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WEATHER SATELLITES AND THE ECONOMIC VALUE OF FORECASTS:
EVIDENCE FROM THE ELECTRIC POWER INDUSTRY

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ABSTRACT

Data from weather satellites have become integral to the weather forecast process in the United States and abroad. Satellite data are used to derive improved forecasts for short-term routine weather, long-term climate change, and for predicting natural disasters. The resulting forecasts have saved lives, reduced weather-related economic losses, and improved the quality of life. Weather information routinely assists in managing resources more efficiently and reducing industrial operating costs. The electric energy industry in particular makes extensive use of weather information supplied by both government and commercial suppliers. Through direct purchases of weather data and information, and through participating in the increasing market for weather derivatives, this sector provides measurable indicators of the economic importance of weather information.

Space weather in the form of magnetic disturbances caused by coronal mass ejections from the sun creates geomagnetically induced currents that disturb the electric power grid, sometimes causing significant economic impacts on electric power distribution. This paper examines the use of space-derived weather information on the U.S. electric power industry. It also explores issues that may impair the most optimum use of the information and reviews the longer-term opportunities for employing weather data acquired from satellites in future commercial and government activity.

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INTRODUCTION

For 2000, the U.S. electric power industry earned an estimated total revenue of $247 billion.[1] Electric power generation is thus a very large and important industry. Modern society depends on electricity to supply much of the power needed to support manufacturing, and daily heating, cooling, and lighting needs. It is therefore an essential part of the infrastructure of the U.S. economy. Even a very small service disruption can have a large social and economic impact. The 1977 blackout in the Northeast U.S. cost the U.S. economy an estimated $340 million (in then-year dollars); the August 2003 blackout may have cost New York City alone some $1.15 billion (estimates of total cost range from $4 to $6 billion).

Neither unusual terrestrial weather patterns nor space weather appear to have caused either of these two blackouts. However, both types of weather incidents are capable of creating major problems with the electric power infrastructure and therefore have the potential for causing large economic losses. Terrestrial weather conditions, typically, are predictable; better forecasts will lead to more efficient management of the electric power system and, as described in this paper, contribute to sizable cost savings. Incidents caused by space weather are not as predictable and can occur within minutes to a few hours of a coronal mass ejection from the sun, but in the last decade, scientists have made measurable progress in understanding the physical basis of space weather and in extending their ability to predict harmful consequences on Earth.

Accurate weather information is only one component of the smooth and efficient operation of the large and complex electric utility industry. Accurate weather information is most important when significant deviations in temperature or

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storm-caused natural disasters are probable. Nevertheless, because the industry is very large, because energy prices are volatile, and because of the high cost of capital facilities for energy production, management, and transmission, improvements in predicting and planning for changes in the weather can result in potential annual aggregate savings of hundreds of millions of dollars for the U.S. economy as a whole.

In particular, finer, more accurate satellite weather observations from improved instrumentation, when combined with enhanced weather models, can provide the basis for more accurate, short-term and long-term forecasts. Improved forecasts can potentially lead to significant cost savings in electric energy production.

The benefits of better terrestrial weather information obtained from satellite data are not limited to the electric power industry. They extend to nearly all socio-economic activities: household, industry, and government.[2] Space weather has a more limited, but important, effect on society as a whole because it primarily affects technological systems, and especially the electric power grid. This paper focuses on the electric power industry because it is one of the largest users of weather data and is potentially one of the largest beneficiaries.

THE VALUE OF TERRESTRIAL WEATHER DATA IN THE ELECTRIC POWER INDUSTRY

TYPES OF USES

Electric utilities use weather information in several different ways. Different personnel, even within the same company, may manage each different type of forecast and use. They generally use different models and different variables, the value of which may vary greatly. In addition, the relationship between the accuracy of the weather forecast and the eventual economic benefit will be different for different uses.

Energy utilities use weather forecasts in the following components of the generation process:[3]

1. Fuel acquisition (both purchasing and transportation of the fuel);
2. Load (demand) forecasting;
3. System planning

Planners use all types of weather and climatic forecasts in preparing for the purchase and transportation of fuel. Such information is used to determine where to purchase fuel and how it to transport it to the power plant.

