy storage is expensive but is able to ramp extremely quickly and handle high power levels while gas turbines are able to provide large quantities of fill-in power at a reasonable cost but have important operational limitations. We investigate a hybrid (gas turbine and energy storage) compensation system by modeling both wind power and the gas+storage system at a 10-second time resolution.

Three results are presented. First, we show that modeling wind and compensating resources using shorter time scales produces results notably different than modeling them in 1-hour blocks. Studies frequently use 1-hour blocks of time, both because of the availability of such data and because the largest amplitude wind fluctuations occur over longer time scales [10]. However, all of the time-based operational limitations of natural gas generators occur sub-hourly and, by modeling in 1-hour increments, gas turbines unrealistically appear to be "perfect" generators capable of fulfilling any power requirements. Thus, the need for finer time resolution is not due to wind fluctuations, but mainly required for the accurate modeling of the response to these fluctuations. Second, we demonstrate that a small amount of energy storage co-located with the wind and natural gas turbines can significantly reduce high-frequency power fluctuations. As mentioned above, energy storage devices can buffer the power spikes and dips from wind fluctuations. The inclusion of energy storage decreases the quantity and size of power fluctuations externalized to the grid, which then requires less regulation service. Third, we demonstrate a wind/natural gas/energy storage hybrid generation block that is capable of delivering a large fraction of wind energy, smoothed to a power variability of less than 0.5%, at a reasonable cost.

## 2. Methodology

We model the wind power/natural gas turbine/energy storage system using a time-series operational framework which takes as an input actual wind generation, measured with 10-second time resolution, and a number of operational constraints, including natural gas ramp rate and system target power output. The model determines the operation of the generation and storage resources required to meet the defined system power requirements. This operational model is used in a scenario analysis which investigates different system combinations and determines their average cost of electricity and the wind energy content of their power output (Figure 1). The objective of the scenario analysis is to identify the systems that can produce power with a particular renewable energy content at the lowest cost.

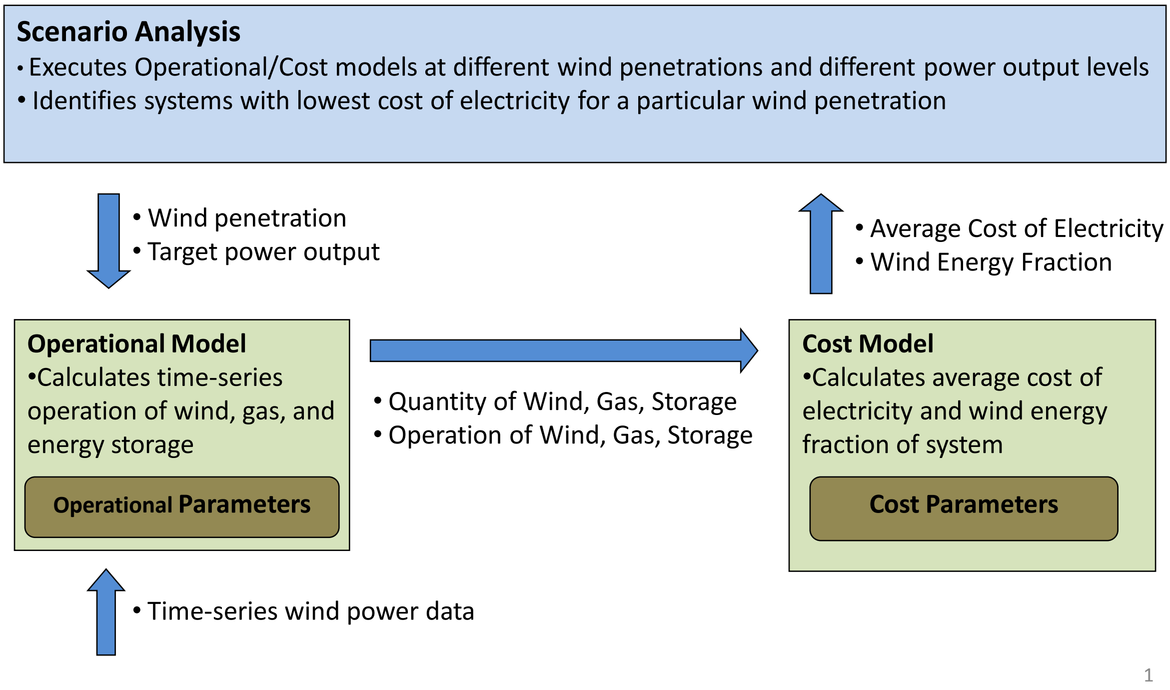

**Figure 1: System block diagram showing structure of scenario analysis used. The higher level scenario analysis runs the operational and cost models under various conditions. The goal of the scenario analysis is to identify systems with the lowest average cost of electricity given a particular wind penetration. Appendix A contains a more detailed description of the scenario analysis structure and the underlying operational and cost models.**

### 2.1. Model Description

For each combination of wind generation, natural gas generation, and power output, the model determines the quantity of fast-ramping energy storage (industrial-scale Sodium Sulfur (NaS) batteries, flywheels, or supercapacitors) required to produce a fixed power output with constrained variability.

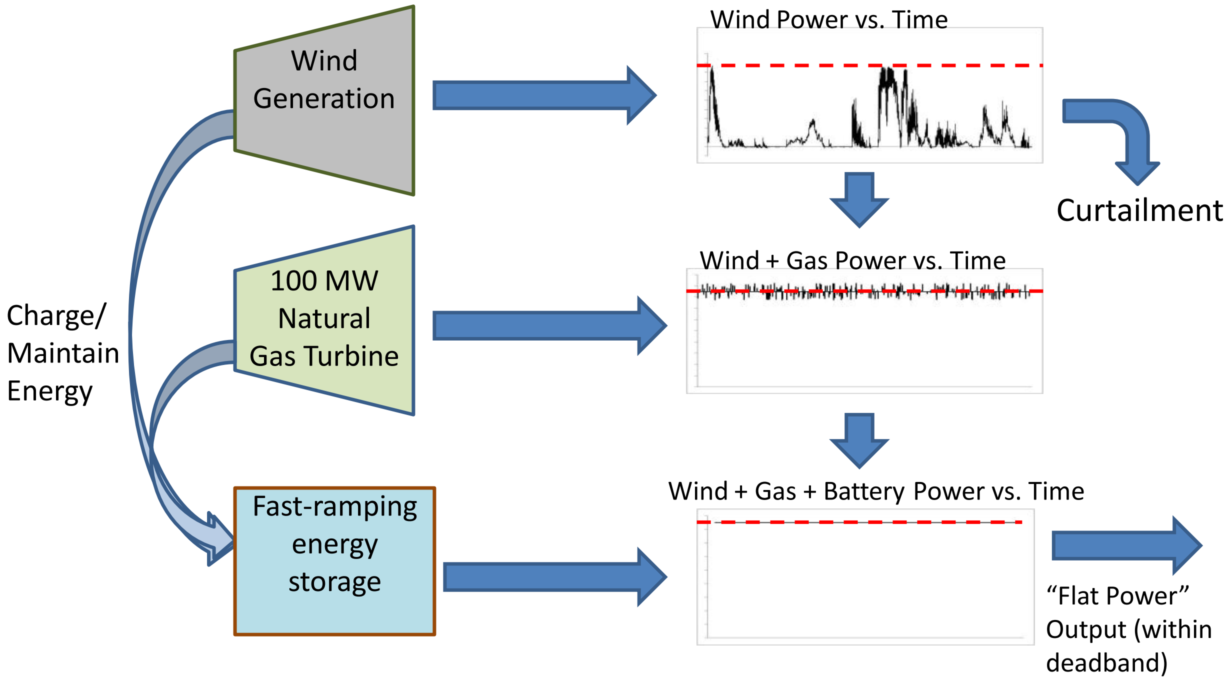

**Figure 2: Model concept of wind/natural gas/energy storage generation block. The scale of wind generation and the wind generation profile are fixed for each run of the model. The 100 MW natural gas turbine attempts to smooth the wind power to the target power output level (red dashed line). Due to the operational constraints of the gas turbine, there may be some residual power transients which are eliminated by a fast-ramping energy storage device, which is sized to the minimum scale required to mitigate the remaining fluctuations.**

For each system examined, the gas generator is modeled to operate such that it provides maximum fill-in power for the varying wind resource in an effort to bring the combined wind+gas power output to the target power output. If the gas turbine is unable to provide all of the required fill-in power due to insufficient ramping capability or cold-start limitations, the residual power is provided by an energy storage device. This residual power includes both positive and negative power requirements from the energy storage, which represent both the discharge energy from the device as well as the required charge energy. Actual 10 second time resolution wind data is used to model the wind generation (Southern Great Plains United States wind farm, sum of 7 turbines, 15 days, 10 second resolution, 46% capacity factor during this period[1]). When necessary, the model allows for curtailment of wind energy (if the storage is fully charged but the combined wind+gas output is higher than the target) by assuming a communications link between the system control and the wind farm control station.

The gas turbine is modeled with finite start-up time, maximum ramp rate, low operating limit, and minimum run time. Performing a time series simulation of a gas turbine with these characteristics more accurately demonstrates the issues involved with traditional generators providing fill-in power for wind variability, and allows a better estimation of costs and emissions due to that power.

