

Managing Variable Energy Resources to Increase Renewable Electricity's Contribution to the Grid

Carnegie Mellon University
Scott Institute
for Energy Innovation

POLICYMAKER GUIDE

Variable Energy Resources, such as wind power, now produce about 3% of U.S. electricity. They can play a significantly expanded role if the U.S. adopts a systems approach that considers affordability, security and reliability. Reaching a 20-30% renewable portfolio standard goal is possible, but not without changes in the management and regulation of the power system, including accurately assessing and preparing for the operational effects of renewable generation.

DEVELOPMENT AND DISSEMINATION OF THIS GUIDE WERE MADE POSSIBLE THROUGH THE GENEROSITY OF THE JESANIS FAMILY.

THE RENEWELEC PROJECT RESEARCH SUMMARIZED IN THIS GUIDE WAS SPONSORED BY THE DORIS DUKE CHARITABLE FOUNDATION, THE RICHARD KING MELLON FOUNDATION, THE U.S. DEPARTMENT OF ENERGY'S NATIONAL ENERGY TECHNOLOGY LABORATORY, THE ELECTRIC POWER RESEARCH INSTITUTE AND THE HEINZ ENDOWMENTS.

CONTENTS

ABOUT THE CARNEGIE MELLON UNIVERSITY

Wilton E. Scott Institute for Energy Innovation

Over the coming decades the world must make fundamental transformations in how energy is used and produced. This will require new science, technology and public policy innovations. That's where we come in.

The Carnegie Mellon University (CMU) Wilton E. Scott Institute for Energy Innovation is addressing several complex challenges:

- How to use and deliver the energy we already have far more **efficiently**
- How to expand the mix of **energy sources** in ways that are clean, reliable, affordable and sustainable
- How to create **innovations** in energy technologies, regulations and policies

Carnegie Mellon University's longstanding **expertise** in technology, policy, integrated systems, and behavioral and social science uniquely suits these challenges. What makes us different is our ability to seamlessly combine these areas for maximum impact.

The purpose of this policymaker guide is to take a systems approach to energy issues—collecting information and research results from throughout Carnegie Mellon University—to provide an up-to-date understanding of energy issues facing today's policymakers.

For more information about the Carnegie Mellon's Scott Institute for Energy Innovation and the research discussed in this guide, visit www.cmu.edu/energy. The institute's directors are Jared L. Cohon, President Emeritus and University Professor, Civil and Environmental Engineering & Engineering and Public Policy, and Andrew J. Gellman, Lord Professor of Chemical Engineering. Deborah D. Stine, Professor of the Practice, Department of Engineering and Public Policy, is the Associate Director for Policy Outreach for the Scott Institute for Energy Innovation. If you have questions about this guide, please contact Dr. Stine at dstine@andrew.cmu.edu.

This policymaker guide was developed by a team led by Jay Apt, Paulina Jaramillo and Deborah D. Stine. Those authoring papers contributing to the guide include researchers from Carnegie Mellon University, the Vermont Law School, the University of Vermont, Van Ness Feldman and the Instituto Superior Técnico who participated in the RenewElec project. These researchers include: Jay Apt, Inês Azevedo, P.M.S. Carvalho, Danielle Changala, Gilbert Cohen, Michael Dworkin, Emily Fertig, Baruch Fischhoff, Iris Grossmann, Mark Handschy, Paul Hines, Eric Hittinger, Enes Hoşgör, David Yaffe, Paulina Jaramillo, Warren Katzenstein, Colleen Lueken, Roger Lueken, Brandon Mauch, Jeremy Michalek, M. Granger Morgan, Robert Nordhaus, David Luke Oates, Scott Peterson, Stephen Rose, Todd Ryan, Kyle Siler-Evans, Mitchell Small, Allison Weiss and Jay Whitacre.

Overview

wind

Solar

variability

OVERVIEW

The purpose of this guide is to provide government and industry policymakers with an understanding of the technical and policy options available for managing variable energy resources such as wind and solar power to produce electricity. The contents of this policymaker guide are based on knowledge gained during Carnegie Mellon University's RenewElec (short for "renewable electricity") project, which began in 2010.[1]

A significantly expanded role for variable energy resources (VER) is technically possible. But, large scale integration of VERs can be achieved only if the U.S. adopts a systems approach that considers and anticipates the many changes in power system design and operation that will be required to make this possible, while doing so at an affordable price, and with acceptable levels of security and reliability. The RenewElec Project was created as an interdisciplinary project led by Carnegie Mellon University to facilitate dramatic increases in the use of electric generation from variable and intermittent sources of renewable power in a way that:

- Is cost-effective;
- Provides reliable electricity supply with a socially acceptable level of local or large-scale outages;
- Allows a smooth transition in the architecture and operation of the present power system;
- Allows and supports competitive markets with equitable rate structures;
- Is environmentally benign; and
- Is socially equitable.

This guide, based on research conducted as part of the RenewElec project, will describe renewable electricity and provide information on renewable electricity's current and potential contribution to electricity generation and the opportunities and challenges presented by national and state policies.

WHAT IS RENEWABLE ELECTRICITY?

