Economic Benefits of Polar Winds from MODIS and GOES-R Winds

Prepared for the

Department of Commerce

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National Environmental Satellite, Data, and Information Service (NESDIS)

Office of Systems Development

September 2007

Section 1

Summary

Several experiments have documented the impact of polar wind measurements in global forecasting. (Borman, Key, Santek, Zapotocny) Polar wind measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the *Aqua* and *Terra* satellites have had positive impacts on the six hour polar wind forecast and the three to five day forecasts in mid-latitudes. At issue is the fact that there is currently no follow-on mission for these NASA satellites, and NOAA future sensors (such as VIIRS on NPOESS) will not provide the same information (Riishojgaard). Consequently, NOAA NESDIS investigated the economic benefits of polar wind measurements to support cost/benefit analyses of potential future polar wind instruments or missions. We also investigated the potential future economic benefits of improved wind forecasts for the wind power industry. The wind power industry does not appear to benefit significantly from MODIS polar wind measurements because the forecasting time horizon for wind power decision making is the one to two day forecast in the mid-latitudes. However, we include it here as potentially benefiting from improved wind forecasts using data from the Advanced Baseline Imager on GOES-R.

The estimated economic benefits are summarized in Table 1. These results combine two different types of analysis. The estimated economic benefits from MODIS winds are based on data about current wind forecast performance improvements that potentially have *current impacts.* In contrast, economic benefits from GOES-R are based on *potential future impacts* that may occur once GOES-R is operational. The present value of the estimated future economic benefits from MODIS winds are projected for a notional 2010 to 2019 mission lifecycle. Benefits are calculated in 2007 dollars. In contrast, GOES-R planning launch date is December 2014 and operational start is planned to begin in 2017 (Gurka). The combined lifecycle for GOES-R and GOES-S is planned to extend more than 10 years, but a 10 year lifecycle is used here for consistency with the notional MODIS winds mission. Therefore, the present value of estimated future economic benefits from GOES-R winds begins in 2017 and ends in 2026. Benefits to the public in the area of hurricane evacuations are attributed to a reduction in hurricane tracking errors due to polar winds, particularly in the horizon of several days before landfall when hurricane evacuations are ordered. Benefits to aviation are attributed to operational efficiencies for polar route flights. MODIS polar winds significantly improve near-term wind forecasts in the polar regions in the time horizon when aircraft fuel needs are planned and fuel is loaded. With more accurate wind forecasts, airlines can carry revenue-generating cargo in lieu of fuel without compromising safety. Finally, more accurate wind forecasts from GOES-R could potentially provide benefits to electric utilities when scheduling power from wind farms since more accurate one to two day forecasts will reduce unit commitment costs when the wind forecast is underestimated or the need to purchase electricity from more expensive sources when wind forecasts are overestimated.

Table 1. Estimated Benefits of Polar and GOES-R Winds (in 2007 $M)

	Application/Benefit Areas*	Marginal Annual Benefits in 2007	Present Value (discounted) Marginal Annual Benefit in 2010	Present Value (discounted) Sum of Marginal Benefits 10-Year Period 2010-2019
MODIS Polar Winds				
Case 1	**Hurricane Track Error Reductions**	**12**	**9.8**	**73.6**
Case 2	**Efficiencies in Polar Flight Fuel Consumption**	**15.3**	**13.6***	**115.7***
Winds from GOES-R			**Present Value (discounted) Marginal Annual Benefit in 2017**	**Present Value (discounted) Sum of Marginal Benefits 10-Year Period 2017-2026**
Case 3	**Efficiencies in Wind Power Operations**	**8.7**	**13.2***	**104.6***

*Present value estimates for the benefits in Case 2 and 3 include growth factors. See Benefit Calculation sections for details.

Methodology

Estimating the benefits of wind products derived from satellites begins with experimental results which have shown improvements in wind forecasts or a product forecast (such as a hurricane track forecast). These improvements may be very specific to particular time horizon of forecast and global location. Based on research into who uses the forecast as input into decision-making, subject matter experts (SMEs) may need to use their judgment to estimate how the experiment results might apply for a forecast of different time horizons and/or geographic locations. Research into how these products are used and the economics involved is conducted. Operational users are contacted and interviewed in order to better understand the marginal impact improved forecasts with satellite wind data will have on the decision making process and the resulting economic value of savings or costs avoided. The general benefits analysis philosophy and methodology can be found in (NOAA 2002, 2004). Some of that information is presented here.

