Application of Satellite Sensor Data and Models for Energy Management

Erica Zell, Jill Engel-Cox, Richard Eckman, and Paul Stackhouse, Jr.

***Abstract*—Effective, environmentally sound development, production, and delivery of energy depend on Earth monitoring information. Satellite remote sensing data and products provide unique, objective information that has the additional advantage of yielding global, homogeneous, and repetitive coverage. Satellite remote sensing data and products have been used extensively in parts of the energy sector for applications ranging from climatology to identification of solar and wind energy sources, yet there is significant potential to expand energy applications. This paper discusses the key energy sector organizations and decision-support tools with the greatest potential to benefit from new applications of satellite remote sensing data, identifies relevant remote sensing data and products with a focus on NASA Earth science resources, and provides examples that show the added value of the Earth observations. These examples come from the application of NASA data to solar energy information needs. Although continued work for support of solar energy is warranted, this paper focuses on areas identified with the greatest demonstrated potential for new or expanded applications: renewable energy (specifically wind, biomass, and hydroelectric resources), load forecasting, and long-term energy modeling. This study also addresses the evolving context of the Global Earth Observation System of Systems (GEOSS), and the broader framework of integrating satellite remote sensing into energy sector decision-support tools.**

I. Introduction

EFFECTIVE management of energy resources is critical for the U.S. economy and environment and, more broadly, for sustainable development and alleviating poverty worldwide. Affordable, reliable, and secure energy supplies for the global community will help address challenges in human health, economic growth and expansion, and preservation of the environment, among other areas. The scope of energy management is broad, including: exploration, production, processing, and transportation of fossil fuel and nuclear energy resources; development and harvesting of renewable energy resources; and generation and distribution of electricity and fuel. Energy management also includes energy use and efficiency; models and forecasting required for effective planning, operation, and regulation of energy resources; assessment of emissions; and mitigation and adaptation to climate change.

Manuscript received nulldate. First published September 30, 2008; current version published nulldate. This work was supported by the NASA Earth Science Applied Sciences program under the Energy Management theme.

E. Zell and J. Engel-Cox are with the Battelle Memorial Institute, Arlington, VA 22201 USA (e-mail: zelle@battelle.org).

R. Eckman is with the Chemistry and Dynamics Branch, Science Directorate, U.S. National Aeronautics and Space Administration, Langley Research Center, Hampton, VA 23681 USA.

P. Stackhouse, Jr. is with the Climate Sciences Branch, Science Directorate, U.S. National Aeronautics and Space Administration, Langley Research Center, Hampton, VA 23681 USA.

Digital Object Identifier 10.1109/JSTARS.2008.2001142

In many of these areas, energy managers and regulators already find value in relying upon satellite remote sensing data for key decisions or analyses, such as the use of climatology data in the prediction of energy demand or, more recently, assessment of solar radiation and wind resources [1]. The geophysical parameters being measured by remote Earth observation sources, and the associated models and analysis systems, are increasing and maturing rapidly. Satellite-based Earth science resources provide unique, objective data that have the additional advantage of yielding global, homogeneous, and repetitive coverage. The demand for more detailed weather and sector-specific information such as wind speed and direction is increasing as energy technologies become more advanced. With the globalization of energy technologies, especially in developing countries, climatological information is needed to fill spatial information gaps and provide globally consistent information for energy project development and operation [2]. To date, there has been much success in the extension of satellite derived estimates of the derivation of solar resources for solar energy applications, and now the International Energy Agency is working to make these resources even more accessible to governments and industry [3]. Beyond solar energy applications, there is significant potential for the energy management sector to benefit from increased extension of satellite remote sensing data and products, as evidenced by targeted examples provided in this paper. Decision-support tools maintained and operated by government, nongovernment, and private energy sector organizations could benefit from new or increased integration with satellite remote sensing data. These tools perform functions ranging from short- and long-term forecasting by electric utilities to assessment of energy policies and regulation strategies by government agencies.

Given the need for innovative, research-focused applications of satellite remote sensing in the energy sector, this paper serves as a case study focusing on the scientific resources of the U.S. National Aeronautics and Space Administration (NASA), a key provider of satellite remote sensing data and products. A similar case study could be prepared focusing on scientific resources of other major space agencies such as the European Space Agency. This paper examines energy management areas with the greatest potential to benefit from new or expanded satellite-based science data products and models. Three major areas of focus were selected [4]:

- renewable energy (specifically wind, biomass, and hydroelectric power);
- load rorecasting;
- long-term energy modeling, and climate change impacts on the energy sector.

For each area, the paper provides a brief introduction of current issues and discusses the key energy sector organizations and decision-support tools with the greatest potential to benefit from new applications of satellite remote sensing data. The paper also identifies relevant remote sensing data and products with a focus on NASA Earth science resources, and provides specific examples of either current value being derived by energy sector organizations from Earth observations or demonstrated potential benefits that can be achieved based on ongoing prototype demonstration projects. The paper concludes with the challenges of integrating satellite remote sensing into energy sector decision-support tools, as being addressed in the development of the Global Earth Observation System of Systems (GEOSS), such as parameterization and postprocessing to translate data to useful information.

II. Application Areas

A. Wind, Biomass, and Hydroelectric Renewable Energy

1) Current Issues: Renewable energy resources are naturally replenishing but flow-limited, including resources such as wind, biomass, hydropower, solar, geothermal, ocean thermal, wave action, and tidal action. Globally, wind energy is one of the fastest growing forms of renewable electricity generation. Wind power provided approximately 44% of total U.S. renewable production in 2006 [5]. Current issues include wind energy forecasting, grid integration of wind energy, improving wind energy technologies for lower wind resource areas, and siting and operation of offshore wind power facilities, particularly in the U.S. Unlike European offshore wind energy sites, many potential U.S. offshore locations are more exposed to severe environmental conditions and will require the application of new information and technologies to be sited in deeper waters with greater wind and wave forces [6].