The Clean Air Act Amendments of 1990 placed new, more stringent emission requirements on electric utilities than they had previously experienced. Weather anomalies (very hot summers, cold winters, etc.) can affect energy costs and their ability to meet emission standards for their service area. Thus, they have to be very sensitive to possible weather changes that might require last minute energy purchases at high prices, either to meet regulations or to meet energy demand. Utilities use forecasts of 1 to 12 months ahead for this planning activity.

Weather factors are also very important in the generation of electricity. Most generating units do not perform as well during periods of high temperatures and humidity as they do during moderate conditions. Thus, short-term forecasts and timely weather observations are critical for the efficient operation of generating plants. Because bringing unused plants into operation during peak periods takes hours and even days, utilities also employ two to ten-day forecasts.

Electric load (demand) imbalances are very costly to the electric power companies. Hence, forecasts are very important to the industry. Historical weather data coupled with other economic and social variables account for up to 95% of the accuracy of demand forecasts. Nevertheless, weather *forecasts* are also critical. The broad geographical distribution of demand and the need in a deregulated world to maximize usage means that utilities both buy and sell power on the market. The industry has a spot market for immediate purchases (in times of high demand the price often reaches very high levels) as well as a day-ahead market. More accurate weather forecasts result in major economic benefits to the industry because utilities can then time their purchases and sales of electricity optimally.

Electric utilities also use weather data to optimize the analysis of sales and corporate earnings, to provide better customer service, to optimize new transmission and distribution lines (the choice of construction materials and the placement of lines), and to balance the supply and demand of electricity at regional levels.

Additionally, they use weather forecasts to plan for and mobilize resources to meet storm and lightning restoration work. Short-term forecasts enable risk management of surges. This includes terrestrial storms and geomagnetically-induced currents caused by space weather,

In short, the electric power industry uses weather information of all sorts for a wide variety of tasks, including risk management, system and capital planning, and trading. It will become increasing important in a deregulated marketplace.

EVIDENCE CONCERNING ACCURACY OF FORECASTS AND ECONOMIC VALUE

Because the industry uses different types of forecasts for different purposes, the value of forecasts will vary depending on use and type of forecasts (i.e. time-frame). This research is focused in part on exploring the relative economic value that can be expected from efforts to improve weather forecasts. One important question is the economic value that can be derived from moving from a seven day-ahead weather forecast to a 10-day ahead forecast.

When the average temperature is between 65^{o} (18º C) and 75^{o} (24º C) the electric power industry benefits little from short-term weather forecasts. The main benefits accrue when temperatures rise above or fall below these temperature. The industry uses a measure of heating degree days (HDD) or cooling degree days (CDD), measured as deviations from 65^{o}.[4] The industry experiences greater economic consequences from inaccurate forecasts during extreme periods of heat than during unusual cold periods.

Beyond temperature variance and time differences, geography is also an important variable. Weather in the Central American isthmus, for example, is extremely difficult to predict because of rapidly changing terrain elevations and the influence of not one, but two ocean systems.[5] Regions characterized by large temperature ranges and strong seasonal effects not only present more difficult forecasting challenges, but may also be the regions where economic benefits from more accurate weather forecasts are the greatest (at least for some types of uses).

Forecasts of temperature have two dimensions: the point estimate of a temperature and the expected variance (as measured by the size of the standard deviation from the forecast). Forecast improvements must encompass both—superior point accuracy and reduced variance.

The following expert opinions illustrate the current knowledge about the value of different types of forecasts. A literature survey reveals that:

- No national or aggregate estimates exist concerning the value of forecasts; and
- Most experts cite examples derived from their experience, usually from one application at one utility company over one time period.

Expert opinions:

"Optimal operation of the distributed generation depends, at a minimum, on accurate 1- to 2-day weather forecasts. When co-generation of heat (cold) is combined with distributed generation installation, the importance of the weather becomes crucial to economic performance."[6]

"For the demand forecast decision, 1 day (operations) and 1 to 20 year (planning) forecasts are valuable. Temperature is the most important variable, along with cloud cover, at the sub-utility/utility/regional scale. The highest value improvements in weather forecasting in the electric industry would accrue here, over the 1-hour to 10-day range. For wholesale purchases and trading decisions, 1 hour information is useful in the spot market, 1 month to 1 year outlooks are useful for planning, and one day to two to 10 day forecasts are needed for most market decisions. The latter are of very high value. Weather forecasts have somewhat less value in the shorter and longer time frames. Temperature and duration of temperature is important, at the regional scale."[7]