This computation is a marginal or differential calculation since the benefits from more accurate wind forecasts are those expected to be achieved in addition to current or future benefits from other sources. For each case study, annual marginal benefits are computed, in general, as follows: 1) Identify operational activity which is dependent upon wind forecasts (e.g., miles evacuated based on hurricane track forecasts); 2) Identify cost of operational activity (e.g., cost of evacuations per mile); and finally 3) Estimate the proportion of activity/costs that could be avoided with better wind forecasts based on data from either MODIS polar winds or GOES-R. All benefits are in 2007 dollars (or increased to 2007 dollars using U.S. Department of Commerce inflation rates). If other “growth” factors apply (such as an expected increase in the number of airline flights crossing the North Pole) then the annual benefits are adjusted accordingly. Finally, per OMB Circular A-94, present value is calculated at a discount rate of seven percent per year.

Once the operational case can be made that a decision maker with better information about winds (either the current analysis or wind forecasts) from MODIS polar winds or GOES-R could take actions to save money (or avoid costs) , the number of occurrences of such cost saving (or cost-avoiding) actions must be estimated. Not all potentially cost-avoiding actions are feasible, nor can they be attributed solely to an improved wind forecast. Therefore, it is unreasonable to assume that *all* such cost-avoiding actions would be taken solely because of improved wind forecasts. On the other hand, given that there are preventable actions that can be taken, it is unreasonable to assume that improved wind information would have no impact at all. Based on facts established that either MODIS polar winds currently has or GOES-R potentially has some impact on reducing errors in wind forecasts, and that these forecasts are critical to economic decisions, it is reasonable to assume that there would be some measurable benefits. The challenge that remains is to determine the magnitude of these benefits.

In summary, the benefits methodology relies on the data provided by a variety of scientists and other subject matter experts and operational users of wind products. A variety of cost data and statistical data collected on industry operations and the impact of wind on these operations was also critical input into the analysis.

Section 3

Economic Benefits of Polar Winds

3.1 MODIS Polar Winds Impacts on Forecasts

Several experiments have documented the impact of polar winds in global forecasting. (Borman, Key, Santek, Zapotocny). This wind product from the MODIS has had positive impacts on the six-hour polar wind forecast and the three to five day forecasts in mid-latitudes. The root-mean-square (RMS) wind speed differences between the MODIS water vapor winds and the six-hour model forecasts with and without the MODIS winds suggest that the 500 hPa water vapor winds "seem to reduce the short-range forecast errors for the winds by about 40 percent." (Santek). In mid-latitudes the impact appears to result from modification "near the polar jet stream and that this effect propagates to lower latitudes in extended forecasts." (Santek). In particular for the tropical cyclone tracks studied, with the addition of MODIS data, "the average (track) error is approximately 22 nm smaller at 72-hours for the 46 cases that occurred that season for this forecast length." (Zapotocny, 2007)

3.2 Hurricane Track Error Reductions: Reducing the Cost of Evacuations

This case highlights benefits from the contribution of MODIS polar winds to improving the accuracy of the mid-latitude three to five day forecast of hurricane tracks.

3.2.1 Problem Statement

Wolshon, et al summarizes the evacuation problem as follows:

> "A critical issue in hurricane evacuations is timing. The earlier the evacuation order is issued, the more time residents and tourists will have to evacuate. Unfortunately, the earlier it is issued the greater the possibility the hurricane could change course before landfall, rendering the evacuation unnecessary or leading evacuees to more dangerous locations. Evacuations that turn out to be unnecessary can also lead to a "Cry Wolf" syndrome in which some people are less likely to evacuate during future threats."

Storm forecasts issued by the Tropical Prediction Center/National Hurricane Center (TPC/NHC) are the primary input used to make the decision of when to evacuate and how large an area. Time requirements for issuing evacuations vary by location, depending on population and traffic routing. Table 2 provides examples of preferred evacuation times by state.