Of the other significant forms of renewable energy, hydroelectric and biomass are promising for new application of Earth observation datasets. There are approximately 75 000 dams in the U.S., of which 3% are used for hydroelectric power generation [7]. The total U.S. hydroelectric capacity (including pumped storage) is 103.8 GW (8% to 12% of total U.S. electricity generation). World hydroelectric capacity generates approximately 20% of the electricity in the world [8]. Hydroelectric power is a mature energy source and major reservoirs have been completed in the United States. Nevertheless, the operation and relicensing of these facilities require considerable amounts of environmental information. The construction of dams continues worldwide, while developing nations seek new sources of power. Issues such as endangered fish, overallocated water resources, and climate variability also depend on new and better sources of information on water availability and use, which NASA science data products and models may be able to provide.

The development of biomass energy in the U.S. was given a Federal priority through the Biomass Research and Development Act of 2000 [Title III of Public Law (PL) 106224] and the subsequent Energy Policy Act of 2005 (P.L. 109190), which authorized funding and launched Federal initiatives to promote the use of biomass energy sources and biobased products. Biomass energy includes liquid fuels, electricity, and industrial heat/steam derived from plants and plant-derived materials, including wood, food crops, grassy and woody plants, residues from agriculture or forestry, and the organic component of municipal and industrial wastes [9]. Biomass is the only renewable source of liquid fuels, in the form of biodiesel and ethanol. Recent attention has focused on cellulosic ethanol, derived from plants and grasses, as an alternative fuel or octane-boosting, pollution-reducing gasoline additive [10]. Electricity is generated by direct firing biomass or cofiring with fossil fuels to run gas or steam turbines.

In addition to looking independently at different types of renewable energy, there is currently a focus on integration of multiple types of renewable energy into a comprehensive solution to meet energy needs. For example, the integration of wind and hydropower can help improve overall energy system performance. Many renewable energy types such as wind, hydroelectric, and biomass are linked by their dependence on weather and climate conditions and, thus, may benefit from similar datasets.

2) Organizations and Decision-Support Systems: The organizations involved in wind, hydropower, and biomass energy include key Federal and state agencies and organizations; the public, semi-public, and private organizations that run generation facilities and the electrical grid; and nonprofit industry associations.

Government Wind Programs: The U.S. Department of Energy (DOE) is the lead U.S. Federal agency for wind energy. Among DOE's programs focusing on wind power is the Wind and Hydropower Technologies Program, including the Wind Powering America initiative established by DOE in 1999 to dramatically increase the use of wind energy in the U.S. In support of the Wind Powering America initiative, the DOE National Renewable Energy Laboratory (NREL) has developed numerous decision support tools and datasets. For example, NREL developed updated high-resolution wind maps for more than 30 states, based on modeling that maps the wind resource at horizontal resolutions of 1 square kilometer or finer [11]. NREL also developed the Hybrid Optimization Model for Electric Renewables (HOMER), a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems, including distributed generation applications. HOMER is a model for specific distributed energy projects, although NREL has run the system for an entire state as a means of more regional planning [12]. HOMER is used most frequently for modeling of solar energy systems, and is supported by the National Solar Radiation Database.

In addition, governmental, nongovernmental, and interdisciplinary organizations at the regional and state levels in the U.S. are actively investigating the viability of offshore wind power generation. For example, on the U.S. East Coast the Virginia Coastal Energy Research Consortium was created by state law as an interdisciplinary study, research, and information resource for Virginia, with an initial focus on offshore winds, waves, and marine biomass. State utility commissions typically have a role in reviewing and permitting wind generation projects and, thus, are also engaged in this sector.

Private Developers of Wind Facilities: There are numerous private companies involved in the development of wind power facilities on land and offshore. For example, BluewaterWind is a developer of offshore wind energy projects that currently has projects in various stages of development in Delaware, New Jersey, New York, and Rhode Island. Bluewater Wind has proposed a project off the coast of Delaware consisting of 150 turbines that would come online by 2014 to supply Delmarva Power with a renewable energy source [13]. The General Electric Company (GE) is another major player in this field. In March 2006, NREL signed a $27 million contract with GE to develop a new offshore wind power system over the next several years [14]. DOE is providing about $8 million for the project, which will design, fabricate, and test an offshore wind turbine capable of producing power at a cost of five cents per kilowatt-hour. The decision-support systems for private developers focus on the assessment of wind resource availability and economic viability. Such major projects represent potential opportunities for the remote sensing community to engage private developers by providing critical data on wind resources.

Electric Power Research Institute: The Electric Power Research Institute (EPRI), an independent nonprofit center for energy and environmental research, helps member utilities address current issues associated with incorporating increasing amounts of renewable energy into their power systems. For example, with respect to wind power, EPRI has worked with the California Energy Commission on regional and wind plant-specific wind energy forecasting systems that will help utilities coordinate wind resources with other generating options. These systems have produced both same-day and next-day hourly forecasts of wind speed and energy generation for major wind resource areas of California [15].

DOE Hydropower Program: The mission of the DOE Hydropower Program is to research, develop, and promote the technical, societal, and environmental benefits of hydropower, including cost-competitive hydropower technologies to develop new and incremental capacity [16]. The Program's decision-support systems include the Hydropower Evaluation Software to evaluate the environmental impact of hydropower sites, Virtual Hydropower Prospector to locate and assess natural stream water energy resources, and state and national hydropower resource assessment reports.

Hydroelectric Facility Operators: Hydroelectric facilities in the U.S. are operated by both Federal and nonfederal organizations, with the larger dams operated by the Federal government. The Federally-run hydroelectric power plants are operated by agencies with varying degrees of Federal support and authority. For example, the Tennessee Valley Authority (TVA) is a Federal corporation and the largest U.S. public power company; TVA operates 29 dams [17]. The U.S. Army Corps of Engineers (USACE) operates 75 hydroelectric facilities producing one-fourth of the U.S. hydroelectric power [18]. The USACE Institute for Water Resources supports some of the decision-support systems for hydroelectric power, such as the Hydrological Modeling System [19]. As part of their operations, the facilities use temperature, precipitation, stream flow volume, snow pack/runoff, and reservoir height to make decisions in operations. For the U.S. Pacific Northwest, these data are provided by the U.S. National Oceanic and Atmospheric Administration (NOAA) National Weather Service Northwest River Forecast Center [20]. Other regions rely on a combination of data from the National Weather Service and gauges and monitors operated by the organizations running the dams.