Renewable electricity is generally defined as derived from any energy resource that is replenished in timescales of days to decades. Renewable electricity can be directly derived from the sun, such as thermal, photoelectric and photochemical energy; indirectly from the sun, such as hydroelectric, wind and photosynthetic energy stored in biomass; or from natural processes in the environment, such as geothermal and tidal energy. Renewable power sources generally have lower environmental externalities than conventional power sources, particularly lower emissions of conventional pollutants and greenhouse gases. However, these resources are not entirely free of environmental externalities. Large hydropower reservoirs, for example, are a source of methane emissions that contribute to climate change. The U.S. Environmental Protection Agency (EPA) defines a further subset of renewable power as green power, which consists of resources that do not directly emit greenhouse gas emissions. These green power sources include wind, solar, geothermal and biomass. Figure 1 shows the schematic of the different power source classifications described by the EPA.

U.S. Energy Supply (not to scale)

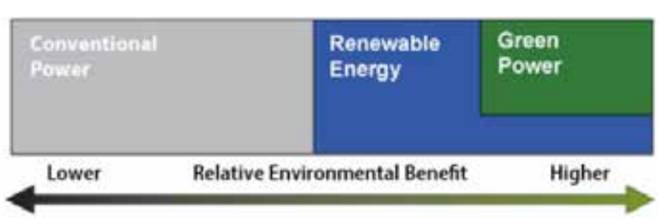


Figure 1: Classification of power sources. Green Power is a subset of renewable energy and represents those renewable resources (solar, wind, biogas, biomass, low-impact hydro and geothermal) that provide the highest environmental benefit.

Source: U.S. Environmental Protection Agency[2]

1 For more information, see www.RenewElec.org

2 www.epa.gov/greenpower/gpmarket

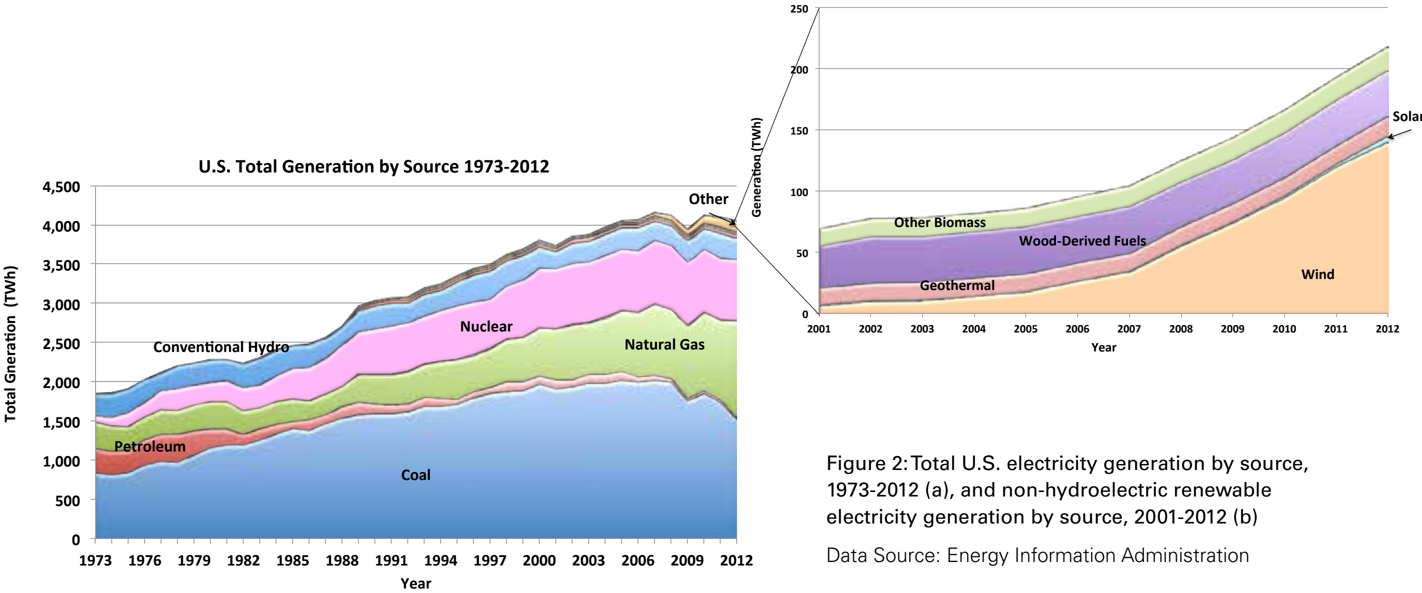


Figure 2: Total U.S. electricity generation by source, 1973-2012 (a), and non-hydroelectric renewable electricity generation by source, 2001-2012 (b)

Data Source: Energy Information Administration

WHAT IS RENEWABLE ELECTRICITY'S PRESENT CONTRIBUTION TO ELECTRICITY GENERATION?