Once the gas turbine has provided all of the smoothing allowable by its operational constraints, the minimum size of the required energy storage device can be directly determined. Given the wind+gas generation, the residual power that must be handled by an energy storage device is calculated, including both charge and discharge energy. From this residual power profile,

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[1] This unrepresentatively high capacity factor is discussed and analyzed in the Sensitivity Analysis section.

the power and energy capacity capabilities required from the energy storage can be calculated. When sizing the energy storage, the power requirement is equal to the maximum power required to/from the energy storage during the operational period. The energy capacity requirement is derived from the maximum energy span (difference between highest and lowest energy state) required from the energy storage. This is equivalent to assuming a battery with infinite capacity, then observing the maximum energy span (which is also the minimum possible storage capacity) and using that value for the required storage capacity. The power requirement of the energy storage is used as determined directly from the model, but the energy capacity requirement is doubled from what the model determines as the minimum possible energy capacity. This reflects the understanding that the 15 days of wind data used might not present the worst case energy cycle to the storage device, as well as a conservative design stance towards this relatively unproven technology.

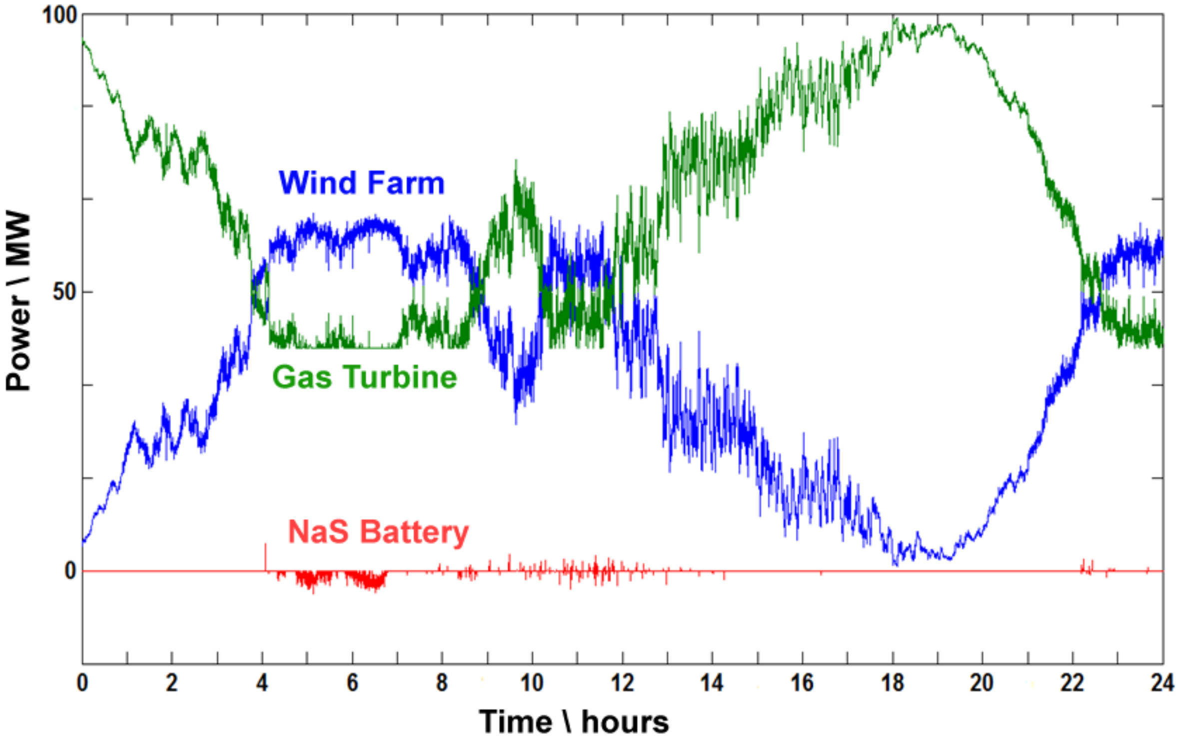

**Figure 3: A sample of the operational output from the Wind/Natural Gas/NaS Battery model. This shows a 24 hour period of operation of a system with 100 MW of natural gas capacity, 66 MW of wind capacity, and a target power output of 100 MW. Positive values for the battery power indicate discharge while negative values are charging events. The battery is required infrequently and generally for short, sharp charges/discharges. As the wind power increases in hours 4 – 7, the natural gas turbine ramps down to its low operating limit of 40 MW and the excess energy is used to charge the battery. The wind generation profile comes from actual 10-sec time resolution data.**

We examined three different types of storage: Sodium Sulfur (NaS) batteries, flywheels, and supercapacitors. This paper focuses on NaS Batteries because that technology was found to be the least expensive at all points in this study. Energy storage is modeled using the most realistic operational and cost data available: efficiency, power/energy ratio, maintenance energy, and a cost model dependent upon both power and energy requirements are all utilized. For consistency, most of the data for operational and cost modeling of energy storage are taken from EPRI's Handbook of Energy Storage [11]. Where additional data is available from the manufacturer, such as the pulse power limitations on Sodium Sulfur batteries, those limitations have also been used [12].

The energy storage device is constrained to have a net energy balance equal to or greater than zero over the studied period. If the energy balance through the device is found to be negative, then the operation of the gas generator is adjusted to produce more charging energy during periods of low gas turbine output. Additionally, wind and gas power are used to provide the maintenance energy for certain types of storage devices, such as flywheels or Sodium Sulfur batteries. We make the assumption that only one type of fast-ramping energy storage will be used in the system, and each of the three investigated technologies are studied in separate runs of the model, allowing comparison between technologies.

In order to keep the study simple and general, the model is constrained to produce power with a small "deadband", allowing for the system output power to vary within 0.5% of the target power output. This is intended as a realistic simulation of the small allowable variation in real power systems (if the allowable deadband is set to zero, then the system is constrained to produce perfectly "flat" power).

The objective function of a single run of the model is to meet the target power output (within the deadband) while minimizing the Power ($P_{batt}$) and Energy ($E_{batt}$) requirements of the energy storage device (Equations 1 and 2), in order to prevent over-sizing of this expensive resource.

*Minimize* – (1)

and

*Minimize* (2)

such that, at all points in time (t), the sum of wind, gas, and battery power minus curtailment and battery maintenance energy is within the deadband around the target power level (Equation 3). The gas generator has a ramp rate limitation (Equation 4), high and low operating limits (Equations 5 and 6), and a minimum run time (Equation 7). The power out of the energy storage device comes at an efficiency penalty (Equation 8), and round trip efficiency of the energy storage device is divided geometrically between the charge and discharge portions of the cycle (Equation 9).

– (3)

– (4)

(5)

(6)

(7)

– (8)

– (9)

where $P_{target}$ is the target power output, $P_{db}$ is the deadband power, $P_{wind}$ , $P_{gas}$ , $P_{batt}$ and are the power outputs of wind, gas, and energy storage, $P_{maint}$ is the maintenance power for the energy storage device, $P_{curt}$ is the curtailed power, $T_{step}$ is the step time (10 sec in this study), $P_{gas,max}$ is the maximum power output of the gas turbine, $C_{lol}$ is the low operating limit constant, $T_{mr}$ is the minimum run time of the gas turbine, $E_{batt,out}$ is the energy discharged from the energy storage device, $\eta_{batt}$ is the round-trip efficiency of the energy storage device, and $E_{batt,in}$ is the charge energy put into the energy storage device.

Once the operation of the wind generation, natural gas turbine, and energy storage device has been determined, the emissions and costs of the system over the studied timeframe can be calculated. The emissions calculation uses results from Katzenstein and Apt [6] showing the effect of partial load conditions on efficiency and $CO_2$ and $NO_x$ emissions of a Siemens-Westinghouse 501FD gas turbine. Capital, variable, and average costs of electricity are also calculated for each potential composite system, including amortized capital costs, other fixed costs, and variable costs of the wind generation, the gas turbine, and the energy storage device. $NO_x$ and $CO_2$ prices are included in the cost calculation. Emissions allowance prices are applied directly to the emissions, and do not account for seasonal or regional variation, and thus present an upper bound on the cost of emissions. Appendix A contains a more thorough and systematic description of the model structure, describing both the operational and cost calculations and the sources for the base-case values.

Table 1: Base-Case Operational and Cost Inputs to the generation block model

| Operational Inputs | Base-Case Value | Cost Inputs | Base-Case Value |
|---|---|---|---|
| **Natural Gas (NG) Low Operating Limit** | 40% of nameplate capacity | **Blended Cost of Capital** | 8% |
| **NG Start-up Time** | 10 min | **NG Capital Cost** | \$620 / kW |
| **NG Ramp Rate Limit** | 25%/min | **NG Price** | \$5/MMBTU |
| **NG Minimum Run Time** | 60 min | **NG Variable Cost** | \$0.0014 / MWh |
| **NG Lifetime** | 30 years | **NG Fixed Operating Cost** | \$10 / kW-year |
| **Wind Lifetime** | 20 years | **Wind Capital Cost** | \$1500 / kW |
| **NaS Round-trip Efficiency (RTE)** | 75% | **Wind Variable Cost** | \$0.015 / kWh |
| **NaS Maintenance Energy** | 2.2 kW/ module | **$CO_2$ Price** | \$25 / tonne |
| **NaS module Power Limit**[a] | 250 kW | **$NO_x$ Price** | \$750 / tonne |
| **NaS module Energy Capacity** | 360 kWh | **NaS Capital Cost** | \$240,000 / module |
| **NaS module Lifetime** | 20 years | **NaS Fixed Operating Cost** | \$8,000 / module - year |
| **Supercapacitor RTE**[b] | 70% | **Supercapacitor Capital Cost due to Power** | \$60 / kW |
| **Supercapacitor Lifetime** | 20 years | **Supercapacitor Capital Cost due to Capacity** | \$143,000 / kWh |
| **Flywheel RTE** | 90% | **Supercapacitor Fixed Operating Cost** | \$13 / kW - year |
| **Flywheel Friction Losses** | 3% of max. power output | **Flywheel Capital Cost** | \$720,000 / module |
| **Flywheel module Power Limit** | 1500 kW | **Flywheel Fixed Operating Cost** | \$78,000 / module - year |
| **Flywheel module Energy Capacity** | 5 kWh | | |
| **Flywheel module Lifetime** | 20 years | | |