Federal Biomass Programs: The Biomass Research and Development Initiative is a partnership among DOE, U.S. Department of Agriculture (USDA), and other U.S. Federal agencies to coordinate and accelerate all Federal biobased products and bioenergy research and development [21]. NREL's Biomass Program focuses on biomass characterization, conversion technologies, product development, and process engineering, as well as biomass in photochemical and environmental applications. NREL is also the lead national laboratory of the National Bioenergy Center, with an emphasis on decreasing the costs of cellulosic ethanol so that it is cost competitive with gasoline produced from petroleum by 2030 [22]. The U.S. Environmental Protection Agency (EPA) Climate Change Division includes a focus on the environmental and cost implications of bioenergy initiatives, and improving the way biofuels are characterized in regional to global models [23].

Independent System Operators (ISOs), Regional Transmission Operators (RTOs), and Electric Utilities: ISOs and RTOs are responsible for coordinating, controlling, and otherwise monitoring the operation of the electrical power system and transmission grid. Some ISOs and RTOs also act as a marketplace of wholesale power, so they are especially interested in complete information on current and future conditions in the service area. One example of an RTO is PJM Interconnection, the world's largest electric grid control system, controlling the electric grid in the Northeast and Mid-Atlantic U.S. PJM is currently facing requirements to accept electricity generated by wind power onto the grid and, therefore, has a need to better anticipate wind generation output on a day-ahead basis. This need is new enough that no major mature decision-support systems are yet available to support wind forecasting.

3) Candidate NASA Science Data Products: The renewable energy field is still developing and, thus, is generally open to the use of new and innovative datasets. NASA datasets have been valuable to the solar and wind energy sectors through the identification of available peak solar and wind resources, most notably the NASA's Surface meteorology and Solar Energy (SSE) prototype website [24], [25]. NASA satellite data have also contributed substantially to the UNEP-maintained Solar and Wind Energy Resource Assessment (SWERA), which provides online high-quality renewable energy resource information at no cost to the user for countries and regions around the world. In addition, data on near-surface offshore wind speed and direction from the SeaWinds sensor on the NASA's Quick Scatterometer (QuickSCAT) platform have been used to analyze offshore winds, for example, off Denmark's coast [26]. Recently, a new algorithm to estimate near-shore winds is being tested using measurements from NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission [27]. NREL wind resource assessment maps may benefit from improved atmosphere modeling data, such as outputs of the NASA Global Modeling and Assimilation Office Atmosphere Model (GMAO) Goddard Earth Observing System (GEOS) assimilations. For bioenergy, NASA science data products related to leaf area index, normalized difference vegetation index, precipitation, and soil moisture have been used in partnership with USDA to assess crops and productivity.

Key general areas where NASA resources are applicable for renewable energy are the identification of the quantity of resources, location for siting generation facilities, forecasting generation outputs, and planning and optimization of production. Potentially relevant remote sensing resources include:

- solar radiation (including various components) and angle;
- meteorology data, specifically wind speed, cloud cover, aerosols, and rainfall;
- surface properties including vegetation, soil type, surface temperatures, soil moisture, and snow cover;
- biomass parameters, such as climate, soil, and vegetation data;
- reservoir height;
- water availability.

TableI lists sensors, models, and analysis packages and prototypes that may serve as a basis for further developing the application of NASA resources to wind, hydroelectric, and biomass renewable energy.

4) Examples Showing Value: Satellite-derived solar energy parameters are currently adding value for energy sector organizations by improving decisions on siting, design, and operation of solar energy facilities. NASA's Surface Meteorology and Solar Energy (SSE) prototype website [28] contains approximately 200 satellite-based and model analysis derived meteorology and solar energy parameters, both directly as data sets and charts, and as input to decision-support systems. Since the first release of the SSE in 1997, website hits have grown to about 170 000 per month (peak month was 280 000), for a cumulative total of 7.5 million hits, with 72% of the activity from businesses. An example decision-support system that pulls data directly from SSE is Natural Resources Canada's RETScreen International Clean Energy Project Analysis Software [29]. RETScreen was developed in partnership with many multilateral and government organizations, including NASA. RETScreen is used to evaluate the energy production and savings, life-cycle costs, emission reductions, financial viability and risk for various types of energy efficient and renewable energy technologies for projects worldwide. RETScreen's climate database uses the NASA SSE solar and temperature parameters at every city that does not have surface measurements, providing an estimate of these parameters for every city in the world with a population of greater than 4 permanent residents. RETScreen has approximately 140 000 users in 222 countries. A 2004 study [30] estimated user savings of $600 million from the use of RETScreen software and related tools, and projected user savings of $7.9 billion by 2012.

The benefits of Earth observations for biomass energy are primarily in a demonstration phase. NASA has a long-standing partnership with USDA demonstrating that measurements from Earth observing spacecraft provide valuable information on crop production, yield, and condition. Current work with the USDA National Agricultural Statistics Service and Foreign Agricultural Service (USDA-FAS) focuses on global and domestic crop assessments to assist end users in making decisions on planting, harvesting, marketing, commodity export and pricing, drought monitoring, and food assistance [31].

The potential benefits of Earth observations for forecasting offshore wind energy are highlighted by a study for the New York State Energy Research and Development Authority on the value of an improved wind forecast [32]. The purpose of the study was to produce empirical information to assist the New York Independent System Operator (NYISO) in evaluating the reliability implications of increased wind generation, given the variability of wind-generated electricity output. An hourly production simulation analysis was performed to examine the impact of 330 MW wind generation on overall operation of the NYISO grid. An hourly analysis of load and wind was carried out for 2001 to 2003, including production cost simulation. The value of forecast accuracy showed that the system variable cost reduction is $25 million for using a perfect wind forecast (backcast) compared to a state-of-the-art wind forecast. Satellite-derived information on wind speed and direction along with meteorological models have the potential to assist with wind forecasting. The NASA SeaWinds sensor provides sea surface winds over the open ocean and the CALIPSO instrument shows potential for doing the same, but even closer to shore. Together, these measurements are important for establishing wind resources in the open ocean, and ultimately forecasting offshore wind resources.