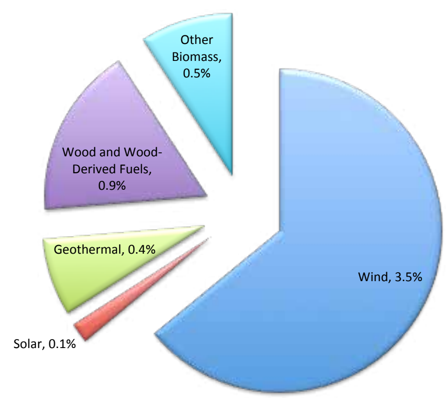


Figure 3: 2012 U.S. Non-Hydro Renewable Generation by source. Values represent the percentage contribution of each resource to total generation.

Data Source: Energy Information Administration

Renewable energy as a source for electricity generation is increasing at a rapid rate. In 2008, renewables, including hydroelectric power, constituted only about 9% of all electricity generation (See Figure 2). By 2012, the share had increased to 12.5%, primarily due to an increase in wind power's contribution (See Figure 3).

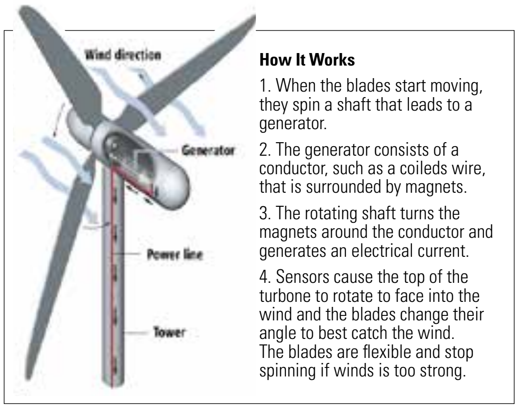
The majority of wood and wood-derived energy is used in combined heat and power generation at pulp and paper processing facilities. These pulp and paper mills using the kraft sulfate pulping process produce black liquor that is used in cogeneration facilities. Mill wood waste is also used both in cogeneration facilities and to co-fire power plants where the majority of the fuel is from coal. There are currently nine U.S. power plants using biomass co-firing. The heat input from biomass co-firing is responsible for a combined total of approximately 70 MW of capacity.[3] Municipal solid waste-to-energy plants and landfill methane are the next largest components of the "other biomass" category. Total capacity of all biomass generation facilities in the U.S. is approximately 11 GW, a bit less than one-quarter of all non-hydroelectric renewable generation capacity, and about 1% of the 1025 GW US generation capacity.[4]

Geothermal power can be competitive in certain locations, and there is potential to extend hydrogeothermal power (where nature supplies the hot water) to enhanced geothermal power, where water is injected into hot underground rock and returned to the surface where it is used to generate electricity. Total capacity of existing U.S. geothermal plants (all hydrogeothermal) is 2.4 GW.[5]

3 Z. Haq, *Biomass for Electricity Generation* Table 1, U.S. Energy Information Administration at www.eia.gov/oiaf/analysispaper/biomass/pdf/biomass.pdf

4 U.S. Energy Information Administration, *Renewable Energy Annual 2009*, Table 1.12, January 2012 at www.eia.gov/renewable/annual/trends/xls/table1_12.xls

5 Ibid.



Turning Wind into Electricity: Wind power is the fastest-growing energy source in the world. Turbines powered by wind are mounted on towers 100 or more feet above the ground, where the wind is faster and less turbulent.

Source: U.S. Department of Energy

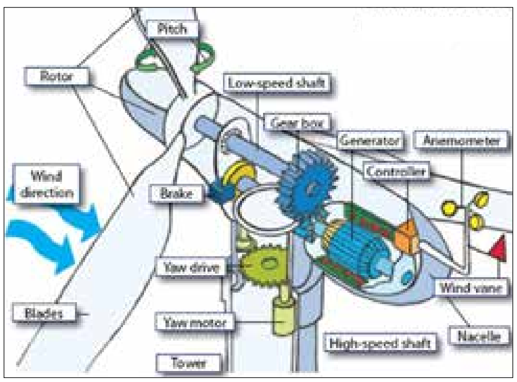


Figure 4: How Does a Wind Turbine Work?

Source: Adapted from Department of Energy at www1.eere.energy.gov/wind/inside_a_wind_turbine.html

While biomass and geothermal power are subject to some variability, both are more constant than wind or solar power. Thus we concentrate our attention here on the issues involved with integration of the latter two sources.

Wind is the lowest cost and most widely available non-hydroelectric renewable resource, so it is expected to continue to dominate the growth in renewable energy. Solar's contribution to the power grid will likely continue to be low compared to wind, but policies currently in place will support some growth. As a result of the inherently variable nature of wind and solar, the growth of these resources may present significant challenges to the operations of the power grid.

Figure 4 shows a schematic of the components of a utility-scale wind turbine. The energy in the wind turns propeller-like blades that are attached to the main shaft, which spins a generator located inside the nacelle (turbine housing) to create electricity. Turbine blades rotate around the horizontal axis. The entire turbine can be rotated along a vertical axis to track changes in wind direction. (Vertical-axis turbines exist, but currently have extremely low market penetration, and none at utility scale.) Once generated, the wind power is transmitted through the electricity transmission grid to consumers.