"TVA's weather information consists of a rolling hourly forecast of temperature and relative humidity for 5 cities in its service area, out to 240 hours from the present hour's forecast (10 days). The value of a correct or incorrect load forecast, especially combined with potential savings for efficiently scheduled maintenance and river operations, can be very high (6-7 figures) for precipitation and 5-6 figures for maintenance. The significance of errors in forecast temperature are less when the temperature is 65 degrees Fahrenheit, and increase if it is warmer or colder, up to 350 MW/degree. Better load forecasts would result from increased frequency of reporting current data, and improved accuracy of short-range meteorological models: model output statistics

(MOS), local mesoscale effects, cloud cover, and precipitation forecasts (especially in summer convection, which affects peak load forecasts). The 2-5-day forecast horizon is becoming more important as forecasts improve. No significant improvement in 1-day forecasts has been seen recently."[8]

"The critical forecast period is from 1 day to 10 days. Beyond 10 days a forecast of the weather patterns is necessary. Beyond two years, a weather (climate) forecast is not useful for demand modeling, as the state of the economy and adoption of technology by consumers takes over in significance."[9]

"The National Weather Service forecasts are less accurate as the lead time increases. The mean absolute error increases from 3.3^{o} F. to 6.6^{o} F. as the lead goes from 1 to 5 days, with the biggest increase coming between day 2 and day 3. (This may be related to the nature of the forecast model.) It is clear that improvements in the 3-5 day range could make a huge difference in value. Annual differences between the 1-2 day and 3-5 day forecasts are on the order of $5 to $10 million.[10]"

"Long-range planning is governed by national and local economics and policy and by technologies used in the local service area; medium-range decisions are dominated by maintenance planning, which is affected by exceptional (not usually expected) weather events; and roughly 20% of the value of industry decisions in the short term is influenced directly by weather."[11]

An official from a California utility indicated that during the summer the cost of an inaccurate forecast can reach $1 million per degree forecast error (in the winter the value may be much less—about $10,000 per degree forecast error).[12]

In summary:

- Expert opinions concerning the value and accuracy of current forecasts show a great deal of consistency.
- Utilities understand well how to manage the supply of electricity; load (demand) forecasting is more important than forecasting supply-side variables for gaining market pricing advantages.
- Forecasts 1 to 5 days ahead are the most critical for load forecasting; after five days, their economic value decreases.
- Hourly weather forecasts are significant for warning of impending disasters, but when incorporated into load forecast models they often result in higher mean errors than using historical trend data.
- Terrestrial weather forecasts can reduce the mean average percentage error of load forecasts from a range of 3% to 5% by roughly 1% to 2%; such an improvement can equal millions of dollars of benefits to a utility. However, the actual benefit achieved will depend on many other factors, including the season and the utility's geographic location.

ISSUES IN IMPROVING TERRESTRIAL WEATHER FORECASTS AND MAXIMIZING THE VALUE OF SATELLITE DATA

Many means are used to improve weather forecasts including: more accurate instruments to measure weather conditions; faster computers to process larger amounts of data, and improved forecasting models. Research and development (R&D) efforts of the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) and private weather companies add constantly to our knowledge and the ability to create better weather forecasts from satellite and other data.

NASA and NOAA are attempting to improve the accuracy of a 7-10 day forecast from 62% to 75% by 2010.[13] (This effort should also improve a 5-day forecast to over 90% accuracy.) The two agencies have also identified other potential enhancements resulting from satellite data, including improved precipitation forecasts, hurricane tracking, and predictions of climate change, particularly over a 6-12 month period.[14] Additionally, new satellite sensors will provide improved understanding of the sun and of space weather.

These improvements are consistent with the types of forecasts that experts in the utility industry have identified as economically beneficial:
"Using forecast temperature as input to the model, which comes at 3-hour averages at airport locations, requires interpolation to hourly intervals and to local grid scales, and results in a mean average percent error of 5% rather than the 1.33% obtained with historical hourly data. Better demand models will require more accurate forecasts of dry bulb temperature at the micro-spatial scale where the electric demand actually takes place, not at airports that may be miles

away, and on hourly time intervals, though higher frequencies would be better. The secondary weather variables needed depend on the region in which demand is to be forecast (local technology, local weather)."[15]