Table 2. Selected States' Preferred Minimum Evacuation Order Advanced Notification Time (in hours) (Wolshon)

State	Hurricane Category				
	1	2	3	4	5
Massachusetts	9 (hrs minimum)	9	12	12	12
Rhode Island	12-24	12-24	12-24	12-24	12-24
Maryland	20	20	20	20	20
Virginia	12	18	24	27	27
South Carolina	24	24	32	32	32
Georgia	24-36	24-36	24-36	24-26	24-36
Mississippi	12	24	24	48	48
Louisiana	24	48	72	72	72

3.2.2 Benefits Calculation

Based on the information in Table 2, the preferred time horizon to issue evacuations is between nine and 72 hours. As shown on Table 3, the average reduction in hurricane track error with MODIS data is 14 percent over the 12 to 72 hours (Zapotocny et al)[1]. TPC/NHC typically warns 300 to 400 miles of coastline, of which 100 miles represents the average diameter of hurricane force winds and the remaining 100 miles on either side a buffer zone due to forecast uncertainty (Willoughby et al). We conservatively assume that behavior of emergency officials does not change; that they will continue to base evacuation decisions on the same historical pattern of 100 miles uncertainty buffer on each side of the approaching storm. We assume that because the track is more accurate, the boundary of this safety zone is placed more accurately. The improvement is therefore equivalent to the average reduction in track error indicated in Table 3, or about 20 miles per major land-falling storm. If we assumed that the improved track accuracy led to a reduced uncertainty buffer, the benefit would be amplified and might be as much as twice the track improvement or up to 40 miles. This approach is particularly conservative because it does not explicitly account for the possibility that in some cases, the improved evacuation decisions will result in lives saved. This benefit would apply to land falling major hurricanes. Approximately two major hurricanes made landfall every three years somewhere along the U.S. Gulf Coast or Atlantic from 1851 through 2006 (Blake et al). The estimated cost of evacuations used here, $1M per mile, is a standard number that has been used for many years and still appears to be valid[2] (Landsea, Perry), and results in $20M of benefits per land-falling storm. Over the ten year lifecycle we assume six land-falling storms, for a total of $120M or $12M per year. The discounted benefit that commences in 2010 is $9.8M ($2007), and the total over the ten year lifecycle 2010 to 2019 is $74M.

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[1] Notice that all error reductions in this experiment are attributed to MODIS polar winds.

[2] Some sources have stated that evacuation costs per mile are less (reference) while others say that $1M per mile is likely an underestimate (reference).

Table 3. 2004 Atlantic Basin Average Hurricane Track Errors (nm) With and Without MODIS (Zapotocny)

Time	00 hour	12 Hour	24 Hour	36 Hour	48 Hour	72 Hour	96 Hour	120 Hour	Average
Control	13.2	43.6	66.5	94.9	102.8	157.1	227.9	301.1	126
Control + MODIS polar winds	11.4	34.8	60.4	82.6	89.0	135.3	183.0	252.0	106
Error Reduction with MODIS Polar Winds in nm	1.8	8.8	6.1	12.3	13.8	21.8	44.9	49.1	20

3.3 Efficiencies in Airline Polar Route Fuel Consumption

This case highlights the benefits of MODIS polar winds pertaining to improved six-hour wind forecasts in the Northern Hemisphere Polar region.

3.3.1 Problem Statement

Globalization and growing economies in the Far East combined with the opening of airspace in China and Russia have initiated an increase in the number of U.S. flights crossing the Arctic Circle into the Northern Polar region. While polar routes have risks such as solar weather impacts to communication, there are significant benefits in reduced flight time and fuel consumption. This is particularly true flying west from the U.S. since strong headwinds can be avoided. Polar route crossings stress aircraft to the maximum with respect to temperature, remoteness, and flying times of up to 18 hours. Airline operators use flight planning models to generate expected fuel consumption based on many factors: distance, aircraft performance, payload (passengers and cargo), air traffic control, and weather. However, prior to the point in the flight planning schedule when passenger and cargo loading become finalized on these long-haul routes where the majority of the flight is not subject to air traffic control impacts, weather, in particular winds, remains the most significant source of uncertainty with respect to expected fuel consumption.

More accurate six-hour forecasts over the poles are potentially useful since this timeframe impacts flight planning just prior to departure. Maintaining safety is the highest priority for commercial operators and this concern, as it pertains to polar operations, is partially addressed by allowing for optional routes or altitudes due to uncertainty of polar winds. Consequently fuel amounts loaded onto an aircraft will necessarily be more than what is expected to be consumed. However, carrying extra fuel is costly because the extra weight of the fuel (about 6.7 pounds per gallon) contributes significantly to fuel consumption and costs[3]. In addition, carrying unused fuel can be particularly uneconomical since instead of fuel the aircraft could be carrying additional revenue-generating cargo.

As the reliability of these more accurate wind forecasts is proven over time, improved polar wind forecasts are expected to reduce airline contingency fuel amounts and possibly the FAA's requirements for reserve fuel, (as has been done in other international route areas), freeing up more capacity for revenue generating cargo or reducing overall fuel costs without compromising safety.