[a] NaS battery model also uses pulse limitations defined by manufacturer

[b] Supercapacitors are modeled with no power limitation

## 2.2. Computational Scenario Analysis

The model described above is executed at a variety of conditions in a scenario analysis. A particular run of the scenario analysis examines different ratios of wind/natural gas capacity in order to determine how the average price of electricity changes with increased wind penetration. Within each wind penetration level, the model is executed at various power output levels in order to determine the power output that allows for the lowest average cost of power, given the particular wind penetration. Every run of the model assumes a 100 MW natural gas turbine, and the quantity of wind generation is varied so that the percent of capacity due to wind varies from 0% to 90%. Once the model has been executed at these 10 wind penetration levels and at 10 different power output levels for each wind penetration (100 runs total), the model is executed another 10 times around the points that demonstrated the lowest average cost of power at each wind penetration. This allows for a more detailed analysis around the most relevant areas and results in a total of 200 runs of the model for each scenario analysis. When a scenario analysis is executed, the program calculates the average cost of electricity, capital costs, variable cost of operation, maximum battery charge/discharge rate, $CO_2$ and $NO_x$ emissions, and delivered wind energy as a percent of total delivered energy for each run of the model.

The model and scenario analysis programs were written in MATLAB. A quad-core PC was used, which could execute a single run of the operational/cost models in approximately 5 minutes, so that a single scenario analysis required 15 hours of processing time.

The goal of the scenario analysis is to use the model described above to study the relationship between wind penetration and the cost of producing power with little or no fluctuations. In particular, this structure can be used to determine which system produces smoothed power at the lowest price, given a desired set of constraints. Furthermore, by applying different conditions to the scenario analysis, the effect of factors, such as varying natural gas price, can be examined.

## 3. Results

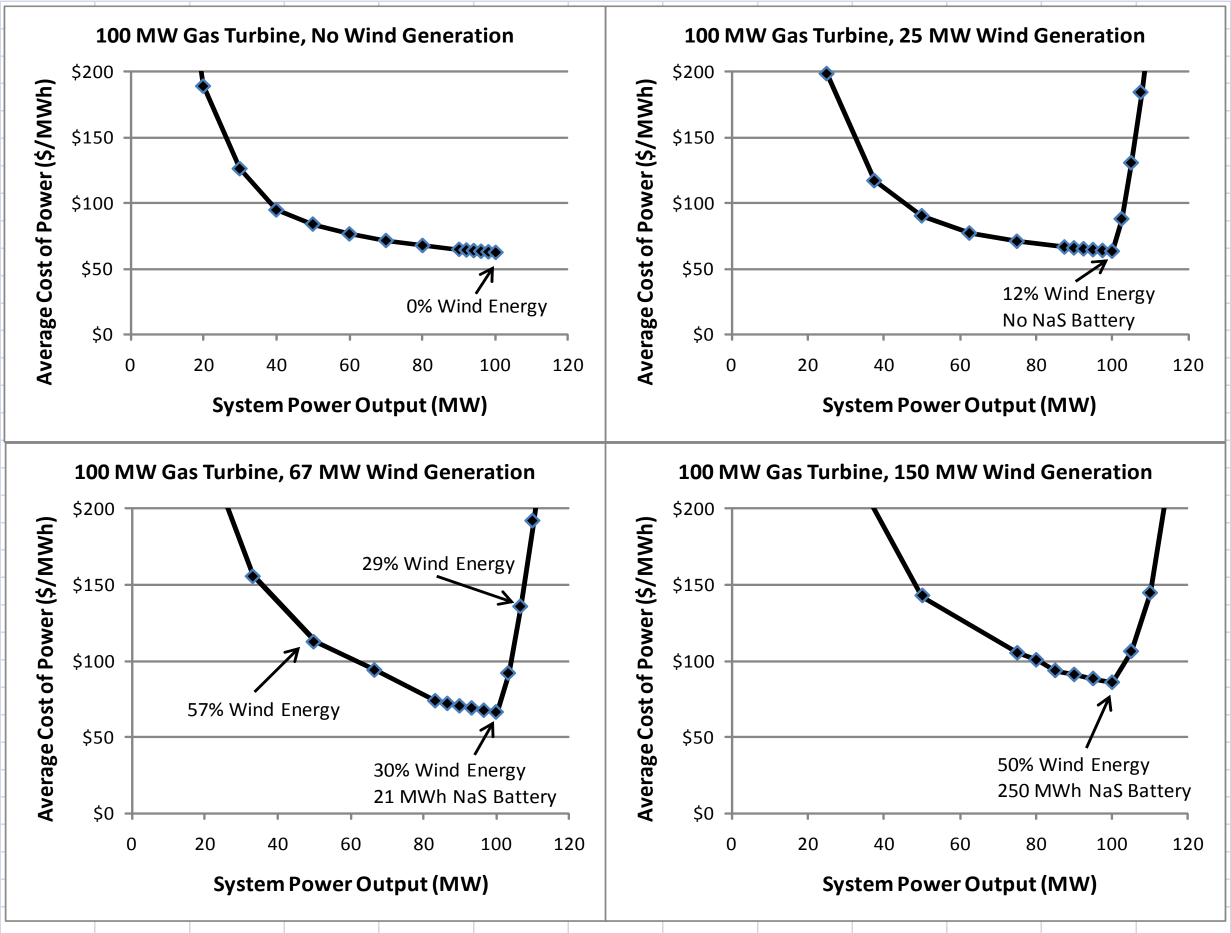

**Figure 4: Average Cost of Power under a variety of wind penetrations. Each chart shows the model output at different power output levels for the Wind/Gas/NaS Battery generation block at a particular wind penetration. The model constraints, including power deadband, are met for all points shown. Each curve has a lowest cost of power point which reflects a balance between inefficient use of capital resources (at low power output levels) and increased need for NaS Batteries (at higher power output levels). In all scenarios examined, the power output with the lowest average cost occurred at or near the firm generation power (100 MW). The increase in cost after the low point is attributable almost entirely to a rapidly increasing energy storage requirement. The sizing and operation of the NaS batteries is discussed in greater detail in Appendix B.**

We first discuss the results for NaS batteries, using the base case assumptions (Table 1). Figure 4 displays the average cost of power under different wind penetrations and power output levels. For all scenarios except the case with only a gas generator, the average cost of power has a minimum because of the balance between efficient use of the capital-intensive generation resources (the gas and wind turbines) and avoiding large-scale deployment of the relatively expensive energy storage systems. This minimum point, representing the system with the lowest average cost of power, is always very close to 100 MW, equal to the firm power provided by the gas turbine. While it is possible to have a relatively flat power output higher than the firm power, the cost of the storage then required to ensure power constrained within the deadband (+/- 0.5%) is so high that it drives the average price of electricity up. Or, to state it an alternate way, the lost value of the curtailed wind energy is less than the cost of the storage required to deliver it within the deadband. This is due entirely to the properties of the energy storage device – if the costs were to decrease or the efficiency were to increase, the lowest cost of electricity point would tend to shift to higher power output levels.