"Facilities need to supplement local forecasts with site-specific data that they measure themselves. …In each case, the load model must have better than 5% accuracy to have value, but every 1% improvement in accuracy below 3% is extremely valuable, particularly in temperature extremes. … for demand forecasts up to 5% accuracy, weather information is of practically no value, whereas every percent improvement below 2% accuracy is worth millions of dollars. Accurate forecasts where the temperature is more than 10°F above or below 65°F are far more valuable than forecasts when temperatures are near 65°F. System-wide and facility-based load models would benefit from the same kinds of improvements in weather forecasts: microclimate adjustments; common data format…; more and better representation of urban weather; and improved forecast of precipitation."[16]

Utilities need technical and scientific advances in forecasting, but they also need improvements in the process of disseminating useful forecasts. Impediments in the dissemination process can sometimes occur, limiting the economic value of even the best forecast.[17]

WEATHER DERIVATIVES

The marketplace generally provides an excellent test of economic value. Electric utility deregulation has brought about the introduction of financial instruments known as weather derivatives. The electric power industry is one of the major users of weather derivatives. Many large utilities trade in derivatives in order to smooth their revenue streams from revenue fluctuations caused by temperature variations.[18]

Weather derivatives are financial instruments that provide a hedge against major losses from the occurrence of unexpected weather. They act very much like puts and calls in the stock and futures markets. The derivatives market makers charge a fee, or premium, for this service.

The use of weather derivatives has increased markedly over the short time they have existed. Enron is credited with creating the first weather derivative contract in 1987. In 1998-99 a survey reported the placement of 695 contracts. Currently (2002-03), some 4,500 contracts are traded worldwide.[19] More than 95% of these weather derivative contracts are based on temperature. In 2002-2003, the total value of weather derivative contracts traded on the Chicago Mercantile Exchange equaled more than $4 billion.

The participants' financial exposure in the markets is well defined by the derivative contracts. Each contract has a maximum payment and specifies a specific geographic location, a period of time, a variable (e.g. heating or cooling degree days), the rate of payment, and a strike price. The latter is an agreed value for the variable, above and below which payments will be made.

The availability and quality of the weather data for derivatives is at the same time both a very simple and a very complex issue. At its simplest level, buyers and sellers pre-determine a few data points and the data source, agree on a time period, a location, a maximum level of financial exposure, and a few other contractual issues and enter into a derivative option contract. Little technical knowledge is required and at the end of the time period it is clear what payments, if any, have to be made to the parties involved.

Behind the scenes the process becomes more complicated. Both the buyer and seller of the weather derivatives need to assess the risks involved and anticipate the costs before entering into the contract. For ease of explanation, assume that the only variable is heating or cooling degree days. The record of temperature (high, low, and mean) is one of the most complete and longest time series available and is relatively consistent within a region. (Rainfall, on the other hand, can vary greatly within a relatively few miles.)

Analysts assess the risk (and hence the value and financial terms) of a weather derivative contract by means of a statistical analysis of these historical data. (At present it is not usual for analysts to use forecasts to assess risk for derivatives.) Analysts use different methods to calculate the distribution of historical temperature information and do not agree on a single method for the task.

One statistical problem is that historical data on temperature appear to fit a normal statistical distribution fairly well. Yet the "noise" (deviations from the mean) in temperature data over time is

Box 1: How a weather derivative works:

An example of a weather hedge based on temperature for a utility providing electricity might be structured as follows:

Based on an average heating degree-day (HDD), a utility might want to cover the risk of losing revenue from the loss of sales of electric power in a warm winter season. As measured in the industry, this means that if cumulative HDDs are less than the long-run mean HDD (i.e. a warmer than usual winter) the utility would be paid a given amount per HDD (this amount would be determined by the company and become part of the derivative contract with a cap on maximum total payments also agreed on.). In this case the utility would buy a put option to cover this risk and also pay a premium for the transaction.

A call option is the opposite, covering the case where the HDD at the end of the season (specified in the contract) is above the average (i.e. a colder than normal winter).

A swap is another type of option contract where no actual premium is paid to buy the contract. A company would agree to a "swap level" of HDD based on its expectations of whether there would be a warm or cold winter. The purchaser of the swap would either have to pay the seller or be paid by the seller depending on the magnitude of the differential HDD from the swap level. In order to compensate the risk taker (seller) with a premium, swaps are often asymmetric with respect to the mean.

not homogenous. This indicates that other factors may affect temperature in a predictable pattern (e.g. global warming) but the relatively short time frame and limited geographic area used for analyzing temperature in derivatives may not register this trend very well. Thus, in assessing weather forecasts, there is no assurance that statistical models based on a random distribution of events in the past will apply to the future.