B. Load Forecasting

1) Current Issues: The energy sector uses short-term (1 h to 2 weeks) load forecasting models to adjust electricity generation to meet demand and to optimize generation and purchase of lower cost power sources. Several basic load models exist, one of the most common types being artificial neural network models. Statistical regression models are also used to estimate load. A major current issue with load forecasting models is that they are not as accurate as desired by utilities, as indicated by utilities utilizing both in-house and privately developed load forecasting tools [33]. Certain weather events, such as fronts stalled over a utility's service area, variations in cloud cover, and regions with microclimates (e.g., the San Francisco Bay area) have proved particularly challenging for load forecasters. The shortcomings of load forecasts are often the result of coarse resolution or limited point source weather data that do not capture local-scale weather events.

2) Organizations and Decision-Support Systems: A variety of nonprofit organizations, government entities, consulting companies, electric utilities, and transmission system operators participate in the load forecasting arena. The role of each of these stakeholders along with the relevant decision-support systems are discussed in this section.

Electric Power Research Institute: EPRI was heavily involved in short-term load forecasting in the 1980s and 1990s, although this work has since been greatly reduced due to an unbundling of EPRI's services. More recently, EPRI has supported two major load models for forecasting, an older model called the Hourly Electric Load Model (HELM) and a newer model called the Artificial Neural Network Short-Term Load Forecaster (ANNSTLF). ANNSTLF forecasts hourly system loads from 1 h to 35 days ahead with errors less than 3% based on historical load and temperature forecasts [34]. The temperature forecasts used by ANNSTLF are based on ten-day NOAA National Weather Service predictions, and sometimes on commercial weather provider forecasts [35].

TABLE I
CANDIDATE DATA PRODUCTS FOR RENEWABLE ENERGY IN WIND, HYDOELECTRIC, AND BIOMASS

Commercial Vendors, Electric Utilities, and Gas Companies: For short-term load forecasting, a majority of electric utilities rely on some combination of their own in-house forecasters and commercial vendors [36]. Load forecasting tools predict future load based on the inputs of historical load and meteorological data, and forecast weather, primarily from ground-based weather stations at airports. The actual weather data input into models often comes from a private value-added weather provider that enhances or reprocesses government-generated weather information. Commercial vendors such as New Energy Associates have developed sophisticated neural networks to predict system load. For example, New Energy's NOSTRADAMUS is neural network-based, short-term demand and price forecasting system, used by electric and gas utilities, system operators and power pools, electric cooperatives, energy marketers, and gas pipelines. The electric utilities and commercial vendors also perform some medium-term forecasting (i.e., roughly six months to one year) through examination of a combination of financial information, past weather trends, and similar days to predict loads.

Independent System Operators (ISOs) and Regional Transmission Operators (RTOs): As discussed previously, ISOs and RTOs are responsible for coordinating, controlling, and otherwise monitoring the operation of the electrical power system and transmission grid, and may also act as a marketplace of wholesale power. ISOs and RTOs produce their own load forecasts for 1 to 14 days for state to regional service areas. The sophistication of ISOs and RTOs in their load forecasts varies, with some relying on commercial vendors and others developing in-house models that incorporate historical load, historical temperature, and forecast weather conditions [37]. Given that weather conditions and forecasts are limited to ground-based stations (often airports), there is a potential for satellite remote sensing data to help fill gaps and improve load forecasting performance.

3) Candidate NASA Science Data Products: Historical and predicted meteorological information is central to load forecasting. Such information can be enhanced by satellite remote sensing information through organizations such as the NASA Marshall Space Flight Center Short-term Prediction Research and Transition (SPoRT) Center, which infuses Earth Science observations, data assimilation, and modeling research into NOAA National Weather Service forecast operations and decision-making at the regional and local levels.

Beyond these specific integrated services, the general remote sensing parameters and models that may be useful for load forecasting include:

- meteorology data, including atmospheric temperature, cloud cover, and visibility;
- surface properties including vegetation, soil type, surface temperatures, soil moisture, and snow cover;
- solar radiation (and related quantities)
- seasonal climatology models.

TableII lists sensors, models, and analysis packages and prototypes that may serve as a basis for further developing the application of NASA resources to load forecasting.

4) Examples Showing Value: The application of NASA Earth observations and model outputs to improve meteorological information for load forecasting is relatively new. Studies have documented the potential benefits of improving weather forecasts. For example, U.S. electricity generators save $166 million per year by using 24-h temperature forecasts to improve the mix of generating units available to meet demand. The incremental benefit of improving forecast accuracy is estimated to be about $1.4 million per percentage point of improvement per year. For a 1°C improvement in accuracy, the benefit is about $59 million per year [38]. NASA is currently pursuing a project to identify and quantify the benefits of incorporating NASA Earth observations and model outputs into load forecast models. This project will seek to improve the accuracy of the load forecasted by NewEnergy Nostradamus, and transfer this capability for broader application. Nostradamus is flexible enough to accept high-resolution satellite or weather forecast model data and parameters available from NASA resources. The results of the project, expected to continue through 2010, will be identification of the regions, parameters, seasons, and other variables that affect the value that can be derived from Earth observations for load forecasting. Preliminary work on this project focused on gas utility forecasting indicates there is a potential for load forecasting accuracy improvement by using NASA data to improve the spatial resolution and consistency of weather inputs. The improvements to the load forecasts appear to be in the timeframe of greatest need, during peak consumption.

C. Long-Term Energy Modeling and Climate Change Impacts on the Energy Sector

1) Current Issues: Long-term modeling includes everything from planning by utilities for developing and managing production over a 1- to 30-year period, to scenario analyses by governments and international organizations for setting regional and national energy policies on long-term timescales (10 to 50 or more years). Utilities use inputs such as historical and projected loads, meteorological and climate data, available energy sources, resource availability, environmental impacts, and economic data for long-term modeling and planning. Due to changes in the structure of the electricity industry, in recent years electric utilities have had a reduced focus on justifying long-term demand to state commissions in order to receive project approval. Instead, the focus has shifted to economic/business analysis of potential projects by electric utilities and investors, which includes consideration of resource availability, prices, and demand, among other factors.

Scenario analyses by governments and international organizations often involve integrated assessment models, which link individual models by bringing together a broad set of areas, methods, styles of study, or degrees of certainty. Such models can contain somewhat arbitrary assumptions about the range of future conditions, and could benefit from more direct use of satellite data and modeled products.