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[3] Aircraft fuel requirements models take into account the weight of fuel when determining final fuel needs. These models also consider fuel consumption rate changes due to acceleration, altitude, and changes in aircraft weight. As fuel is consumed, the aircraft is lighter and therefore consuming less fuel.

3.3.2 Benefits Calculation

For this case study, benefits are the potentially avoidable opportunity costs airlines incur when they carry fuel instead of payload. Benefits will be calculated by first identifying how much fuel weight on average is avoidable without compromising safety. Whereas the highest benefit will likely be achieved in the region directly over the pole, it is expected that forecast accuracy improvements due to polar wind measurements will exist, though to a diminishing degree over lower latitudes down to 65 degrees.

Table 4 provides an example of the aircraft fuel requirements breakdown. FAA regulations require airlines to add fuel for holding and flying to an alternate destination for safety. In addition, the airlines add fuel at their discretion ("Contingency") based on several factors with wind being one of the most significant.

Table 4. Example of Typical FAR Part 121 International Dispatch Release – Flight Fuel Requirements Breakdown for a Typical Polar Route Flight

	Time (hours:minutes)	Fuel (lbs)	Comment
Destination	13:36	162,890	Burn takeoff to touchdown
Alternate	00:51	14,920	Fuel to most distant alternate
Reserve	01:19	16,670	10 percent of origin to destination time
Hold	00:30	6,910	30 minutes hold at 1,500 feet
Minimum Equipment List (MEL)	xx:xx	0	Fuel for any maintenance penalty
--Federal Aviation Regulations (FAR) Required --	16:16	201,390	Minimum fuel per regulation
Contingency	00:15	3,580	Company policy or dispatch/pilot preference
Total	16:31	204,970	
(Note: Maximum fuel capacity for this example is 320,863 lbs.)			

An analysis of a major U.S. airline's polar flight data for 2006 revealed that on average flights consumed roughly four percent less fuel, or 8700 lbs, than planned. Note that this is the delta of actual fuel consumed to the "Destination" fuel requirements in Table 4, so this is extra fuel carried in addition to "Reserve" and "Contingency" totals. Also note that if the "Destination" fuel requirements could be reduced due to more accurate wind forecasts this would impact the "Reserve" totals since this is a simple percent of the "Destination" total.

The amount of "Contingency" fuel is left to the discretion of airlines, pilots and dispatchers, but typically ranges between five minutes and 15 minutes of extra fuel (Still telecom). This range reflects "Contingency" fuel that is discretionary and above what the FAA requires. These facts highlight that there is a significant amount of additional fuel that is carried and not consumed, which supports the potential to reduce the amount of fuel carried without compromising safety.

There has been no specific study of the impact of the apparent 40 percent improvement in six hour forecasts due to MODIS winds on reducing fuel contingencies. However, with wind being one of the primary drivers of fuel consumption on these long distance flights, and as airlines gain increased experience with forecasts using MODIS winds, it seems reasonable that these forecasts will have a significant impact on fuel consumption planning. For this analysis, we assume conservatively that the fuel savings impact would be five minutes of fuel burn saved, or 2025 lbs of fuel, and that the impact would be more over higher latitudes and diminish over lower latitudes where the impact of the improved forecast would not be as great.

From the example in Table 4, the contingency of 3,580 lbs for 15 minutes translates to a burn of 239 lbs per minute. This example is an approximate average for an MD-11, a three engine aircraft. Fuel consumption is a function of various parameters, most significantly the type of aircraft. A Boeing 777 which is a two engine aircraft can burn an average of 255 lbs per minute while a Boeing 747, a four engine aircraft, can burn 570 lbs per minute (Stills). For the purposes of this analysis we will assume an average of 405 lbs per minute.

Table 5 shows an estimate of the numbers of U.S. flights crossing the polar region and the highest latitude reached (FAA). It is assumed that flights at higher latitudes (above 85 degrees) will receive the maximum benefit (100 percent) and flights with maximum latitude near 65 degrees will receive a minimum benefit (20 percent)[4].