Even the choice of the number of years of history to analyze is not clear. Most articles suggest that less than 20 years is too short a time period and 100 years is too long. Many variables enter into this choice, including the exact location of the instruments the Weather Bureau has used over time and the accuracy of the instruments.

Weather financial derivative instruments and the underlying information used in writing these contracts is still being tested and adjusted. Therefore selling these financial instruments involves significant speculative risk.

If perfect weather forecasts existed, the firms that now purchase weather derivatives would be major beneficiaries. These firms would be able accurately to plan for short-term fluctuations in demand based on highly accurate primary weather information from government and private forecasters. Countering this social gain would be reduced activity in the market for derivatives. The net social loss would be infrastructure associated with the financial industry which now is a clearing house and trading center for speculative activity. Firms would no longer be willing to pay a premium for purchasing derivatives and speculators would migrate to other more profitable markets. However, it is unlikely in any reasonable time frame that: 1) perfect forecasts will be available for both temperature and precipitation, and 2) that the impact on the financial market infrastructure would be very large since weather derivatives are still a very small percentage of the futures market trading.

Satellite weather data are not specifically used in analyzing these weather contracts. Of course, as better information is accumulated in historical records, the contribution of satellite data is important. One potential explicit use is in the rapid verification of contract temperature data. Another is in providing accurate point estimates of temperatures and precipitation within larger regions. Both uses can enable new types of weather derivative contracts to be written as well as assisting in timely conclusion of a contract.

In summary, although satellite information is not currently of direct importance in weather derivatives, the rapid increase in the use of derivatives, particularly in the electric power industry, illustrates one aspect of a true economic value of better weather predictions. The value of contracts has grown rapidly over the past few years to over $4 billion and represents mainly the value of HDDs and CDDs which are the key measures of temperature variations used not only for derivatives but also for load forecasting and the management of electric power facilities.

SPACE WEATHER

Space weather, which results from complex physical interactions between Earth and the sun, often affects modern technological systems (e.g., satellites, powerlines, radio transmission) adversely, causing economic loss and social disruption. Systems in the high magnetic latitudes, such as the northern United States, Canada, Scandinavia and Russia, are at particular risk. In order to provide warning of impending adverse space weather effects, the United States has placed space weather instruments on several research and operational satellites. These instruments gather data on solar activity, magnetic conditions above the Earth, energetic particle flows, and X-rays. These data are assembled, processed, and delivered to the public in the form of space weather alerts, warnings and forecasts by NOAA's Space Environment Center.[20] In addition, a few small companies provide tailored forecasts to a variety of private customers.

The electric power industry is one of the major beneficiaries of space weather information and forecasts. The space weather risk to electric power systems arises from the fact that changes in Earth's magnetic field, caused by high energy particle streams from the sun, create potential differences between grounding points in the grid, which in turn induce small, slowly varying currents to flow along electric power lines and into transformers. The longer is the power line, the greater the current flow will be for a given change in magnetic field. Normally, these geomagnetically induced currents (GICs) are small enough that the electric power system can adjust to them. However, when a significant space weather event occurs, GICs can quickly grow large enough to damage system transformers and disrupt the power supply to consumers. Very large, abrupt GICs can even destroy transformers, causing widespread power disruptions and even large scale electrical blackouts.

As the power grids become more integrated and lines stretch over greater distances, the systems have become more vulnerable to space weather events. As power expert John Kappenman has warned**, "**The sprawling North American power grid resembles a large antenna, attracting electrical currents induced by giant solar storms. Severe space weather occurring during solar cycles has the potential to cause a large-scale blackout in North America."[21] Further, in recent years, electrical power distribution transformer design has become less tolerant to space weather events, adding to the potential for severe loss.[22]

As an example, in March 1989, space weather initiated GICs caused the HydroQuebec power grid to fail for about nine hours, costing the power company some $13.2 million for system response and repair. The storm-caused outage also disrupted the lives of HydroQuebec's six million residents who were left without power for some nine hours[23]. Secondary losses from this power outage, which included the emergency supply of alternate energy sources for public consumers, maintaining traffic flow, hospital operations, and other emergency services, as well as lost production, have been estimated at between $10 million and $100 million. The same storm caused losses of some $27 million to power firms in New Jersey.