A related aspect of long-term energy modeling is the impact of climate change on energy management. This impact has re-

TABLE II
CANDIDATE DATA PRODUCTS TO ENHANCE MEDIUM-TERM ENERGY FORECASTING TOOLS AND SERVICES

TABLE III A
CANDIDATE DATA PRODUCTS FOR LONG-TERM CLIMATE MODELING

TABLE III B
CANDIDATE DATA PRODUCTS FOR LONG-TERM CLIMATE MODELING

ceived little attention in current energy models. Government policymakers and electric utility planners are interested in climate change information on a variety of different scales. The most relevant information for electric utility planners is the regional and temporal allocation of climate change rather than information on overall, long-term global trends. Changes in climatology, which form the basis for system design and contingency planning, could have a variety of impacts on the energy sector, including:

- changes in wind speed and wind patterns relevant to wind power;
- changes in precipitation patterns impacting water supply available for hydroelectric power generation;
- changes in cooling water availability for thermal power plants;
- changes in biomass location and quantity impacting biomass power generation and carbon sequestration;
- changes in percent cloud cover relevant to solar energy generation;
- changes in demand for energy for cooling, air conditioning, and heating, depending on the expected temperature changes for a particular location;
- increased storm frequency and intensity or wildfires that could lead to increased disruptions in power production and transmission;
- sea-level change that could impact coastal refineries and production facilities.

2) Organizations and Decision-Support Systems: A variety of government agencies, nonprofit organizations, and private companies conduct long-term energy modeling to meet their own or support others' specific decision-making needs. Historically, a number of DOE national laboratories along with EPRI and other groups produced energy forecasts. The DOE Energy Information Administration (EIA) is a major player in this area since it develops and maintains a number of related long-term energy models. However, due to a number of factors including deregulation in some U.S. states, many of these forecasts are no longer produced, leaving the EIA models and publications as important sources that feed into multiple models and decision-support tools [39]. Other organizations involved include individual electric utilities, commercial vendors, DOE's Pacific Northwest National Laboratory (PNNL), and the International Energy Agency (IEA).

Commercial Vendors and Electric Utilities: Similar to load forecasting, electric utilities rely on some combination of their own in-house staff and commercial vendors for long-term planning. In general, planning by utilities assumes that the future climate will be the same as the past. Utility planners have expressed a need for relevant decision-support systems and data for treating climate variability, where, for example, certain regions do not experience weather as cold as they did 40 years ago [40]. In August 2007, the Tennessee Valley Authority had to suspend operation of one unit at its Browns Ferry nuclear plant in Alabama because the Tennessee River was too warm to provide adequate unit cooling [41]. Events such as this highlight the need for utilities to consider longer-term scenarios of climate change such as those from NASA models, but scaled down to a regional or local level.

Energy Information Administration (EIA): The EIA is an independent statistical agency of the DOE. The EIA provides policy-independent data, forecasts, and analyses to promote sound policymaking, efficient markets, and public understanding regarding energy and its interaction with the economy and the environment. One of the major tools that EIA uses for its forecasts is the National Energy Modeling System (NEMS) [42].

NEMS is a computer-based, energy-economy modeling system of U.S. energy markets for the mid-term period through 2025 used by EIA to project the energy, economic, environmental, and security impacts on the U.S. of alternative energy policies and different assumptions about energy markets. The model includes supply, conversion, demand, and integrating modules [43]. The model achieves a supply/demand balance in the end-use demand regions by solving for the prices of each energy product that will balance the quantities producers are willing to supply with the quantities consumers wish to consume. NEMS relies on input data such as economic information and historical environmental information from a variety of sources. For example, the National Solar Radiation Database (NSRDM) is incorporated into the renewable energy portion of NEMS. NASA is partnering with NREL to provide assessment and supplemental information for NSRDB. However, NEMS does not incorporate current or projected (modeled) environmental data.

Pacific Northwest National Laboratory (PNNL): PNNL, a DOE national laboratory, has developed two related integrated assessment models: MiniCAM (Mini Climate Assessment Model) and SGM (Second Generation Model). The MiniCAM has been used for a wide range of studies of strategies to stabilize atmospheric concentrations, focusing on the role of technologies, such as simulations for the U.S Climate Change Technology Program. The SGM is one of several process-based models that are used for focused studies. The SGM is a computable general equilibrium model with energy technology detail that is used for analysis of climate policies over the next several decades. NASA solar data and ocean wind parameters have been used to provide a background climatology for these simulations.

3) Candidate NASA Science Data Products: With climate change uncertainty and rapidly growing energy needs, the need for better and more relevant data for long-term energy models is significant. However, the task of integrating climate change information must account for the uncertainty in both climate change models and the other complex sets of assumptions and calculations that are part of long-term energy modeling. Because of its leadership in the development of climate models and the integration of datasets in these areas, NASA is a potentially important source of information for long-term modeling. For example, energy resource modelers at PNNL and beyond have identified specific areas for which more direct use of satellite data could replace current assumptions such as wind variance, particularly over coastal areas. In addition, the scale of NASA science data products and model outputs is important. NASA is currently involved in downscaling global climate change models to assess regional climate change variability, a scale that is critical for local and regional decision-makers. For example, the NASA Goddard Institute for Space Studies is working on downscaled global circulation model predictions, which can be used to inform decision-making for energy load forecasting.

The general remote sensing parameters and models that may be useful for long-term modeling are as follows:

- meteorology data;
- climate models;
- renewable energy resources, such as solar radiation and wind sources, and expected changes to those resources due to long-term climate changes;
- general circulation models and other climate models.

Tables III A and B list sensors, models, and analysis packages and prototypes that may serve as a basis for further developing the application of NASA resources to long-term energy modeling.

4) Examples Showing Value: Earth observations and model outputs are currently helping energy sector stakeholders address potential impacts from climate change by supporting deployment of clean energy technologies. For example, a 2004 study [44] estimated that RETScreen is contributing to the deployment of $1.8 billion worth of clean energy technologies worldwide, and helping stakeholders take action to reduce greenhouse gas emissions in the order of 630 kilotons CO_2/yr to-date and a projected 20 Megatons CO_2/yr by 2012. Further examples will be forthcoming as NASA is engaged with NREL and NOAA on seasonal weather prediction, and with additional partners on climate and long-term market prediction.