There are many different mechanisms to convert sunlight into energy. Figure 5(a) provides an illustration of a solar parabolic trough collector, which is the most common type of a concentrated solar power system. In such a system, the receiver tube is positioned along the focal line of each parabola-shaped reflector. The tube is fixed to the mirror structure, and the heated fluid—either a heat-transfer fluid or water/steam—flows through and out of the field of solar mirrors to where it is used to create steam (or, in the case of a water/steam receiver, it is sent directly to the turbine). The largest individual trough systems have the capacity of 80 megawatts.[6] However, individual systems being developed will have capacities of up to 250 megawatts.[7] In addition, individual systems can be co-located in power parks. Their capacity would be constrained only by the transmission capacity of nearby power lines and the availability of contiguous land.

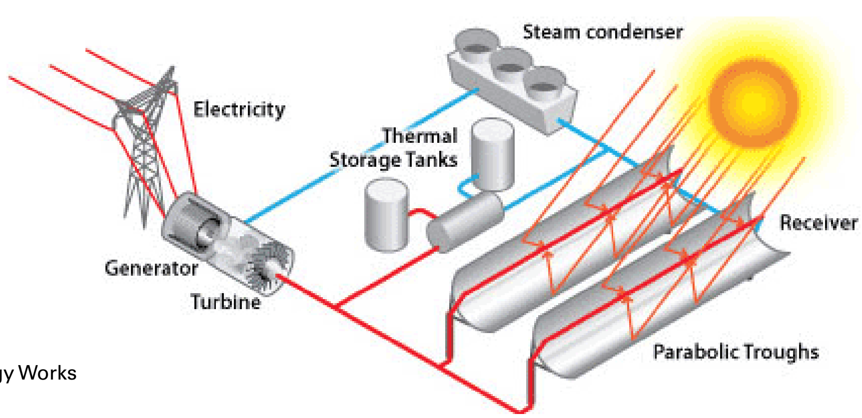


Figure 5a: How Solar Thermal Energy Works

Source: Department of Energy [8]

6 U.S. Department of Energy, *Linear Concentrator Systems for Concentrating Solar Power*, at www.eere.energy.gov/basics/renewable_energy/linear_concentrator.html

7 Ibid.

8 Ibid.

Photovoltaic (PV) systems are also a common technology for generating solar power. PV cells convert sunlight into electricity at the subatomic level. This occurs when the semiconductor materials in the PV cells absorb protons in sunlight and release electrons. PV cells are connected together to form modules, which in turn can be connected to form PV systems able to generate large amounts of electricity. Figure 5b illustrates how a solar photovoltaic system is attached to the grid.

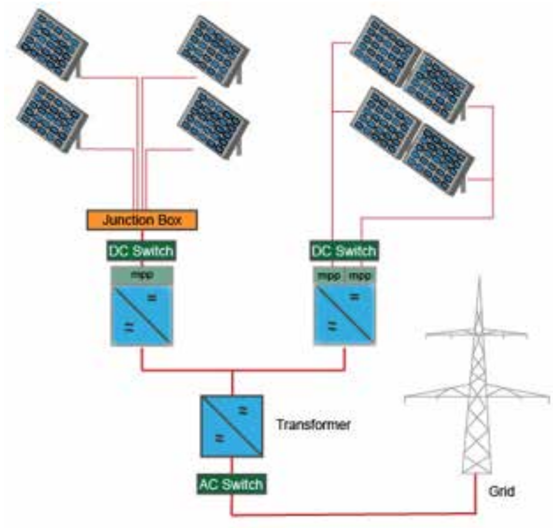


Figure 5b: How Solar Photovoltaic Energy Works

Source: Green Rhino Energgreen[9]

WHY ARE THERE CHALLENGES IN INTEGRATING WIND AND SOLAR POWER INTO THE POWER GRID?

Currently, there are limited opportunities for storing electricity, so that power supply and demand must be matched instantaneously. The existing power system heavily relies on power plants that have a controllable power output. Natural gas plants, for example, can be turned on and off as needed, or their output can be increased or decreased to balance changes in power supply. Wind and solar power are not as controllable as conventional generation resources and they thus present some challenges to the operation of the power grid. The key challenges facing the increased use of wind and solar power are:

- Wind and solar power do not produce a consistent amount of power. As an illustration, Figure 6 shows how hourly renewable electricity production varies over the course of two separate days in California. Changes in power output also occur at shorter time scale. Figure 7 shows the 5-minute variability of wind power output in the Bonneville Power Authority between January 1, 2012 and January 8, 2012.