Table 5. Calculation of Potential Fuel Weight Savings with Improved Wind Forecast over North Pole

Location	# Flights per year	Total number of pounds of fuel saved assuming 2025 lbs per flight	Impact Factor of Improved Wind Forecast to Fuel Carried	Net fuel saved (in lbs)
Above 85 deg	108	218700	100%	218700
80 to 85 deg	1476	2988900	80%	2391120
75 to 80 deg	1344	2721600	60%	1632960
70 to 75 deg	3972	8043300	40%	3217320
65 to 70 deg	3840	7776000	20%	1555200
Total	10740			9015300

Instead of calculating benefits based on the cost of this additional fuel, (since unused fuel on one flight can be used on the next), we assume that airlines will choose to substitute fuel with additional cargo at an average revenue of $1.60 per pound (Williams) in 2005 dollars, or $1.70 in 2007 dollars, using an inflation factor of 1.0628 (U.S. Department of Commerce).[5] Consequently, an estimated savings in fuel carried of 9,015,300 lbs per year could result in potential revenue of $15.3 M per year. Due to availability of modern aircraft with a 6,000 to 9,000 miles range and growing economies in the Far East, traffic on polar routes is projected to grow at above average rates, with average annual growth estimates of 13.9 percent in 2009, 20.4 percent in 2014 and 12.7 percent in 2019. (Hildner). However, to be conservative, we assume growth in polar cargo traffic of 3 percent, which is half the current projection for commercial cargo (Boeing) of 6 percent annually. Discounted benefits in 2010 are estimated to be $13.6M, and the total over the ten year lifecycle of 2010 to 2019 is $115.7M

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[4] These impact factors do not take into account the amount of time spent in these regions. This information was not available in the database used.

[5] Nationwide average of aviation fuel is around $4.00 per gallon (AirNav.com) or, since jet fuel weighs around 6.7 pounds per gallon, $.6 per pound. Carrying cargo versus simply not carrying the fuel would appear to be the most cost effective decision. The weight of the fuel carried is factored into calculations for fuel required so replacing fuel not needed with cargo does not increase fuel consumption.

Section 4

Benefits of GOES-R Winds

4.1 Improvements in Wind Forecasts Due to GOES-R

GOES winds currently appear to provide a significant contribution to forecast accuracy. A study of a variety of satellite-based datasets currently assimilated into forecast models showed that "the most consistently positive forecast impact from the remotely sensed data season to season was from GOESCD (GOES Imager infrared cloud-drift wind)…" (Zapotocny, 2002). The GOES-R series is expected to provide improved wind speed measurement accuracy due to higher spatial and temporal resolution of the Advanced Baseline Imager. Since wind vectors are derived by measuring the movement of clouds and water vapor features from one image to the next, increasing the precision and frequency of these images should result in increased accuracy of wind vector measurements. The overall objective for GOES-R winds is a 20 percent increase in vector accuracy (Velden) but the specific impact to surface winds in the one to two day timeframe has not been explored. Consequently, we assume that there will be some improvement to the surface wind forecast, and for the purposes of this analysis we will assume a ten percent reduction of the annual mean absolute error (MAE) in CONUS surface wind-speed forecasts from GOES-R in the one to two-day timeframe. NOAA statistics for the 24 to 48 forecasts for November 2006 to November 2007 for CONUS show an MAE of about 3.5 kts or 1.8 m/sec (NOAA NWS NDFD). A ten percent reduction (improvement) in MAE would result in an average annual MAE of about 1.62 m/s.

4.2 Efficiencies in Wind Power Operations

4.2.1 Problem Statement

Large-scale integration of wind power for electricity generation poses challenges for electric utilities and grid operators. Grid operators are responsible for ensuring a constant flow of electricity to customers while minimizing costs. Because electricity currently cannot be stored economically, grid operators place a high premium on reliability. While wind is a relatively low cost source of electric power, it is also relatively unreliable compared with other sources of electric power such as combustion cycle plants or hydroelectric facilities. When the wind speed is too low, other, usually more expensive sources must be committed to generate power. Because of the lead-time inherent in generating unit commitments, these decisions are based on wind speed forecasts. For example, based on a low wind speed forecast in the day-ahead horizon, grid operators will commit the generation of electricity from more expensive sources. If the wind is actually more productive, these commitment costs could have been avoided. Similarly, if the wind speed forecasts are higher than actual, the shortfall in electricity will be made up by higher-cost purchases on the spot market. In either case, significant costs can result from inaccurate wind speed forecasts. Although the direction of error is likely random and may have asymmetric cost implications (e.g. over-estimates may be more costly than under-estimates), we do not address these potential asymmetries.