III. Discussion and Conclusion

The potential for satellite remote sensing to contribute to energy management hinges on an appropriate framework. This case study highlights the need for increased collaboration between satellite remote sensing organizations and the energy sector, and prototyping of projects to establish specific parameter requirements and postprocessing needs.

The involvement of energy sector organizations at an early stage in satellite product development would allow energy sector decision makers to guide the development and availability of satellite sensor data and models that would be most useful for their own decision needs. Further, it would be beneficial to form partnerships between satellite sensor scientists and energy management organizations at an early stage in the development or enhancement of energy decision-support systems, so they can be based on integration of current or future satellite remote sensing data products. The need for early partnerships and development of prototype projects was also echoed by a preliminary engagement of interested parties and potential stakeholders at a breakout session on Earth Observation Systems and Energy Programs at the National Council for Science and the Environment's national conference [45]. In the case of solar energy, the involvement of dedicated grassroots stakeholders in the solar energy field and a focused national laboratory significantly improved the availability and usability of NASA data relevant to solar energy. This stakeholder-driven model should be applied to wind energy and other renewable and distributed energy applications. For more centralized initiatives, such as Federally run hydroelectric facilities and long-term energy modeling, NASA working with a core set of existing partners, specifically the USACE and DOE (EIA, NREL, and other national laboratories), would be the most effective means to bring satellite remote sensing resources to the energy sector.

A key aspect of integrating satellite remote sensing data and model outputs into energy sector decision-support tools is translating it into useful information from the perspective of the user. In some cases, processed information from a single sensor or combination of sensors may be most useful to energy stakeholders. However, sensors do not always provide the required temporal and spatial averaging, and, therefore, the output of models may be a more appropriate finished product for energy stakeholder use. Climatological datasets are frequently used as a proxy to estimate the likelihood of future events. Thus, the use of deterministic seasonal prediction models may also be useful. By establishing partnerships early on between satellite scientists and energy sector stakeholders, these important issues can be addressed so that there is a data user pull rather than a producer push of the Earth observation data.

The importance of Earth monitoring information for the energy sector is particularly timely given the evolving development of the Global Earth Observation System of Systems (GEOSS). The GEOSS 10-year implementation plan [46] defines the purpose of GEOSS to achieve comprehensive, coordinated and sustained observations of the Earth system and identifies nine societal benefit areas including improving the management of energy resources. A GEOSS Energy Strategic Plan is currently under preparation. Renewable energy is included under the GEOSS societal benefit area to better monitor and manage energy resources and is included in the GEOSS ten-year implementation plan and supporting documents, specifically understanding and optimizing renewable energy potential (development, siting, and incorporation into the electrical grid) [47], [48]. Likewise, the U.S. components of GEOSS, the United States Group on Earth Observations [49] (USGEO) defines nine societal benefit areas including monitoring and managing energy resources, with a focus on improved Earth observations to optimize decision-making, provide and protect energy supply, and protect the environment and human health [50].

Improved load forecasting through use of integrated remote sensing data will help GEOSS and USGEO achieve the societal benefit to improve management of energy resources. Similarly, improved long-term forecasting will address the GEOSS societal benefit of improving management of energy resources, specifically better energy planning, adaptation to climate variability, and reduction of risk to energy infrastructure due to climate change. The wind and solar energy sectors are examples of those already benefiting from satellite remote sensing data and products, and there are many other opportunities for potential applications in the energy sector. Our research indicates that load forecasting, long-term energy modeling, and renewable energy (particularly wind, biomass, and hydroelectric energy) are areas with the greatest demonstrated potential to benefit from new applications of satellite remote sensing data and products. Connecting satellite remote sensing data to energy sector (and broader societal) needs will increase in importance given the evolving context of GEOSS. The potential partnerships suggested in this study should be reinforced through the development and support of prototype energy sector projects. By establishing these partnerships and developing a process and projects to maintain and build upon them, satellite remote sensing data providers and the energy sector can work synergistically to improve decision-support systems, providing benefits to energy sector stakeholders and society as a whole. The critical ingredient for success is the involvement of champions from both the satellite remote sensing community and the relevant energy sector.

ACKNOWLEDGMENT

The authors would like to thank the participants of the NASA Energy Management Program Stakeholder Workshop, who provided valuable insights into the current issues faced by the energy industry and potential opportunities for satellite remote sensing contributions (NASA Energy Management Program Stakeholder Workshop, March 29, 2007, Battelle Arlington Office, 2101 Wilson Blvd, Suite 800, Arlington, VA).

REFERENCES

[1] C. H. Whitlock, P. W. Stackhouse, W. S. Chandler, J. M. Hoell, and T. Zhang, "Renewable energy applications from NASA satellite analysis and modeling," in *13th Conf. Amer. Meteorological Soc. Satellite Meteorology and Oceanography* , Norfolk, VA, Sep. 1317, 2004.

[2] P. W. Stackhouse, Jr., C. H. Whitlock, R. C. DiPasquale, D. E. Brown, II, and W. S. Chandler, "Meeting energy-sector needs with NASA climate datasets," *Earth Observ. Mag.*, vol. 11, no. 8, Aug. 2002.

[3] P. W. Stackhouse, Jr., D. Renn, H.-G. Beyer, L. Wald, R. Meyer, M. Schroedter-Homscheidt, R. Perez, and M. Suri, "Towards designing an integrated earth observation system for the provision of solar energy resource and assessment," presented at the IEEE Int. Geoscience and Remote Sensing Symp., Geoscience and Remote Sensing, Aug. 2006.

[4] E. Zell and J. Engel-Cox, "National aeronautics and space administration earth science research for energy management," Part 1: Overview of Energy Issues and an Assessment of the Potential for Application of NASA Earth Science Research, 2005 [Online]. Available: http://aiwg.gsfc.nasa.gov/esappdocs/evalreports/NASAEnergy.pdf, Revision 2, Revised Oct. 24

[5] *Energy Information Administration, Monthly Energy Review Table 10.1*, , Oct. 2006 [Online]. Available: http://www.eia.doe.gov/emeu/mer/pdf/pages/sec10_3.pdf

[6] "U.S. department of energyEnergy efficiency and renewable energy offshore wind turbine technology," Wind and Hydropower Technologies Program, Jan. 2007 [Online]. Available: http://www1.eere.energy.gov/windandhydro/printable_versions/wind_offshore.html

[7] W. L. Graf, "Dam nation: A geographic census of American dams and their large-scale hydrologic impacts," *Water Resources Res.*, vol. 35, pp. 1305–1311, Apr. 1999.