As Forbes and St. Cyr have shown,[24] even moderate space weather events may cause sufficient disruption to raise the cost of power to consumers. Analyzing both the real-time and day-ahead markets in the Pennsylvania, New Jersey, Maryland (PJM) power grid over an 19 month period, they estimate that moderate GICs increased the cost of power in the grid by approximately 3.3 percent. These costs are necessarily passed on either to consumers or investors.

The forecasts of space weather effects on Earth systems, whether on satellites in orbit or electric power grids on terra firma, can only be determined from space-based instruments because of the short time (minutes to hours) between the solar event and the suffered effect. Space weather observations, fed into models that reflect the behavior of specific electric grids under the influence of GICs, could markedly reduce the exposure of electric power companies to the damaging threat of space weather.[25]

NOAA operates space weather sensors on its geostationary Earth orbit (GEO) satellites and its polar orbiting series. However, to forecast space weather events with sufficient warning to avoid damage to technological systems, operational sensors at great distances from Earth will be needed, for example at the L_1 point. The utilities need about 1 hour warning. Hence, to be most useful, these observations need to be collected as far from Earth as possible, in order to allow sufficient time to react and to mitigate their effects.

SATELLITE WEATHER DATA AND LOAD PREDICTION

What can satellite data add to the effort to operate the electric power grid more efficiently, thereby reducing operational costs? The answer to this question is complex, and depends on many factors beyond the control of NASA and NOAA. Nevertheless, a deeper examination of the ways in which electric utilities use weather information offers some pointers.

As noted, load (demand) forecasting is a basic and crucial element in the operational planning of electricity buyers and sellers. Load forecasters derive their estimates of future system load from computer models developed over the years and constantly tested against experience. Different terrestrial weather variables (e.g., temperature, cloud cover) are put into these models at specific spatial and temporal resolutions, yielding outputs with well-defined error ranges. The more accurate are the input data, the more accurate the forecast can be. Forecasts can be improved both through development in the computing process and through the quality and spatial detail of the data used as inputs.

Load forecasting models require accurate historical (2-5 years past) and current weather data as inputs. Forecasters universally use dry bulb temperature as an input, but typically also include dew point, cloud cover and wind speed. (The season, time of day, and presence of holidays also factor into the load forecast.) Data typically derive from stations located in towns and cities and therefore yield load forecasts only down to a certain level of spatial resolution.

Load forecasting models allow operators to schedule power loads for particular zones at particular times. The New York Independent Service Operator Model, for example, is used primarily for the day-ahead market. It yields predictions of hourly loads, total daily loads and daily load peaks for each of the 11 constituent zones of the entire New York Control Area system, and combines these for predictions of load on the system as a whole. This load-forecasting model uses historical weather data from recent years, as well as data on current daily weather conditions and forecasts from the weather service.[26] The model delivers hourly load forecasts that can be used in the day-ahead bidding process for each zone, or can be combined into system-wide day-ahead load forecasts. For purposes of error-correction, forecasts are archived for later comparison with actual weather data.[27]

Two sources of error exist in forecasting software: model error, which can contribute about 1.5% mean average percent error (MAPE), and weather forecast error, which can vary from 1% to 8% MAPE depending on the forecast period (from hours out to 7 days). Load forecast models would be significantly improved if the combined MAPE for the annual average of the national, daily load forecast could be improved to less than 2% for the day-ahead forecast.[28]

Commercial weather information vendors such as Itron, Inc., Weather Bank, Inc. and Weather Services International specialize in providing load forecasts and forecasting software to energy utilities and independent system operators. They obtain raw data from the National Weather Service, add other, more detailed data, and provide tailored information products to electric power industry customers on a regular basis. The most common electric power applications are for the very-short-term (minutes to hours ahead) to the short-term (1 to 10 days ahead); forecasts for the very-short-term are produced using regression techniques while short-term forecasts are made using artificial neural networks.[29]

The Electric Power Research Institute (EPRI) finds that artificial neural network based models have the potential to yield highly accurate forecasts with MAPE statistics of 2% for the day- to hour-ahead. EPRI also notes that industry development and the use of advanced modeling software could lead to a technology pull for weather data. The electric power industry is rapidly moving toward continuous use of short-term load forecasts to keep up with extreme weather events and continuous and reliable real-time weather updates will be necessary to do this.[30]

In populated areas, additional weather data to meet this need can be provided by enhanced ground networks. However, such networks are expensive to develop and maintain in sparsely populated areas. Further, they may not provide the repeatability or accuracy of satellite observations. Improved satellite observations can provide a crucial input to the improvement of electric grid forecast models.