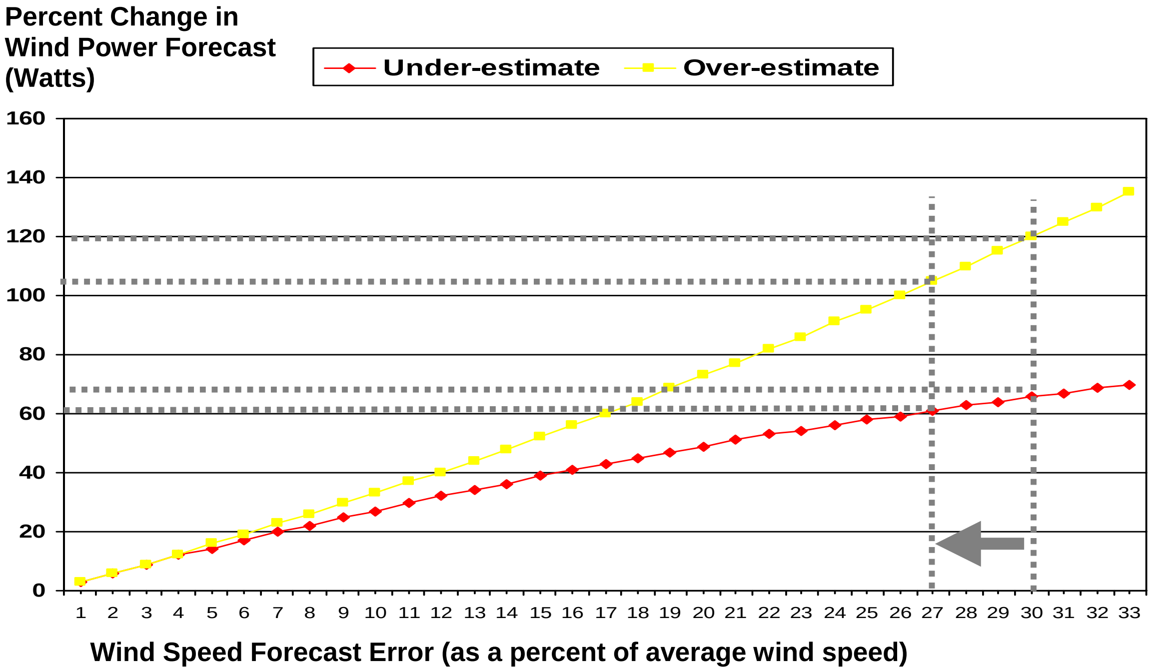
4.2.2 Benefits Calculation

The studies investigated here have shown the cost impact or benefit of the forecast accuracy of the power of the wind generated by a turbine, not the forecast accuracy of the wind speed. So in order to calculate the benefit of more accurate wind speed forecasts, we first need to understand the relationship between wind speed and wind power generated by a turbine. Commonly known as the "cube-power law," the usable power (in Watts (W)) generated from a wind turbine is related to wind speed as follows (Danish Wind Industry Association):

$P = ½ \delta\rho v^3 \pi r^2$, where: P = power of the wind measured in W; δ=the efficiency of the wind turbine; ρ = the density of dry air measured in kg/m3 (kg per m^3) which depends on temperature and altitude; v = velocity of the wind measured in meters per second (m/s); π =3.14 and R = radius of the rotor measured in meters. Note: the kinetic energy in the wind is $P = \rho v^3 \pi r^2$, but the *usable* energy that can be extracted by a wind turbine is reduced by the terms ½, and δ.

Therefore, the error in the forecasted power produced by a wind generator will be greater than the error in the wind speed forecast and is represented, assuming all other values are known and constant, by $\alpha P = (\beta V)^3$, where α is forecast error of power generated given the wind forecast error, β We calculated the approximate relationship between different levels of forecast error improvement as a percentage of the wind speed forecast error and wind power forecast error. Calculating this relationship revealed that turbine power output errors are more sensitive to forecast overestimates of wind speed than to underestimates of the wind speed. Given that wind speed forecast uncertainty is random, we will use the average impact on wind power forecast errors for our calculation of potential economic benefits. Figure 1 shows the relationship between change in wind speed forecast under-estimate and over-estimate errors to change in power forecast errors using the relationship defined above, and illustrates the impact of a 10 percent reduction in wind speed forecast error.

Figure 1. Relationship of Wind Speed Forecast Error to Power Forecast Errors



Given our assumption of a ten percent reduction in wind speed forecast error Figure 1 illustrates the impact on wind power forecast error for a typical case. Wind power generators are usually located in areas where the average wind speed is about 6 m/s or greater. At 6 m/s, the CONUS-average wind speed MAE of 1.8 m/s represents a 30 percent forecast error. Decreasing this error by 10 percent would decrease the MAE to 27 percent of the average wind speed. This would reduce the wind power forecast error by about 15 percent in the case of over-estimates, and about 5 percent in the case of under-estimates. Averaging the two reductions yields a typical reduction in wind power forecast error of about 10 percent. These calculations show that even a small decrease in the absolute error of a wind forecast can have a significant impact on wind power forecasts.