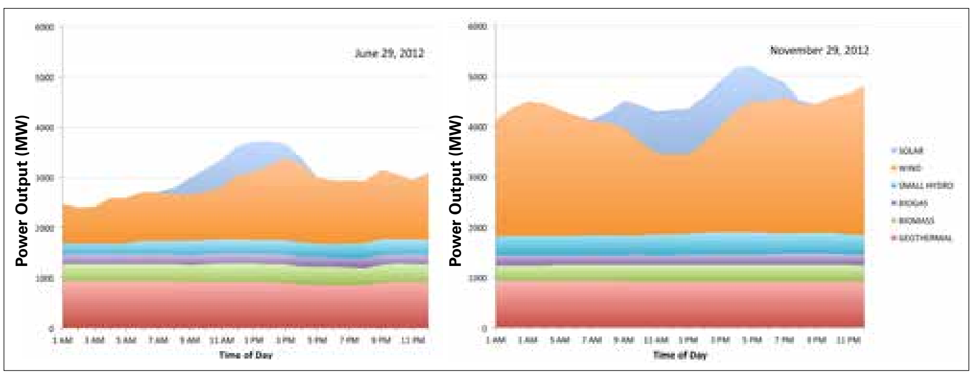


Figure 6: Hourly Renewable Power Output in California for 6/29/2012 and 11/29/2012

Data Source: CAISO -www.caiso.com/market/Pages/ReportsBulletins/DailyRenewablesWatch.aspx

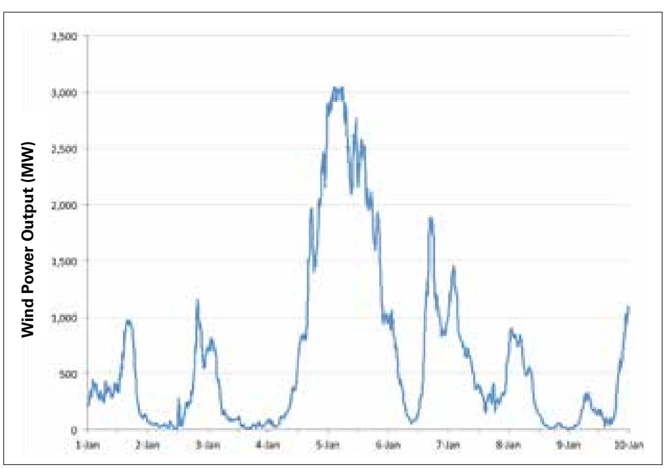


Figure 7: 5-Minute Wind Power Output in BPA, 1/1/2012 to 1/8/2012.

Data Source: BPA - transmission.bpa.gov/Business/Operations/Wind/

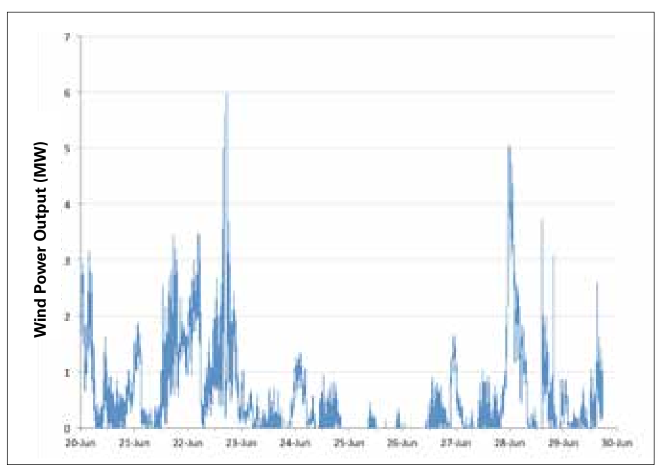


Figure 8: 1-Second Wind Power Output for 10 Days from One Wind Farm.

Source: Apt 2007[10]

9 www.greenrhinoenergy.com/solar/technologies/images/pv_system_blocks-02.jpg

10 J. Apt *The Spectrum Of Power From Wind Turbines*. Journal of Power Sources 2007, 169, 269–374.

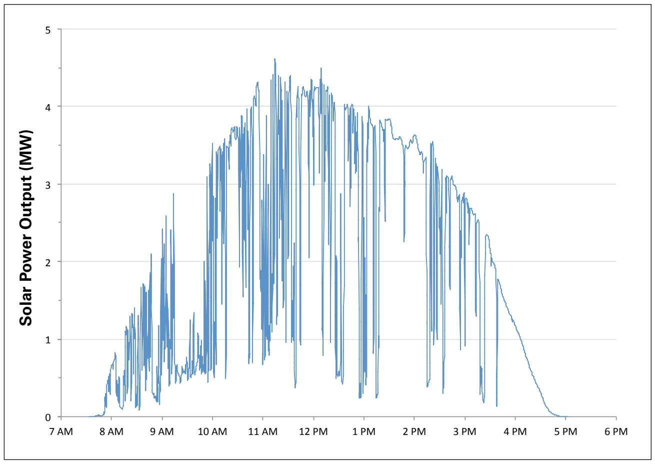


Figure 9: Solar photovoltaic output from a 4.6 MW solar power system in Arizona sampled with 10-second time resolution for the daylight portion of one day.

Source: Apt and Curtright[11]

Figure 8 shows the 1- second variability in power output for 10 days in one wind farm in the Middle Atlantic. Like wind, solar photovoltaic power is variable. Figure 9 shows the output of a large utility-scale solar PV array in Arizona sampled every 10 seconds.

• The sun does not shine at night, and there are cloudy days; there are also days-long lulls in wind power. Just as there are rainy years and drought years for hydroelectricity, preliminary research indicates there will be windier years and calmer years for wind power.

WHAT NATIONAL AND STATE POLICIES ARE IN PLACE THAT INFLUENCE RENEWABLE ELECTRICITY'S CONTRIBUTIONTO THE GRID?