The next-generation Geostationary Operational Environmental Satellite System (GOES-R) will markedly improve the quality of meteorological data available to the electric power industry. The key instruments on GOES-R, the Advanced Baseline Imager (ABI) and the Hyperspectral Environmental Sounder (HES), will offer more frequent measurement updates, finer horizontal resolution, finer spectral resolution, and the ability to determine temperature, pressure, and humidity in vertical columns through the atmosphere.[31] NOAA scientists estimate a 2% improvement with ABI and HES for temperature forecasts 24 hours ahead, and a 25% improvement 3 hours ahead.[32] NOAA estimates the savings of this improvement for one application – reductions in unnecessary power generation and spot market purchases – at $479 million/year (2002 dollars) beginning in 2015 when GOES-R becomes operational. Forecasts with different time horizons, not to mention improved system reliability, would surely provide additional economic value.[33]

The Tropical Rainfall Measuring Mission (TRMM) satellite already offers significant improvement in data quality for precipitation. By using TRMM derived atmospheric latent heating estimates, meteorologists have created Global Cloud Models (GCMs) with improved ability to predict rainfall. Day-ahead GCM rainfall predictions using TRMM latent heating data may be improved by as much as 30% over existing models.[34]

Precipitation is a unique weather variable because it is more dynamic and less homogeneous than measurements of temperature or pressure. For this reason, higher spatial and temporal resolution is necessary for accurate measurement of precipitation. In particular, a 3-hour location return rate for microwave measurements would be desirable, though TRMM cannot presently offer this capability. Techniques incorporating infrared data from GEO satellites for 3-hour estimates currently yield precision uncertainties greater than 50%. The next generation Global Precipitation Measurement (GPM) system, a constellation of up to nine satellites, could reduce this uncertainty to around 20%.[35]

Better quality weather information from satellites can facilitate not only demand-based market decisions, but also improve the reliability of the electricity supply. As noted by the California Energy Commission (CEC), the reliability rating of certain power system elements "will improve in direct relationship to improvements in the accuracy of short-term weather forecasts."[36] Ambient temperature measurements are particularly relevant for determining the loadability and reliability of transmission hardware.[37] Here, the new capabilities afforded by GOES-R, GPM, and other satellite systems that gather weather data will assist with improved data inputs. In particular, space-based remote sensing devices offer the possibility of higher spatial resolution for measuring thermal data (including atmospheric temperature, cooling power of the wind, solar radiance, etc.) without building new terrestrial weather stations or adding additional radiosonde balloons to collect vertical temperature profiles in the atmosphere.

TECHNOLOGY TRANSFER

In the end, the benefits of weather data will depend on their ability to be attained and understood by end users in industry.

"While much new information is being generated and used to answer research questions, there is a significant lag in its "uptake" and use to inform decision-making processes by the business community. There are many reasons for this. Among the major barriers are lack of awareness of the availability and relevance of the information, lack of knowledge of the reliability of the information, lack of business 'access portals' to the information and the lack of "know-how" as to how to use the information in business operation and planning decisions."[38]

Changnon et al.[39] come to much the same conclusion for climate forecasts. They conducted a survey of decision makers at electric utilities with responsibilities in load forecasting, fuel acquisition, power trading and systems planning, finding that the current use of climate forecasts is minimal. Nevertheless, survey respondents believed that climatological data would be valuable to their work if it were made more user-friendly. Feedback between suppliers of meteorological data/forecasts and the end users of such information is therefore crucial for matching the capabilities of the former with the needs of the latter.