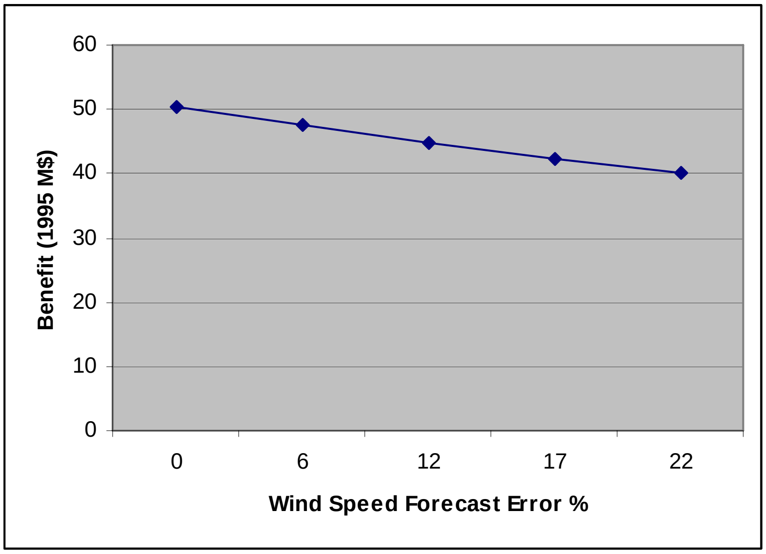
Two sources of cost data were investigated for this analysis. The results from each will be discussed below.

The first is a study by Milligan et al, in 1995. This study modeled the benefit of an accurate power generation forecast from a 1250 MW wind turbine for two utilities. Interestingly, it was shown that the impact on cost of an under or over estimate is not consistent for the utilities. For one, an under forecast had more of a cost impact and for the other the opposite was true. It was found that these results were sensitive to the utility's contractual and power pool arrangements (Milligan et al), so for this analysis we averaged the cost impacts from both utilities. Table 6 contains the results of their analysis, showing that a perfect power generation forecast had an average value of $50M to the utilities with losses in value as the quality of the power generation forecast decreases. Using the data from this study and relating cost to wind speed forecast error using the relationship in Figure 1, the resulting relationship of wind speed forecast error to benefit is shown in figure 2. This linear relationship shows that a 10 percent improvement in wind forecast error from 14% to 12.6% has a value of approximately \$.66M in 1995 dollars, or \$.86M per year in 2007 dollars using an inflation factor of 1.2973 (U.S. Department of Commerce).

Table 6. Annual Value of Wind Forecast to Utilities (Milligan) (1995 millions of dollars)

Power Generation Forecast Error (%)	Value of Forecast to Utility A	Value of Forecast to Utility B	Average
0	53.8	47.0	50
20	53.0	42.0	48
40	52.4	37.0	45
60	51.7	33.0	42
80	50.9	29.0	40

Figure 2. Value of Wind Speed Forecast Error Using Data from Milligan et al



In order to use this data to compare with data from other sources and to extrapolate to benefits for the entire U.S., we need to convert this annual benefit to the utilities to dollars per Mega Watt-hour (MWh). This calculation requires an estimate of the number of hours the wind turbine generates power per year, which was not provided in this study. The nationwide average from 2004 was 2028 hours per year (Department of Energy), so that a 1250 MW turbine would generate 2.5 M MWh. So the value of a 10 percent improvement in wind speed forecast error per MWh is: \$.86M/2.5M MWh = \$.34 per MWh in 2007 dollars.

The results of a second study investigating the cost of wind power forecast errors are in Table 7 (UWIG). If we map these costs to the wind speed forecast error with the relationship shown in Figure 1, we get the resulting relationship between wind speed forecast error and cost in Figure 3.