In the United States, three major constituencies have advocated for growth in sources of renewable energy and energy efficiency measures, including an:

1. Environmental constituency worried about fossil fuels' contribution to climate change and pollution,
2. Energy security constituency worried about national security and the need to reduce dependence on foreign fossil fuels, limit demand, and lower cost,[12]
3. Economic vitality constituency that views renewable energy as a source of new jobs.[13]

Two policy changes at the national and state level have led to the rapid increase of renewable energy: renewable portfolio standards (RPSs) at the state level and the federal tax credits. The federal tax includes the production tax credit (PTC) used primarily by wind developers or the investment tax credit (ITC) used primarily by solar developers.

Although there is no U.S. national renewable energy standard, twenty-nine states and the District of Columbia have RPSs requiring that some percentage of their electric power come from sources defined as renewable.[14] The language in the different RPSs can vary significantly, and while some states have a single (primary) standard, some states have several types. Colorado, for example has a primary standard that applies to investor-owned utilities and a secondary standard that applies to electric cooperatives.[15] Similarly, some states have "set-asides" that require that

11 J. Apt and A. Curtright, *The Spectrum of Power from Utility-Scale Wind Farms and Solar Photovoltaic Arrays* Carnegie Mellon Electricity Industry Center Working Paper CEIC-08-04, wpweb2.tepper.cmu.edu/electricity/papers/ceic-08-04.asp.

12 U.S. Department of Defense, *Defense, Interior Department Join Forces on Renewable Energy*, Armed Forces Press Service, August 6, 2012 at www.defense.gov/news/newsarticle.aspx?id=117413
Pew Charitable Trusts, *Energy Innovation Seen as Needed to Reduce Dependence on Foreign Oil, Save Money*, July 24, 2012 at www.pewtrusts.org/news_room_detail.aspx?id=85899407170

13 Long, Jane C.S. *A Blind Man's Guide to Energy Policy*, Issues in Science and Technology, Winter 2008 at www.issues.org/24.2/long.html

14 The Database of State Incentives for Renewable Energy, www.dsireusa.org

15 Also DSIRE: www.dsireusa.org/rpsdata/RPSFieldDefinitionsApril2011.pdf

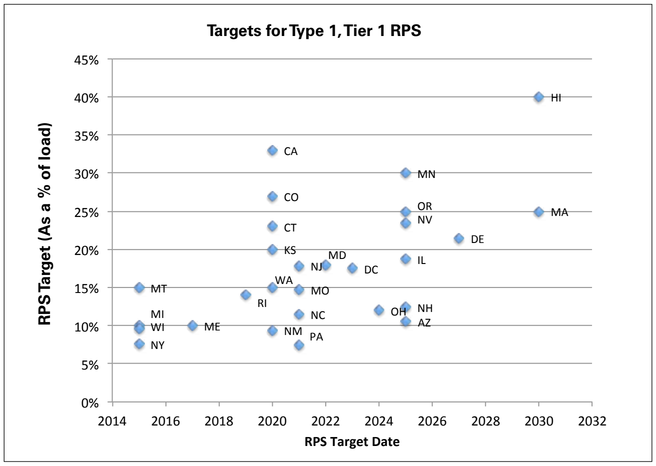


Figure 10a: Primary, Tier 1 RPS targets in the final target year. This figure includes the contribution of all the renewable resources covered in each state's RPS. Data Source: DSIRE[16]

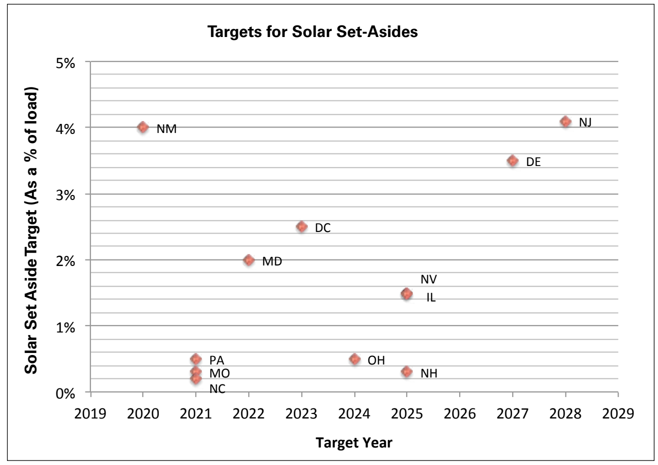


Figure 10b: Primary targets for solar set-asides. Data Source: DSIRE[16]

certain technologies be used to meet a given RPS level.[17] Figure10a shows the primary RPS requirements that apply to large, investor owned utilities, as well as the target year for the final target. Figure 10b shows the targets for solar set-asides. An RPS is not an effective tool without penalties for non-compliance. Figure 11a shows penalties that have been established for primary renewable standards that affect wind development, while figure 11b shows the penalties for not meeting the solar set-asides. The penalties for non-compliance are called Alternative Compliance Payments (ACP). The ACP's rate and the use of the collected funds vary by the state. In Massachusetts, for example, the ACP is paid by "Any Retail Electricity Supplier that is required to comply with the Massachusetts Renewable Energy Portfolio Standard (RPS) and Alternative Energy Portfolio Standard (APS) regulations may, if necessary, discharge some or all of its obligations by making an Alternative Compliance Payment (ACP) in the appropriate amount to the Massachusetts Clean Energy Center (MassCEC)."[18]