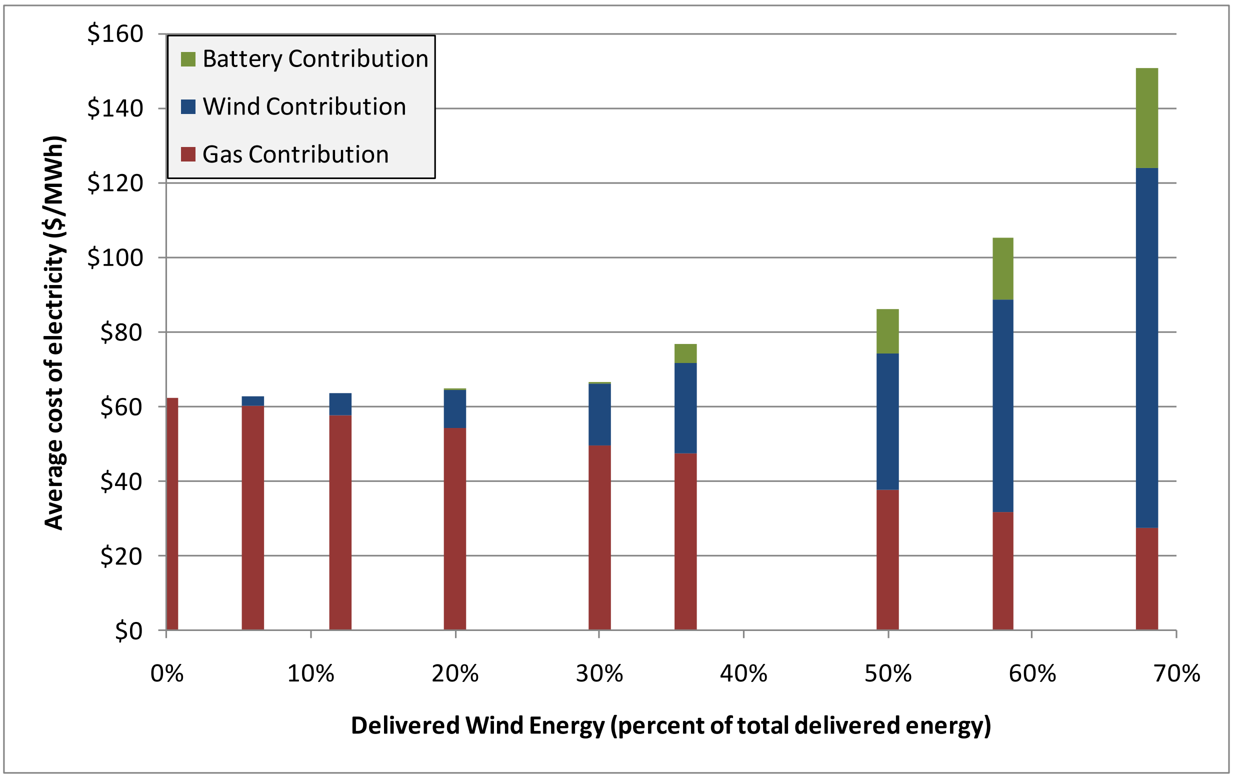

**Figure 5: Average cost of power in the Wind/Gas/NaS Battery system as a function of delivered wind energy and divided according to system component. Each bar represents a system with 100MW of gas generation and corresponds to the lowest cost of power for a particular wind/gas ratio. Due to the 0.5% deadband allowance, NaS Batteries are not required until after 12% delivered energy from wind. There is a slight discontinuity after 30% wind energy, corresponding to the point at which wind power fluctuations are so great that they force the gas turbine to shut down at times to prevent the generation of excess power. Costs due to emissions are attributed to the gas turbine. Costs are for generation only, and exclude transmission costs.**

The wind/gas/NaS Battery systems with the lowest average cost of electricity from each wind/gas capacity ratio are plotted in Figure 5, which demonstrates that the contribution to electricity cost due to the required NaS batteries is negligible over a wide range of wind penetrations. This result also shows that the average price of electricity stays fairly constant as wind penetration increases up to 30%. This result is in part due to the unrepresentatively high wind capacity factor of 46% (2008 US average wind capacity factor was 34%) which, given the base assumptions, results in a cost of $55/MWh for unsmoothed wind energy [13]. The effect of more typical capacity factor is discussed in section 4. These results also demonstrate a noticeable transition around 30% wind energy. This change is due to a change in the operation of the gas turbine: while the turbine is ramped up and down in all scenarios, it is occasionally forced to shut down entirely with systems that have greater than 30% wind energy. The need to startup and shutdown the turbine produces notably lower efficiencies and requires more energy storage.

The average cost of power from the system increases rapidly at higher wind penetrations due to three factors: the need for increased quantities of energy storage, the inefficient fuel utilization of the gas turbine at partial power, and the reduced capacity factor of the gas turbine as a capital resource. If the variability of generation was irrelevant, energy costs of a wind/natural gas system would be a linear interpolation of the energy costs of the two technologies, which would be less expensive. Figure 6 shows the cost of smoothing services by comparing the energy costs of naturally variable wind/gas combinations (no smoothing) with the flattened “baseload” power produced by the described systems (smoothed to within 0.5% deadband). These results are comparable with the wind integration costs determined in other studies [14].

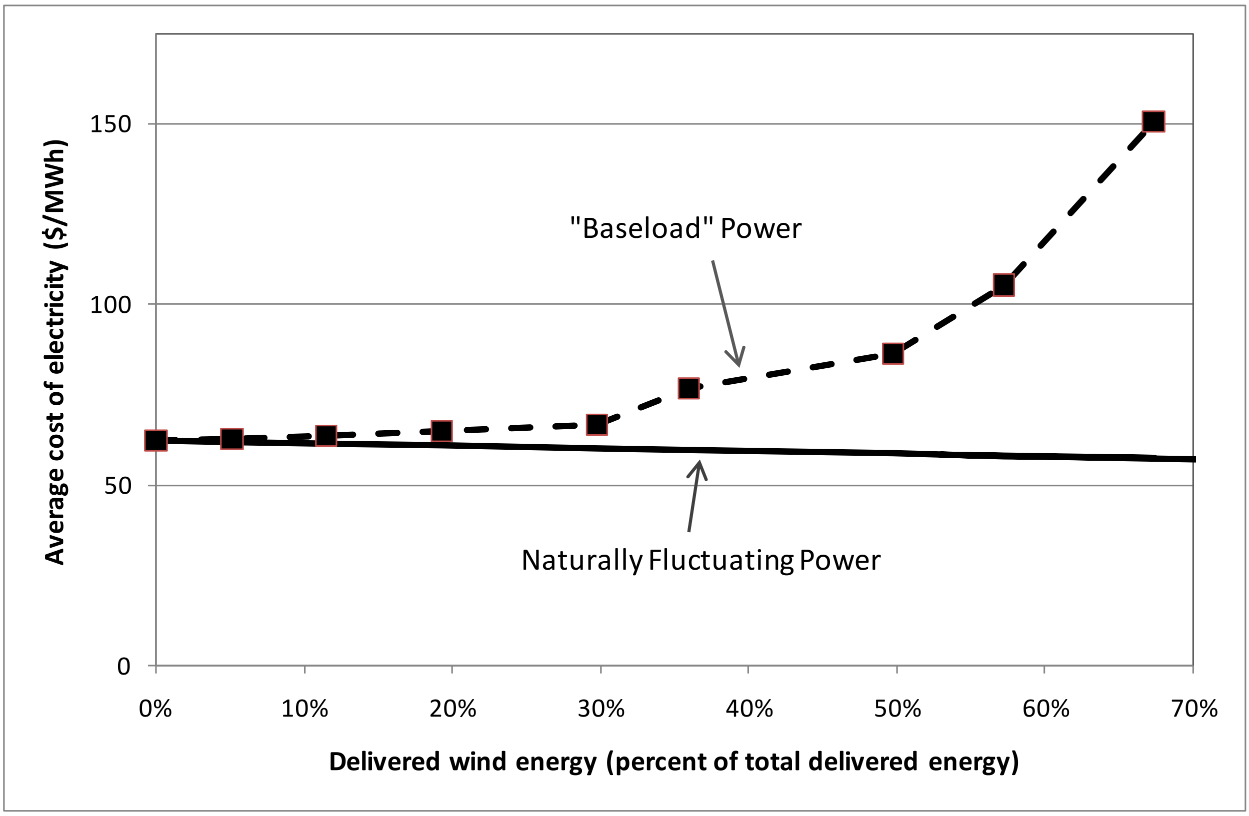

**Figure 6: Average cost of energy for the described "baseload" systems, which regulate power output to 100 +/- 0.5 MW, and a mix of gas generation and unsmoothed wind energy. The naturally fluctuating wind/gas line is a linear interpolation of natural gas power, at a cost of $62/MWh, and wind power, calculated at $55/MWh using the base-case inputs. The difference between the two lines is the cost of reducing power fluctuations to +/- 0.5%, attributable to inefficient utilization of the gas turbine and the requirement for energy storage.**

We found NaS batteries to be more cost effective than flywheels or supercapacitors for this application, although the other technologies are still viable options at low wind penetration levels. Flywheels were found to be expensive for this application due to the constant and sizable losses due to friction. Despite their excellent performance, supercapacitors currently have very high capital cost (per kWh) approximately 200 times greater than that of NaS batteries. Figure 7 compares the three energy storage technologies and their effect on average cost.

As discussed earlier, the operation of the system is engineered to minimize the energy services from the energy storage devices. The energy throughput for each case has been calculated and normalized to the full storage capacity of the device. For the scenarios calculated, the energy throughput varies between 14 and 240 complete charge/discharge cycles (equivalent) per year, though it should be noted that they are never fully cycled in the model. This amount of energy throughput is well within specifications for any of the three storage technologies examined.