Problems of utilization are magnified when technology and knowledge transfer occurs across borders and across cultures. As mentioned above, Central America could benefit greatly from more accurate forecasts of its uniquely complex weather patterns. Sixty percent of Central American power comes from hydropower, which is sensitive to precipitation. Yet power companies in the region often rely on weather information available on the internet and rarely utilize the commercially-tailored models U.S. companies use. Forecasts would also be valuable for small-scale agriculture in Central America, yet power and communications infrastructure is often out of the reach of local farmers, impeding the transmission of forecast information. If technologies such as television, radio or internet are available, potential users may have to learn how to access and utilize the forecast information. They may even have to be convinced that such an effort is worth their while.[40]

The transfer of scientific knowledge and technical knowhow from research into applications has always been a challenge for government laboratories. Over time, NASA and NOAA, for example, have spent considerable resources to bridge the gap between research and applications. For improvements in weather information and forecasts, this transition continues to be a problem, in part, because the science community and the applications community (the end users of information) have different goals, different assumptions and generally often speak a different argot.[41] For a variety of reasons, advances in the state of the art do not make it into practice. Hence, one of the challenges for NASA and NOAA will be to bridge this gap by reaching out to the end user, helping them incorporate advances in weather forecasts into their work flow.

CONCLUSIONS

Weather forecasts of all types have economic significance to the electric power industry, as well as to virtually all other industries. This paper has focused on the electric power industry because of its importance as an integral part of the economic infrastructure as well as its very large size. Although national data on benefits are not available, the available case studies coupled with the expert opinions of those working in the industry indicate that the impact of improved weather forecasts may add up to hundreds of millions of dollars of avoided costs per year.

This study indicates that using weather data to forecast the power grid load (demand) accurately allows utilities to trade on the day-ahead market more effectively, manage the start-up and shutdown of generating plants more efficiently, and plan with greater assurance for future capital expenditures. Improvements in the two to five-day weather forecast may result in the greatest impact on the load forecast and consequently on the economic impact to these utilities. These shorter-term improvements in weather forecasting ability will result from improving week-ahead and ten-day-ahead weather forecasts.

There is much room for improvement in the accuracy of terrestrial weather forecasts and in providing forecast users with better models, customized to specific uses. Although most of the literature focuses on the temperature forecast because it is the primary variable in electric load forecasting, other weather data, such as humidity and precipitation are also valuable and will provide industry with economic benefits. Further, the electric power industry will benefit from greater spatial detail in weather data. Satellites can be particularly helpful in this realm.

As Forbes and St. Cyr have shown, the major costs associated with disruptions from space weather in the electric power industry are associated with the day-ahead market. This is the same day-ahead market that is affected by predicted changes in terrestrial weather. Improved space weather predictions would help utilities adjust not only for the major disruptions caused by large electromagnetic storms, but also for the moderate ones that can similarly drive up electricity costs. Ultimately, the electric utilities will benefit from additional, routine operational satellite observations of impending space weather, not only from GEO and polar orbits, but also far out in space from the L_1 and other distant positions, which will allow greater warning times.

Smaller utilities often lack the resources to take advantage of sophisticated information and/or participate in specialized derivative trading markets. Not only could better forecasts and a more user-friendly delivery of the forecasts to these smaller companies enable them to reduce costs and increase profits, it could also contribute to improved operation of the national electric grid.

The recent attention to the vulnerability of the U.S. electric power industry after the Northeast blackout of 16 August 2003 reminds us how complex the system is. Economic and regulatory incentives may lead to inefficient solutions. Improving the weather forecasts adds only one small increment to a more efficient electric power system. Nevertheless, the evidence shows that even small improvements can translate to large economic benefits in this sector.

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[4] The exception to this is for other types of weather-related disturbances to the system such as outages caused by natural disasters or, as described below, space weather. These latter causes may require very short-term predictions (minutes or hours) in advance rather than days or weeks.

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[10] Brooks, Harold E., & Douglas, Andrew P., *Value of Weather Forecasts for Electric Utility Load Forecasting*, AMS Conference on Weather Analysis and Forecasting, Phoenix, Az., 11-16 January 1998, J224-27

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[12] SAIC, op. cit.

[13] Birk, Ronald, "The View from on High," Paper presented at "Space-Tax Revenue at Work, AAS, 19 June 2003.

[14] Ibid.

[15] Hackney, op. cit.

[16] Ibid.

[17] See Hertzfeld and Williamson, op. cit.

[18] Not all companies use this tool. Since it is a relatively new financial device, companies with particularly conservative management have chosen not to participate in this market.

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[30] *Day Ahead/Hour Ahead Forecasting for Demand Trading: A Guidebook*, EPRI, Palo Alto, CA, 2001, p. 7.1.

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[33] Ibid, pp. 24-25.

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