The production tax credit (PTC), a per-kilowatt-hour tax credit for electricity generated by qualified energy resources, has been in existence for many years.[19] The wind PTC was first introduced in the Energy Policy Act of 1992 and has expired and been reinstituted several times.[20] Most recently it was extended for one year at the end of 2012. The PTC presently provides a tax credit of 2.2 cents/kWh of wind energy produced during the first 10 years of the wind farms covered, and it thus supports the economic viability of wind energy projects.[21] Figure 12 shows that when the PTC is active, it has a demonstrable effect on incremental wind power installation. The current PTC applies to generation that begins construction by December 2013.[22]

---

16 Pennsylvania has an alternative energy portfolio standard (AEPS), which mandates a percentage of electricity in the state comes from qualified resources. Unlike a renewable portfolio standard, the AEPS allows for the use of resources like waste coal and IGCC coal technology.

17 The DSIRE database characterizes the set-asides as tiers. Tier 1 generally includes large-scale wind development (except in Minnesota where wind is covered in the second tier of their primary requirement to Xcel Energy). Other tiers include set-asides for other renewable energy technologies. Set-asides specify a specific amount of electricity that needs to be generated with as specific technology to support meeting the goals of a given RPS.

18 *Alternative Compliance Payment Rates* at www.mass.gov/eea/energy-utilities-clean-tech/renewable-energy/rps-aps/retail-electric-supplier-compliance/alternative-compliance-payment-rates.html.

19 For an extensive history of the PTC, see www.eia.gov/oiaf/aeo/otheranalysis/aeo_2005analysispapers/prcreg.html

20 See energy.gov/savings/renewable-electricity-production-tax-credit-ptc for a detailed history.

21 DSIRE: dsireusa.org/incentives/incentive.cfm?Incentive_Code=US13F

22 DSIRE: dsireusa.org/incentives/incentive.cfm?Incentive_Code=US13F

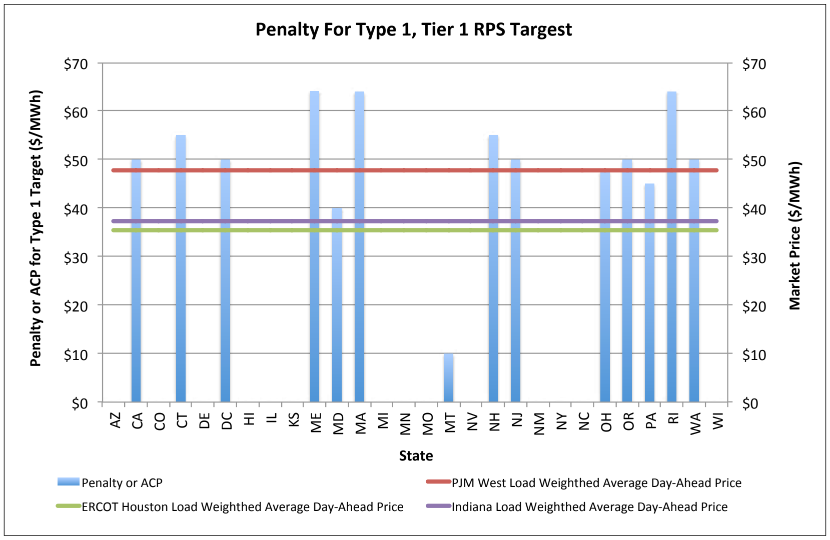


Figure 11a: Wind-related penalties for non-compliance with RPS requirements. The horizontal lines show the load weighted average prices for three major electricity-trading hubs for 2012.

Data Source: DSIRE and Energy Information Administration

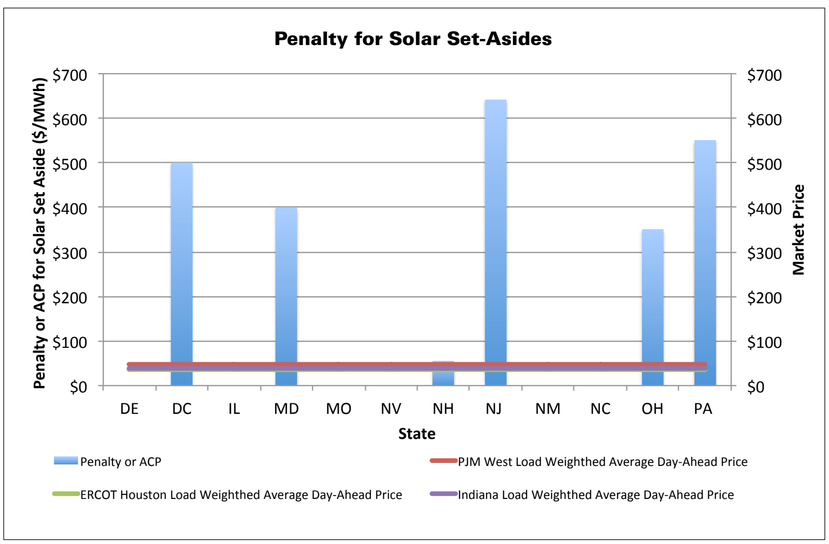


Figure 11b: Solar-related penalties for non-compliance with RPS requirements. The horizontal lines show the load weighted average prices for three major electricity-trading hubs for 2012.