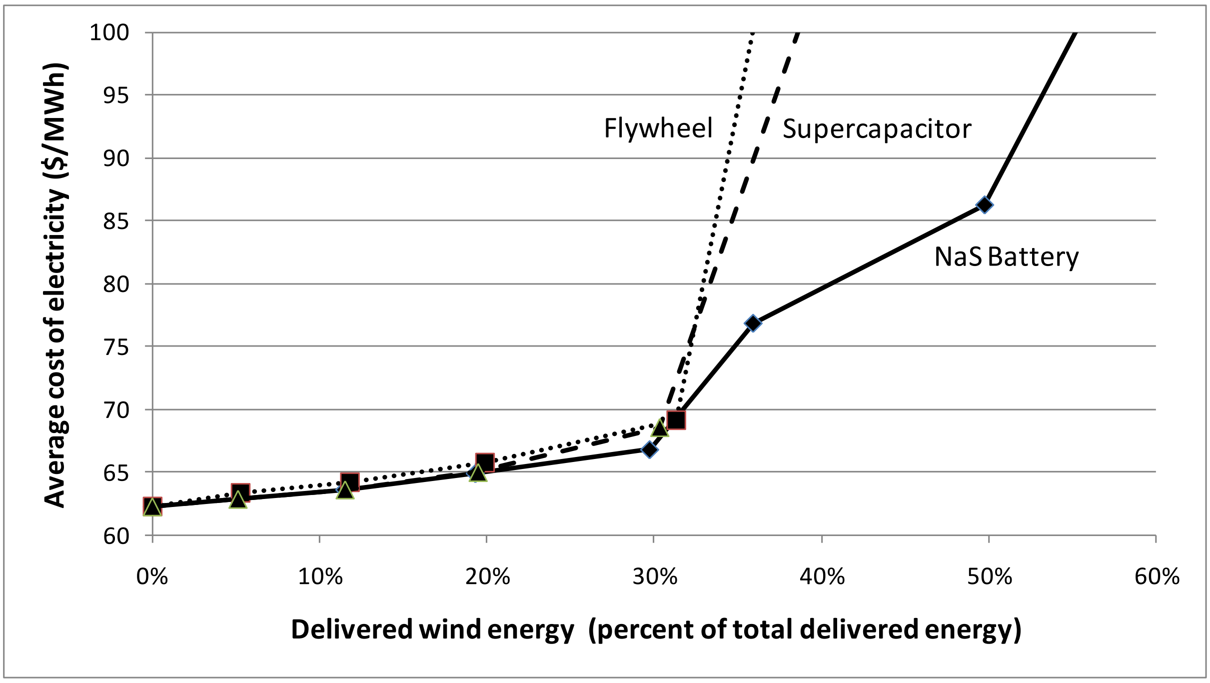

Figure 7: Average cost of power in the Wind/Gas/Energy Storage system for three different energy storage technologies. At lower wind penetrations, the cost contribution of energy storage is negligible and the chosen technology has little effect on the average cost of power. At higher wind penetrations, when storage cost becomes important, NaS Batteries dominate the other options.

The $CO_2$ and $NO_x$ emissions from operation of the natural gas turbine were calculated using a time-series analysis that determines the emissions for each ten second step of operation. The turbine is modeled as a Siemens Westinghouse 501FD, using published emissions data [6]. The emissions of the systems producing the lowest average cost of power can be seen in **Error! Reference source not found.**. These results re-affirm the conclusion of Katzenstein and Apt [6] that a single gas turbine, when providing fill-in power for variable renewable generation, does not result in proportional decreases in $CO_2$ emission and can cause increases in $NO_x$ emission as renewable penetration increases (these authors also considered systems with multiple turbines supplying regulation). It is further demonstrated that the addition of an energy storage device does not substantially alter the finding.

Table 2: Cost, Emissions, and NaS Battery Capacity for Wind/Gas/NaS Battery Systems

| **Wind Nameplate Capacity (MW)**[a] | **0** | **25** | **43** | **67** |
|---|---|---|---|---|
| **Delivered Wind Energy** | **0%** | **12%** | **19%** | **30%** |
| **Average Cost of Electricity ($/MWh)**[b] | 62 | 64 | 65 | 67 |
| **Contribution of NaS Battery to Average Cost of Electricity (percent)** | 0% | 0% | 0.5% | 1% |
| **Average $CO_2$ Emissions (tonnes/MWh)** | 0.34 | 0.31 | 0.29 | 0.26 |
| **Average $NO_x$ Emissions (g/MWh)** | 50 | 44 | 40 | 164 |
| **NaS Battery Capacity (MWh)** | 0 | 0 | 10 | 21 |

[a] *All systems include a 100MW gas turbine.*

[b] *The average cost of electricity includes emissions prices of $25/tonne for $CO_2$ and $750/tonne for $NO_x$.*

We summarize the important results from the base-case scenario analysis in **Error! Reference source not found.**. These systems all produce electricity with very little variation (100 +/- 0.5 MW at all times) and show that a large quantity of wind energy can be integrated into the electrical grid at a reasonable cost, if the compensating resources are chosen and operated appropriately.

While the results above are presented in the abstract, we now turn to a more concrete example. Texas, the US state which currently has the most wind power, also gets a large fraction of electrical generation from natural gas. The Integrated Environmental Control Model (IECM)[2] was used to calculate that, in west Texas (elevation: 3000 ft), the power output of a GE 7FA gas turbine would be 108 MW, though this value can vary slightly due to environmental conditions. This turbine is modeled as co-located with a wind farm consisting of 48 1.5 MW turbines experiencing a capacity factor of 30%, and 60 NGK Insulators PQ NaS Battery Modules. Using the base-case assumptions from Table 1, this co-located wind/natural gas/NaS battery system can produce a continual 108 MW of power (within a 0.5% deadband) at an average cost of $69/MWh, getting 20% of the delivered energy from wind power[3]. With a Production Tax Credit of $21/MWh for the wind energy, the average cost of power for this system would drop to $65/MWh. This is only $3/MWh (5%) greater than the calculated cost for a gas turbine-only system.

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[2] The Integrated Environmental Control Model is a tool designed to calculate the performance, emissions, and cost of a fossil-fueled power plant and was developed at Carnegie Mellon University. More information about the IECM can be found at http://www.cmu.edu/epp/iecm/

[3] The figure of 20% energy from wind accounts for all of the wind energy produced. At 30% capacity factor, the wind farm produces an average power of 21.6 MW, which is 20% of the target power output of 108 MW.

# 4. Sensitivity Analysis

We performed sensitivity analysis for natural gas price, blended cost of capital, wind capacity factor, and deadband range. In each sensitivity analysis, only the target parameter is varied and each data point represents a complete re-run of the scenario analysis under that varied parameter.

Since 2001, the price of natural gas as delivered to industrial customers has varied between $3.5 and $13 per MMBTU, with an average value around $6.50/MMBTU [15]. The base-case natural gas price used in the cost model is $5/MMBTU, and that figure is varied from $4/MMBTU to $10/MMBTU in the sensitivity analysis. As seen in Figure 8, the sensitivity of average electricity price in the wind/gas/NaS Battery system to natural gas price is a function of the percent of energy from natural gas generation. As the wind penetration increases, the system becomes less sensitive to natural gas price. At higher natural gas prices, the average cost of electricity decreases with increased wind penetration, up to 30% wind by energy.

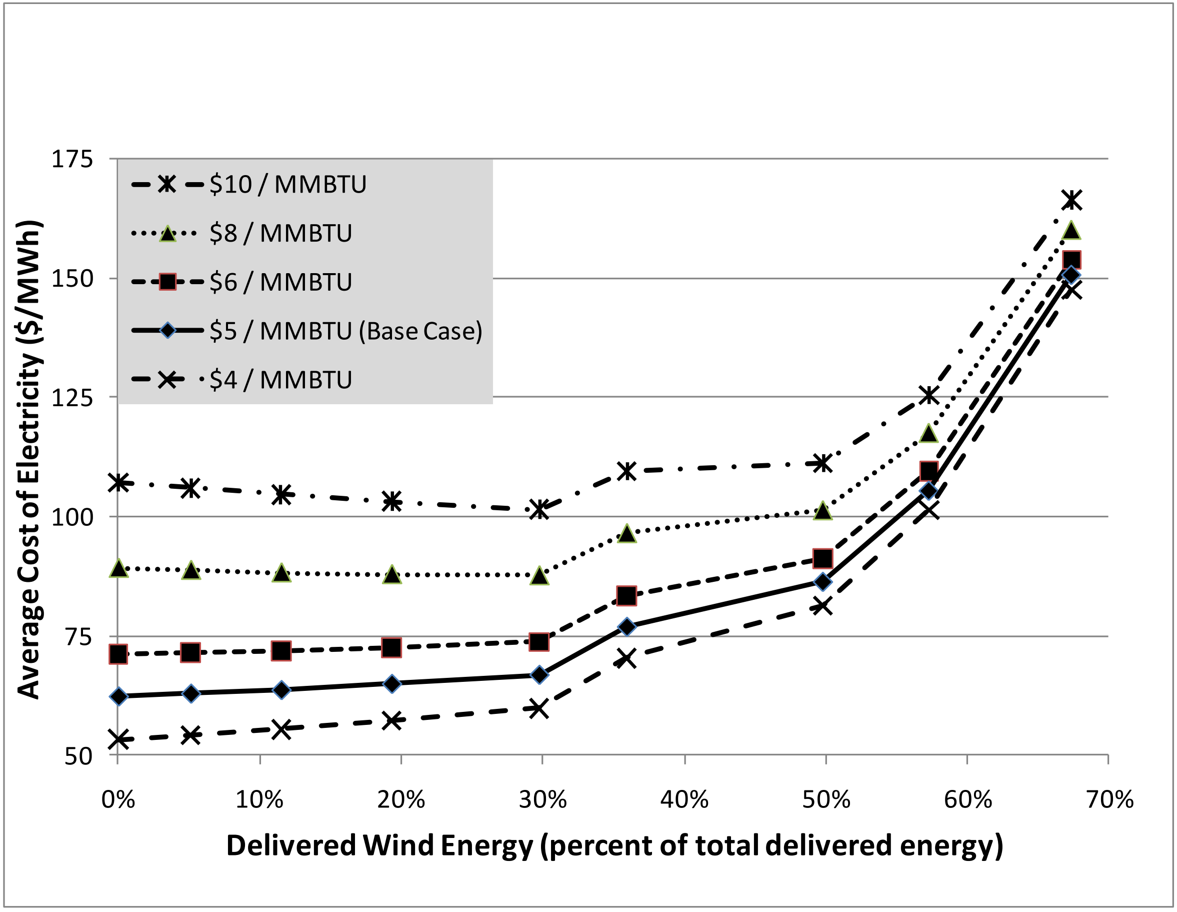

**Figure 8: Sensitivity of Scenario Analysis output to natural gas prices between $4 and $10 per MMBTU. The Wind/Gas/NaS Battery systems are most sensitive to natural gas price at low wind penetrations. At higher natural gas prices ($8 and $10 per MMBTU), the average cost of electricity decreases as wind generation is added, up to 30% of energy from wind.**

The base-case blended cost of capital used in the model is 8%. This rate is varied between 6% and 12%. Figure 9 shows that the sensitivity to interest rate is low for the case where only a natural gas turbine is used and increases with wind penetration. Gas generation requires a low capital investment relative to its total cost, while wind turbines and energy storage devices have almost all of their lifetime costs up front in the form of capital investment.