Table 7. Cost of Wind Forecast Inaccuracy as a Function of Forecast Error[6] (UWIG)

Distribution Range +/-(%)	10	20	30	40	50
Extra Cost ($/MWh)[7]	0.391	0.716	0.995	1.231	1.436

Figure 3. Marginal Cost of Wind Forecast Error (UWIG)

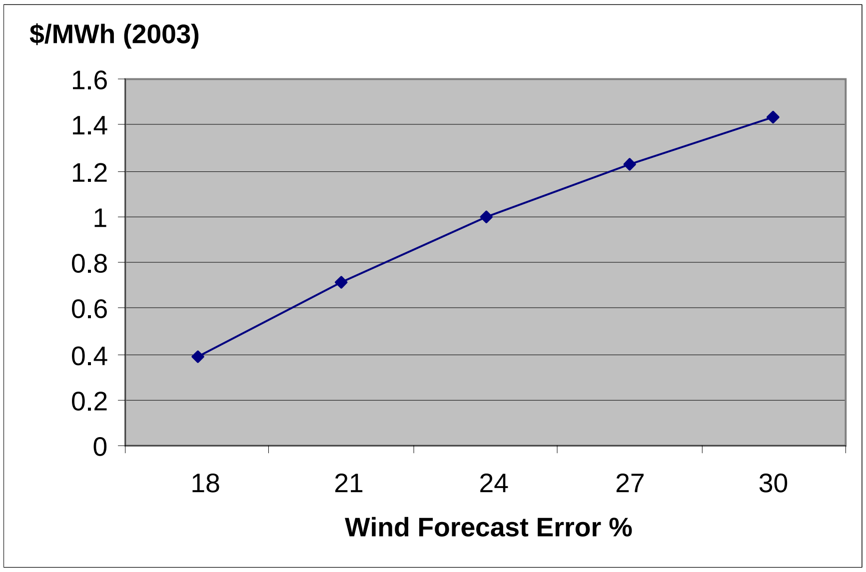


Figure 3 shows that if the current wind forecast error is 30 percent and with GOES-R the wind forecast error is reduced by 10 percent to 27 percent error, the value of that improved forecast would be approximately $0.20 /MWh in 2003, or $0.22 / MWh in 2007 dollars using an inflation factor 1.1232 (U.S. Department of Commerce).

These two studies provide us with a range of $0.22/MWh to $0.34/MWh as the value of a ten percent improvement in wind speed forecast error. For this analysis, we will assume an average of $0.28/MWh. It is interesting to note that another source from 2005 showed that the value of a "state-of-the-art" wind forecast versus no wind forecast was $10.70/MWh (Piwko), however no details were provided to allow a calculation of a marginal improvement.

In 2006, wind generation production was around 31 B kWh (American Wind Energy Association), so that the annual value of an improved wind forecast at the above rate would be $8.7M. To calculate present value, we use the average per year benefit derived above and adjust for growth in annual wind generation projected by DoE for 2017 through 2026 which is 93B kWh and 125B kWh, respectively (DoE, Annual Energy Outlook 2008). Adjusting for this growth results in a present value ($2007) in 2010 of $13.2M, and the total present value over the ten year lifecycle 2017 to 2026 would be $105M.

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[6] "Forecast Error" in this table refers to the error of the forecasted power output, not the error of the wind speed forecast. This was verified with the authors.

[7] It is assumed that these are 2003 dollars.

In addition to these savings noted above, potential financial penalties which are incurred when estimates of available electricity are inaccurate could be avoided with more accurate wind forecasting (Renewable Energy Law Blog). One example from an Oklahoma electricity producer in 2004 showed that although the actual cost of the wind generated was around $2.2M, generator imbalance charges were around $4M (The Journal Record).

Section 5

Summary

We highlight here three economic areas where there is a significant reliance on wind forecasts. With the exception of the quantification of hurricane track improvements due to the MODIS winds, the impact described in the other two case studies is based on assumptions of the magnitude of improvement to wind forecasts and not based on experimental results. For example in the polar route case study, it would be helpful to model the specific wind forecast improvements due to MODIS winds for products currently used by the aviation community flying polar routes and to understand how the wind forecast quality degrades towards lower latitudes and longer term forecasts. Further, it would be helpful to discuss with the FAA, pilots and dispatchers whether they have information indicating the current impact of these MODIS winds forecast improvements. It is certainly possible that they have already made adjustments to their route and fuel plans without directly attributing these benefits to improved wind forecasts. Finally it would be useful to understand if they would benefit from potential future improvements in wind forecasts if a new Polar winds mission is planned. For the wind power industry case study, more work is needed to understand what impact GOES-R will have on the one to two day forecast near the surface. As one expert in the industry described, this is the “holy grail” of forecasts for wind power. As seen from the numbers provided in this study, the benefit of more accurate wind forecasts is significant. What we have done here is to outline case studies that could support a more robust cost/benefit analysis in the future if better quantification of product improvements is available.

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