[8] *Hydro Facts, National Hydropower Association*, Nov. 2, 2005 [Online]. Available: http://www.hydro.org/hydrofacts/facts.asp

[9] *Biomass Energy Basics, Learning about Renewable Energy and Energy Efficiency*, Nov. 15, 2005 [Online]. Available: http://www.nrel.gov/learning/re_biomass.html, National Renewable Energy Laboratory

[10] *Biomass Program, Energy Efficiency and Renewable Energy*, Nov. 15,, 2005, [Online]. Available: http://www.eere.energy.gov/biomass/, U.S. Department of Energy

[11] Elliot and Dennis, "National renewable energy laboratory, environment Ohio," Statement on Ohio's Wind Energy Resources Oct. 8, 2007 [Online]. Available: http://www.environmentohio.org/energy/ohios-wind-energy-future/statement-on-ohios-wind-energy-resources

[12] Dec. 9, 2005, Personal Communication (J. Engel-Cox, Battelle, and P. Lilienthal, Senior Economist, International Programs, National Renewable Energy Laboratory).

[13] *Bluewater Wind*, Oct. 2, 2007 [Online]. Available: http://www.bluewaterwind.com/delaware.htm, Current Projects, Delaware

[14] *DOE to Develop Offshore Wind Turbine with General Electric*, U.S. Department of Energy, EERE News (March 9, 2006), Jan. 2007 [Online]. Available: http://www.eere.energy.gov/news/news_detail.cfm/news_id=9823?print

[15] J. Douglas, "Renewable: A promising coalition of many," *Elect. Power Res. Inst. J.,* Summer 2007, Electric Power Res. Inst.

[16] *Hydropower*, Nov. 23, 2005 [Online]. Available: http://hydropower.id.doe.gov/, Idaho Nat. Lab.

[17] Nov. 23, 2005 [Online]. Available: http://www.tva.gov/, Tennessee Valley Authority

[18] USACE, Services for the Public Nov. 23, 2005 [Online]. Available: http://www.usace.army.mil/public.html

[19] HEC-HMS, Hydrologic Modeling System Nov. 23, 2005 [Online]. Available: http://www.hec.usace.army.mil/software/hec-hms/hechms-hechms.html

[20] NOAA National Weather Service Northwest River Forecast Center Nov. 23, 2005 [Online]. Available: http://www.nwrfc.noaa.gov/

[21] Biomass Research and Development Initiative Jul. 27, 2005 [Online]. Available: http://www.bioproducts-bioenergy.gov/

[22] NREL's Biomass Research Fuels National Energy Dialogue Sep. 24, 2007 [Online]. Available: http://www.nrel.gov/features/01-07_biomass.html

[23] in *NASA Energy Management Stakeholder Workshop Summary Rep.*, Arlington, VA, Mar. 29, 2007.

[24] Surface Meteorology and Solar Energy Database Jul. 27, 2005 [Online]. Available: http://eosweb.larc.nasa.gov/sse/, Release 5.1

[25] W. S. Chandler, C. H. Whitlock, and P. W. Stackhouse, Jr., "NASA climatological data for renewable energy assessment," *J. Solar Energy Eng.*, vol. 126, no. 3, pp. 945–949, 2004.

[26] Y. Hu, K. Stamnes, M. Vaughan, J. Pelon, C. Weimer, D. Wu, M. Cisewski, W. Sun, P. Yang, B. Lin, A. Omar, D. Flitler, C. Hostetler, C. Tretle, D. Winker, G. Gibson, and M. Santa-Maria, "Sea surface wind speed estimation from space-based lidar measurements," *Atmos. Chem. Phys. Discuss.*, vol. 8, pp. 2771–2793, 2008.

[27] C. B. Hasager, P. Astrup, P. Nielsen, M. B. Christiansen, and M. Nielsen, "Satellite ocean surface winds in offshore wind engineering," *Geophys. Res. Abstr.* vol. 9, 2007 [Online]. Available: http://www.cosis.net/abstracts/EGU2007/01605/EGU2007-J-01605.pdf, 01605

[28] Surface Meteorology and Solar Energy database Jul. 27, 2005 [Online]. Available: http://eosweb.larc.nasa.gov/sse/, Release 5.1

[29] *RETScreen Int.*, Feb. 19, 2008 [Online]. Available: http://www.retscreen.net/

[30] "Natural resources Canada," RETScreen International: Results and Impacts 19962012, Created December 15, 2004, Updated October 29, 2007, Feb. 19, 2008 [Online]. Available: http://www.retscreen.net/ang/impact.php

[31] "Agricultural efficiency program element FY 20052009 plan," NASA Science Mission Directorate, Earth-Sun System Applied Sciences Program Mar. 15, 2005, Version 1.2.

[32] The Effects of Integrating Wind Power on Transmission System Planning Reliability and Operations Report Phase 2 New York State Energy Research and Development Authority, Mar. 2005 [Online]. Available: http://www.nyserda.org/publications/wind_integration_report.pdf

[33] in *NASA Energy Management Stakeholder Workshop Summary Rep.*, Arlington, VA, Mar. 29, 2007.

[34] Artificial Neural Network Short-Term Load Forecaster (ANNSTLF), Fact Sheet, EPRI Aug. 2, 2005 [Online]. Available: http://www.epriweb.com/public/000000000001011532.pdf

[35] Nov. 10, 2005, Personal Communication (E. Zell, Battelle, and V. Niemeyer, Electric Power Res. Inst.).

[36] EPRI Solutions Nov. 10, 2005, Personal Communication (E. Zell, Battelle, and I. Rohmund).

[37] in *NASA Energy Management Stakeholder Workshop Summary Rep.*, Arlington, VA, Mar. 29, 2007.

[38] T. Teisberg, R. Weiher, and A. Khotanzad, "The economic value of temperature forecasts in electricity generation," *Bull. Amer. Meteorol. Soc.* pp. 1765–71, Dec. 2005.