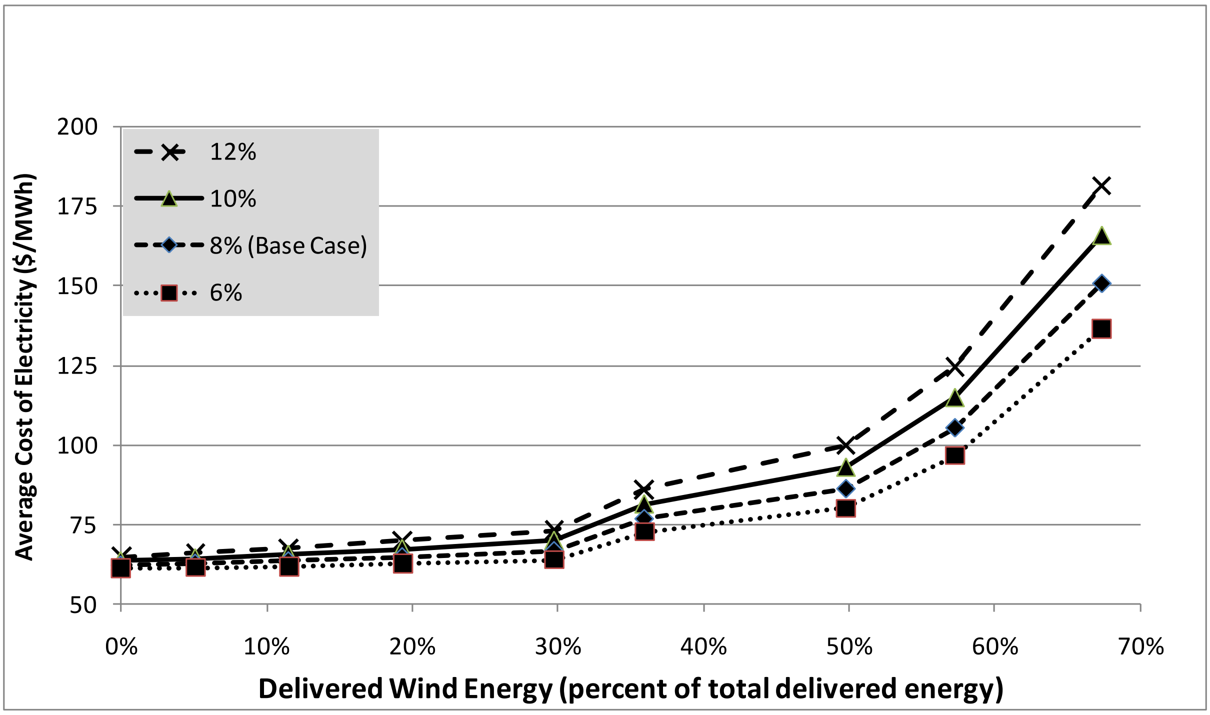

**Figure 9: Sensitivity of Scenario Analysis output to Cost of Capital Rates between 6% and 12%. The Wind/Gas/NaS Battery systems are most sensitive to interest rate at high wind penetrations due to the capital-intensive nature of wind generation and energy storage.**

The wind capacity factor of the wind data used in this study is 46%, unrepresentatively high for onshore wind generation [13]. As a result, it is important to investigate the effect that a lower wind capacity factor would have on the average price of electricity from the wind/gas/NaS Battery systems studied. Lower capacity factors are modeled by using smaller portions of the wind data set that have lower capacity factors. These contiguous subsets (of the original 15 days of wind data) are extracted and represent between 5 and 9 days of operation. The wind capacity factor is varied from the 46% base case down to 20% and demonstrates that varying the wind capacity factor has the largest effect on average cost of electricity at higher wind penetration levels (Figure 10).

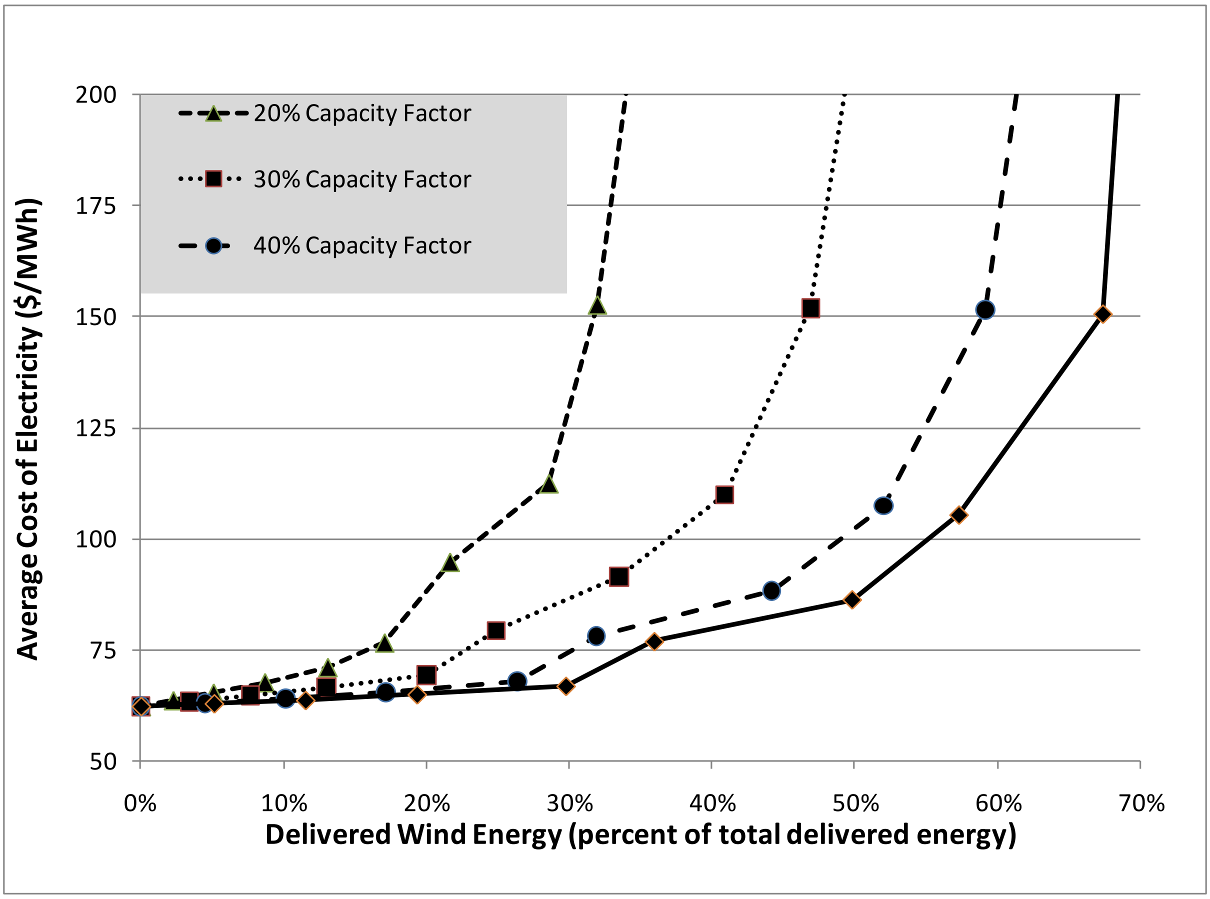

**Figure 10: Sensitivity of Scenario Analysis output to wind capacity factor between 20% and the base-case value of 46%. Wind capacity factor has a very large effect on average cost of electricity for systems requiring a large fraction of delivered energy from wind.**

The allowed deadband range is a function of the power quality required from a given generator. In a small grid, where there are insufficient compensating resources, generators would be more constrained in their unrequested fluctuations, while in large grids with significant compensating resources, power deviations are less burdensome. The base case deadband range is 0.5%, and this figure is varied in sensitivity analysis from 0% to 10% (Figure 11). The change in deadband range has very little effect at low wind penetrations, as the gas turbine can easily compensate for the wind variability and any energy storage required has a negligible cost. At higher wind penetrations, a larger deadband displaces the need for costly batteries and effectively increases the operating range of the gas turbine, lowering the average cost of electricity. Furthermore, a larger deadband enables the acceptance of wind energy that would otherwise be curtailed and thus results in a larger fraction of delivered wind energy. With no deadband allowed, all wind penetration levels require some amount of energy storage, while increasing the deadband to the base-case of 0.5% allows systems up to 12% energy from wind to operate without any storage.