[39] EPRI Solutions Nov. 10, 2005, Personal Communication (E. Zell, Battelle, and I. Rohmund).

[40] in *NASA Energy Management Stakeholder Workshop Summary Rep.*, Arlington, VA, Mar. 29, 2007.

[41] J. Reeves, *Hot Weather Forces Partial Shutdown of TVA Nuclear Plant, Common Dreams News Center*. New York: Associated Press, Oct. 8, 2007 [Online]. Available: http://www.commondreams.org/archive/2007/08/18/3255/

[42] Energy Information Administration, The National Energy Modeling System: An Overview 2003 Aug. 1, 2005 [Online]. Available: http://www.eia.doe.gov/oiaf/aeo/overview/index.html

[43] Energy Information Administration, The National Energy Modeling System: An Overview 2003 Nov. 21, 2005 [Online]. Available: http://www.eia.doe.gov/oiaf/aeo/overview/figure_2.html

[44] "Natural resources Canada," RETScreen International: Results and Impacts 19962012, Created December 15, 2004, Updated October 29, 2007 Feb. 19, 2008 [Online]. Available: http://www.retscreen.net/ang/impact.php

[45] "Energy for a sustainable and secure future," in *6th Nat. Conf. National Council Science and the Environment*, Washington, DC, Jan. 2006.

[46] "Global earth observation system of systems," GEOSS Feb. 2005, 10-year Implementation Plan, Group of Earth Observations, GEO 1000.

[47] "Global earth observation system of systems," GEOSS Feb. 2005, 10-year Implementation Plan, Group on Earth Observations, GEO 1000.

[48] "Global earth observation system of systems," GEOSS Feb. 2005, 10-year Implementation Plan Reference Document, Group on Earth Observations, GEO 1000R.

[49] U.S. Group on Earth Observations Jul. 13, 2005 [Online]. Available: http://iwgeo.ssc.nasa.gov/

[50] *Monitoring and Managing Energy Resources Technical Reference Document*, , Nov. 8, 2004 [Online]. Available: http://iwgeo.ssc.nasa.gov/docs/review/Energy_Technical.pdf

Erica Zell received the B.S. degree in environmental engineering from Northwestern University, Evanston, IL, in 1996, and the M.S. degree in environmental engineering from the University of California, Berkeley, in 1997.

She has ten years of experience performing environmental work in the regulatory, assessment, and research arenas, both domestically and internationally. Her areas of specialization include analysis of environmental impacts of electric power generation, distributed and renewable energy technologies, air quality policy research, geographic information systems, and regulatory analysis and compliance. She has evaluated satellite remote sensing data applicability for international air quality and energy sector applications, and analyzed the environmental impacts of coal, natural gas, renewable energy generation and transmission, solid waste management in developing countries, mercury in consumer products, and fuel cells. She has served as a project manager and technical lead for U.S. Environmental Protection Agency (EPA) and National Aeronautics and Space Agency (NASA) projects. She worked with Philippine communities and local governments to prepare environmental management plans in the local language as a U.S. Peace Corps volunteer. She also worked at EPA Region 9 where she served as liaison to Arizona's air quality permit program.

Jill Engel-Cox received the B.S. degree in mechanical engineering, energy and fluids block, and the B.A. degree (Plan II Honors Liberal Arts Program) from the University of Texas at Austin in 1989, the M.S. degree in mechanical engineering, environmental focus, Colorado State University, Boulder, in 1993, and the Ph.D. degree in environmental science, University of Maryland, Baltimore County, in 2004.

She has significant experience managing and participating in a broad range of international and domestic projects, with expertise in the application of complex environmental data to public policy. She has worked with the U.S. Environmental Protection Agency (EPA), the U.S. Agency for International Development, the National Aeronautics and Space Administration, the Food and Drug Administration, the National Institute of Environmental Health Sciences, the Department of Energy, United Nations, local regulatory agencies, private industry, and others. Her recent research efforts have focused on the application of scientific data to environmental and policy decisionmaking, including the use of scientific review panels and stakeholder facilitation. She has coauthored two books on pollution prevention and on public communication and authored multiple journal articles and technical reports for government and private industry projects.

Richard Eckman received the B.A. degree in physics and astronomy (cum laude) from the University of Pennsylvania, Philadelphia, in 1980, and the Ph.D. degree in astrophysical, planetary, and atmospheric sciences from University of Colorado, Boulder, in 1985.

He has been involved with both theoretical modeling and interpretation of measurements of trace species in the middle atmosphere and the utilization of NASA observations in the energy sector. He spent two years at Cambridge University, Cambridge, U.K., working with a 2-D middle atmospheric model with emphasis on future trends in stratospheric ozone used by the U.K. Department of Environment for the Montreal Protocol negotiations. He joined the NASA Langley Atmospheric Sciences Division in 1988 where he has been active in several areas of stratospheric research utilizing a state-of-the-art 3-D general circulation/transport model. He has participated in NASA-sponsored model intercomparisons and the Intergovernmental Panel on Climate Change and High Speed Research Program assessments of the atmospheric effects of aviation. His publications include topics in both the stratosphere and mesosphere, and he has presented papers and chaired sessions at national and international conferences. He is the Acting Program Manager of the Energy Management element of NASA's Applied Sciences Program, responsible for advancing NASA Earth observations and model predictions to inform decision support.

Paul Stackhouse, Jr. received the B.S. degree in physics and atmospheric science at Drexel University, Philadelphia, PA, in 1986, and the M.S. and Ph.D. degrees in atmospheric sciences from Colorado State University, Bouler, in 1989 and 1995, respectively.

He is a Senior Research Scientist at NASA's Langley Research Center, Hampton, VA, which he joined in 1997. His expertise lies in atmospheric radiative transfer and remote sensing as specifically applied to problems related to the Earth's surface energy budget. He has served as the lead scientist on several NASA projects including: the NASA/World Climate Research Programme Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget Project, and the Prediction of Worldwide Energy Resource Project that has provided energy sector related data set prototypes and has improved and expanded the Surface Meteorology and Solar Energy Web-based Information System. He is now serving as a Co-Chair on the GEWEX Radiative Flux Assessment team and participates as a team member on an International Energy Agency Task entitled Solar Resource Knowledge Management.