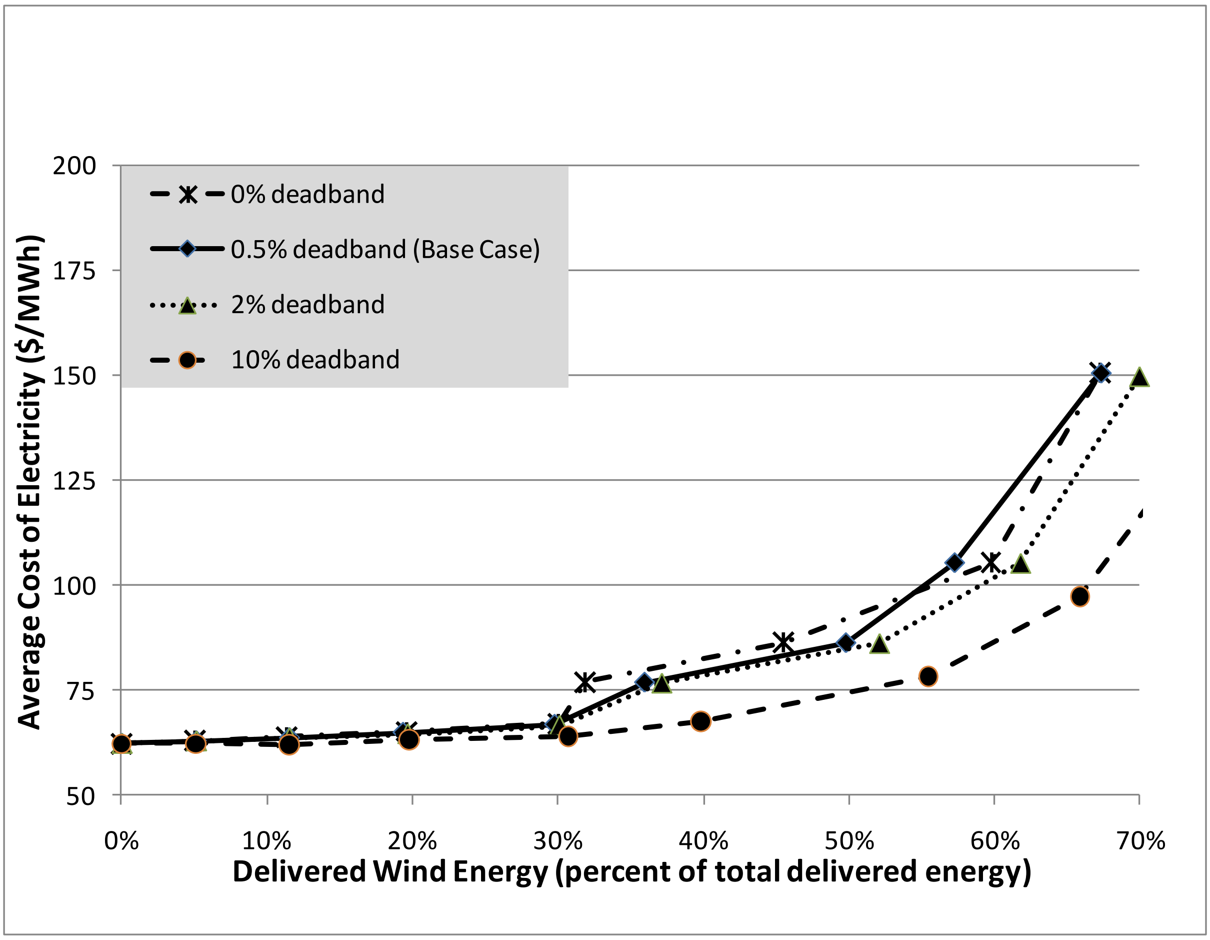

Figure 11: Sensitivity of Scenario Analysis output to deadband range between 0% and 10%. Higher deadband allowance results in the need for less energy storage, which is fairly negligible at lower wind penetrations but becomes important at higher wind penetrations.

**Error! Reference source not found.** summarizes the sensitivity analysis results at three wind penetration levels.

Table 3: Sensitivity analysis summary of wind/gas/NaS battery systems

| Parameter | Range of Values | Effect on Price at 0% Wind Energy | Effect on Price at 30% Wind Energy | Effect on Price at 60% Wind Energy |
|---|---|---|---|---|
| **Natural Gas Price** | $4 to $10 per MMBTU | -17% to +72% | -11% to +52% | -4% to +19% |
| **Blended Cost of Capital Rate** | 6% to 12% | -2% to +4% | -5% to +9% | -9% to +15% |
| **Wind Capacity Factor** | 20% to 46% | No effect | +209% to 0% | Unfeasible* to 0% |
| **Deadband Range** | 0% to 10% | No effect | +0.3% to -4% | +4% to -13% |

*The system with 20% wind capacity factor is unable to deliver 60% wind energy due to NaS battery maintenance energy.

## 5. Discussion

The systems described above utilize a hybrid compensating system to produce fill-in power for wind, smoothing the power output. Unsurprisingly, the cost of the smoothing service comes at a premium, and is greater than the linear combination of natural gas energy cost and wind energy cost. It is important to determine what circumstances make this premium for smoothed power worthwhile.

In most electric markets, policies encourage the deployment of wind generation. As part of this encouragement, coupled with the limited deployment of wind resources, there are currently few restrictions on the variability of the power produced by wind farms. But, as the penetration of wind power increases, particularly in the attempt to achieve the renewable portfolio standards that have been adopted by 29 US states, the variability of wind power will become an increasingly important issue. Already, electrical systems that utilize a relatively large fraction of wind energy, such as ERCOT and Nord Pool, are considering enacting or have enacted limitations on the ramp rate of wind power [16, 17]. Determining who bears the responsibility for dealing with the variability of wind will become an important policy decision in the coming decades. But regardless of who is responsible, compensating for large-scale penetrations of wind energy requires careful planning.

In the near term, there are other applications for the described systems, such as small electrical grids that are unable to rely on a large base of traditional generators to provide compensation. Ireland plans to generate 13.2% of its electricity needs from renewable power in 2010, with wind power supplying the vast majority [18]. Ireland currently has a maximum demand of around 6.5 GW with an installed wind capacity of almost 1.5 GW. At times, almost 40% of the island's power comes from wind power and this fraction will only increase as more wind generation is constructed [19]. Hawaii has a peak firm power capacity of approximately 2 GW and already has a 10% wind penetration on the Big Island [20]. Additionally, motivated by the high electricity prices in Hawaii, the governor has announced a goal of 70% of energy from "efficiency and renewable resources" by 2030 [21]. A higher price of electricity, a desire for increased renewable penetration, and a smaller generator base in these electric grids makes them candidates for systems similar to those described herein. The costs for integrating wind are shown to be reasonable and the required technology can be co-located with the wind generation, avoiding the need to rely on a large base of traditional generation resources that is non-existent in small electrical grids such as Hawaii and Ireland.

Our results suggest a different policy guideline for large electrical systems attempting to integrate wind generation, especially those with flexible traditional generators such as ERCOT. While the hybrid wind/gas/storage systems are shown to be a financially viable option, the scenario analysis results also show that a small deadband (0.5%) allowance and the availability of compensating generation permits wind energy fractions of up to 12% before any storage is required, while a deadband of 0% requires some energy storage at all wind penetration levels. This suggests that energy storage may not be needed, on a system level, until approximately 10% of energy is produced by wind. Despite this, large electricity markets may still find a use for fast-ramping energy storage as a substitute for the close coordination required to provide fill-in power through the market. We have shown that the use of energy storage to smooth the sharpest fluctuations, allowing a gas turbine to provide the remaining fill-in energy, is a cost-effective application. As a result, complex electricity markets might consider enacting lightly binding limitations on the bus-bar ramp rate of wind generators, which could then motivate the deployment of small energy storage systems co-located with wind generation.

This model of wind/gas/energy storage generation systems demonstrates a potential method for integrating significant quantities of wind energy while reducing power fluctuations to a small deadband and maintaining a reasonable cost of electricity. Furthermore, over a wide range of wind penetrations relatively little energy storage is needed and this energy storage acts to mitigate potentially harmful transient pulses. By studying these wind/gas/energy storage systems, we are better able to understand the issues associated with wind integration and the value that traditional generation and energy storage can provide, especially when working in concert with one another to mitigate undesired variability.

## Acknowledgements

This work was supported in part by the Gordon Moore Foundation, the Environmental Protection Agency through the EPA STAR fellowship, the National Energy Technology Laboratory of the Department of Energy, and the Electric Power Research Institute under grants to the Carnegie Mellon Electricity Industry Center (CEIC). This research was also supported through the Climate Decision Making Center (CDMC) located in the Department of Engineering and Public Policy. This Center has been created through a cooperative agreement between the National Science Foundation (SES-0345798) and Carnegie Mellon University.

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# Appendix A: Model and Scenario Analysis Description

The critical tools in this study are the scenario analysis structure used to investigate different wind/gas/storage systems and the underlying operational and cost models. This appendix describes each of these components in detail.

## A.1. Scenario Analysis

The scenario analysis is the highest level of the program and utilizes repeated runs of the operational and cost models with the goal of surveying a wide variety of wind/gas/storage systems. A scenario analysis consists of two cycles of 100 runs each, where the second cycle investigates the “areas of interest” from the first cycle in greater detail. The objective of the scenario analysis is to identify the systems with the lowest average cost of power, given a particular fraction of delivered energy from wind.

At the start of a scenario analysis, the operational and cost parameters are set to the base-case values or, for sensitivity analysis, a single parameter is changed from the base-case value. The operational and cost parameters are then held constant for the duration of the sensitivity analysis.

The first cycle of the scenario analysis consists of 100 runs of the operational and cost models. The scenario analysis varies two parameters: the system wind penetration and the target power output. Wind penetration is varied from 0% to 90% system wind capacity in 10% increments (10 levels) while the system power output is varied from 10% of total system generation capacity (gas capacity plus wind capacity) to 100% of total system generation capacity in 10% increments (10 levels). The scenario analysis runs every combination of these two parameters, giving the total of 100 runs. The scenario analysis collects data on each run of the model including average cost of power, energy from wind, energy from gas, $CO_2$ and NOx emissions, and magnitude of required energy storage.

In the second cycle of the scenario analysis, the target power output that resulted in the lowest average cost of electricity is identified for each wind penetration level. These “areas of interest” are then investigated in finer detail in the second cycle. At each wind penetration level, the system power output is varied +/- 10% around the lowest average cost point in 2% increments (10 levels). The wind penetration levels used are the same as in the first cycle of the scenario analysis. This results in another 100 runs of the operational and cost models. The relevant data are again extracted from each run and saved for later analysis.

## A.2. Operational Model

The operational model is the most complex part of this study. This model takes as inputs the pre-defined operational parameters, the wind penetration and system power output values from the scenario analysis, and a file representing a time-series wind data set. The wind data used in this study is actual 10-sec resolution data taken from a southern Great Plains wind farm (sum of 7 turbines), though the model is configured to accept any time-series data with equally spaced samples. The wind power used for the model is proportionally scaled directly from the input wind data.

The model assumes a single gas turbine, which operates to provide fill-in power for the wind generation within its operational limitations and within the defined deadband. The gas turbine limitations are a high operating limit, a low operating limit, a ramp rate limit, a must-run time, and a start-up time. The turbine is forbidden to operate above the high operating limit or below the low operating limit. The ramp rate limitation is applied by converting the ramp rate constant (in percent per minute) to a maximum power change per step, and restricting the power output change per step to that value. The must-run time defines the minimum amount of time that the gas turbine must operate before it can shut down. If the gas turbine has been running for the required period and gets a signal to provide a power output of zero, then it immediately shuts down and ceases to deliver any power. Thus, as the power required from the gas turbine decreases, the gas turbine ramps down to the low operating limit then holds at that point until it is prompted to turn off completely. If the gas turbine is off and gets a signal to deliver any amount of power, then it begins the start-up process. This process is modeled as delivering no power for the duration of the start-up time and then immediately jumping to the low operating limit. The start-up process is not cancelled if the gas turbine ceases to receive a signal to produce power. The start-up and shut down processes are the only exceptions to the ramp rate limitation.

The gas turbine attempts to bring the total wind plus gas power output to the target power output level at every point in time. Thus, the deadband range becomes important only for the determination of the energy storage operation. Once the power output of the wind and the gas turbine are defined, the power requirement to/from the energy storage device (the “residual power”) is calculated. This residual power is equal to the target power output minus the power outputs of the wind and gas generation. The magnitude of the residual power is then reduced at each point by the deadband power, reducing the power requirement levied on the energy storage device. Importantly, the residual power has both positive and negative values, corresponding to discharge and charge power.

The model next calculates the quantity of energy storage that would be required to provide the residual power defined above. For NaS batteries and flywheels, the systems come in modules with fixed power limitation and energy capacity. Thus, for these technologies, the amount of storage needed is the maximum of the amount required to provide the capacity needs and the amount required to provide the power needs. Because supercapacitors have essentially no power limitation, the power and energy capacity requirements are considered separately. NaS batteries and flywheels both require a fixed maintenance power which is unrelated to their round-trip efficiency. This power requirement is then added to the output of the gas turbine which, in effect, acts to slightly scale up the size of the gas turbine so that it provides all of its previous services as well as providing a fixed power output to the energy storage devices. The round-trip efficiency (RTE) for the energy storage devices is defined as the ratio of AC energy in to AC energy out.

The model requires that the energy storage charge state at the end of the studied period be equal to or greater than its initial state. To do this, the model determines whether the defined residual power, given the round-trip efficiency of the energy storage, is sufficient to achieve a concluding charge state greater than the initial charge state. If the concluding state is determined to be lower, than the gas generation is adjusted to provide more charge energy.

If it is required that the gas turbine produce more power, this is done in a non-forward looking way that attempts to maximize the efficient use of the turbine. As long as more charge energy is required, the model first increases any local minima in the gas turbine power output. If there are no local minima, then it increases the lowest global point. If the gas turbine is at maximum power output at all points when it is operational, then the model extends the periods of operation. The energy output of the gas turbine is increased in this manner until there is sufficient energy through the energy storage device to meet the described constraints. If the gas turbine is operational at all points in time and is at the high operating limit the entire time, then the system is declared “insufficient”, model execution is ceased, and no data is returned to the scenario analysis for that system.

### A.3. Cost Model

The cost model uses the data regarding quantity and operation of the wind, natural gas, and energy storage resources to calculate the cost of the system. Additionally, it contains a set of pre-defined cost parameters, such as cost of capital rate and natural gas price.

The cost model calculates the amortized capital cost of each technology using the lifetime of that resource and the global cost of capital rate. It then calculates the other fixed costs of each resource using the pre-defined cost parameters. The variable cost of the natural gas generator is separated into the cost due to fuel and emissions and other variable costs. The cost model uses the emissions and efficiency data for a Siemens-Westinghouse 501FD from Katzenstein and Apt [6]. Fuel consumption, $CO_2$ emissions, and NOx emissions are calculated for each operational step and summed. These values are used to determine the cost of natural gas and the costs due to emissions. The cost module uses all of the data described above to calculate the average cost of electricity, the capital cost of the resources, and the variable cost of operation of the system.

### A.4. Sources for Operational and Cost Parameters

The base-case parameters used in the model come from a variety of sources. The operational and cost data associated with energy storage technologies is taken, with little modification, from the EPRI-DOE Handbook of Energy Storage [11]. For NaS batteries and flywheels, the Handbook of Energy Storage has cost information that regards power and energy as independent costs, while the system is forced to purchase an actual production module with a fixed performance. Costs for the natural gas turbine and wind generators were adapted from the DOE/NETL Cost and Performance Baseline for Fossil Energy Plants [22] and the Levelized Cost of Energy Analysis from Lazard, Ltd [23]. The natural gas price of $5/MMBTU was chosen to approximately reflect the current price. All prices were brought to 2010 dollars by applying a 2%/year inflation rate.

# Appendix B: Battery Energy Statistics and Value

When wind variability is smoothed exclusively by a gas turbine, there are fast transient pulses that the gas generator is unable to accommodate due to operational limitations. This results in short-duration power spikes and drops that would be externalized to the grid without an energy storage device to act as a buffer. In order to determine what services the energy storage device is providing in the wind/gas/storage generation block, it is critical to characterize the nature of the power spikes and drops that would result in the absence of such a device.

A brief statistical characterization was performed over the power fluctuations resulting from a wind/gas system to investigate the time between power fluctuations and the total energy deviation of those fluctuations. Firstly, power fluctuations within the deadband are considered complete acceptable and are not factored into the calculations. Power spikes/drops that persist over multiple time steps are considered a single event rather than a series of smaller events, as the most important factor of an event is the total energy lost or gained during that event. For simplicity, and due to the fact that the positive and negative energy deviations appear to be approximately equal in size and frequency, they are treated as equivalent and the absolute value of the energy deviation is used. Given these definitions, there are three factors that are relevant to the analysis of this data set: the time between events, the length of events, and the energy of events. Of these, the time between events and the total energy delta of the events are the more important factors.

The analyzed scenarios are those demonstrating the lowest average cost of electricity, given the base-case parameters, for wind penetrations of up to 50% energy from wind. Because of the base-case deadband of 0.5%, the first three scenarios (0%, 5%, and 12% energy from wind) do not have any power fluctuations outside of the deadband and thus do not require any energy storage at all. Higher wind penetrations have fluctuations with greater energy deviations, but these events are not necessarily greater in quantity. A summary of the descriptive statistics for these cases is contained in Table 4. The contribution to the average electricity price due to the NaS battery system, scaled to eliminate the described fluctuations, is also included for reference.

**Table 1: Summary of power fluctuations without energy storage.**

| **Wind Nameplate Capacity (MW)**[a] <br> **Delivered Wind Energy (percent)** | **43** <br> **19%** | **67** <br> **30%** | **100** <br> **36%** | **150** <br> **50%** |
|---|---|---|---|---|
| **Average Time Between Fluctuation Events (sec)** | 7130 | 176 | 397 | 553 |
| **Average Length of Fluctuation Events (sec)** | 10 | 23 | 177 | 320 |
| **Average Total Energy Deviation of Fluctuation Events (kWh)** | 0.79 | 0.72 | 4.8 | 92 |
| **Maximum Energy Deviation of Fluctuation Events (kWh)** | 9.7 | 23 | 1900 | 9500 |
| **Maximum Power Deviation (MW)** | 1.5 | 4.9 | 13 | 80 |
| **Contribution of Mitigating NaS Battery to Electricity Price ($/MWh)**[b] | $0.31 | $0.73 | $5.13 | $11.84 |

[a] *All systems have a 100 MW natural gas turbine.*

[b] *The last row shows the cost of the NaS Battery which is able to mitigate the described power fluctuations to within the base-case deadband level of +/- 0.5% of target power output.*

The value of the energy storage device in these systems is a function of both the perceived value of power quality and the cost and performance of other mitigation options. Without a thorough review of power quality requirements and smoothing alternatives, which is beyond the scope of this study, a definitive statement about the value of the energy storage system cannot be made. Regardless, it is clear that the value proposition of the co-located energy storage device is not unreasonable, and should be considered as a potential option for mitigation of these short time-scale fluctuations.