Data Source: DSIRE and Energy Information Administration

The Business Energy Investment Tax Credit (ITC), has been in existence since 1978 with many modifications and extensions.[23] The ITC provides a 30% tax credit for solar, fuel cells, small wind and PTC-eligible technologies and a 10% tax credit for geothermal, microturbines, and combined heat and power generators. The current ITCs are set to expire at the end of 2016.[24] Because solar systems are very capital intensive, it has generally been more economically advantageous for a developer to take the ITC than the PTC for such systems.

Eighteen of the states[25] shown in Figure 11a must meet their RPS within the next ten years (by 2023). If all these states are to meet their standards, a total of 90 GW of qualifying renewables must be available by 2023. The historical rate of construction of installed wind capacity for the U.S. as a whole has followed an exponential curve, as shown in Figure 12. Following the same growth rate for qualifying renewable capacity as predicted by the historical wind installation data in these states would lead to an installed capacity of roughly 150 GW, more than sufficient to meet the aggregate targets. Figure 13 shows the trend that would be needed to reach the 90 GW target by 2023. This figure suggests that, given past construction rates, it appears quite feasible to build enough capacity to meet the combined requirements of the eighteen states. It is important to note, however, that the growth rate in installed wind capacity has not been constant for individual states, and that some states may require higher installation rates than others as they move to meet their targets.

A detailed discussion of the economic rationale for the policies adopted by various governments, such as those described above, is not the focus of this guide; however, we provide a brief primer for those interested in the topic. Generation of electric power produces not only electricity but also pollutants that enter the environment, both during the manufacturing of the generator and during its operation. Economists call the costs of this pollution "externalities." For conventional pollutants, these costs can be estimated by observing the human health effects, but such estimates are quite uncertain in magnitude

23 Database of State Incentives for Renewables & Efficiency (DSIRE), *Federal Incentives/Policies for Renewables & Efficiency,* Updated January 3, 2013 at www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US02F

24 Ibid.

25 CA, CO, CT, DC, KS, ME, MD, MI, MO, MT, NJ, NM, NJ, NC, PA, RI, WA, WI

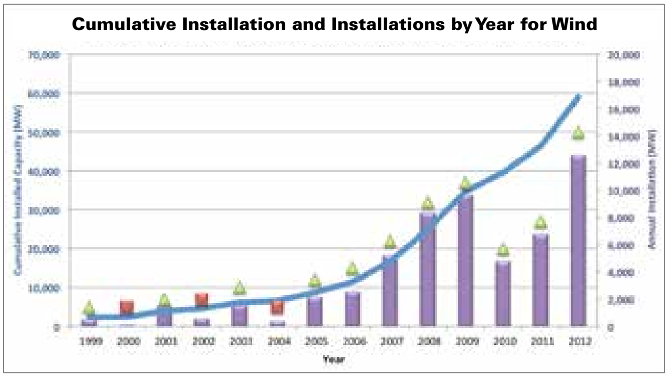


Figure 12a: U.S. cumulative (left scale) and Incremental (right scale) wind power installations, 1999-2012. Green and red markers indicate the status of the Federal production tax credit (PTC) supporting wind projects in a given year. Green markers indicate policy is in place. Red markers indicate policy is not in place.

Data Source: Energy Information Administration

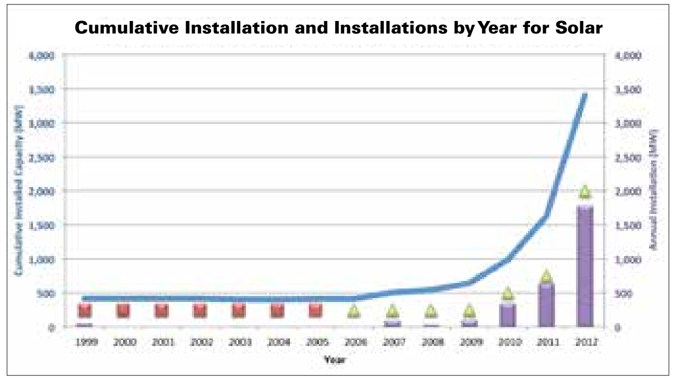


Figure 12b: U.S. cumulative (left scale) and Incremental (right scale) solar power installations, 1999-2012. Green and red markers indicate the status of the Federal production tax credit (PTC) supporting investment tax credits (ITC) supporting solar projects (b) in a given year.

Data Source: Energy Information Administration

and timing for greenhouse gas pollution. If the costs of this pollution are not included in the price of electricity, an economist would say that the artificially low prices cause customers to consume more power than the economically efficient amount.

Some jurisdictions forbid all or most of the pollution (command-and-control regulation). Economists realized that sort of regulation can lead to retiring a generator before its useful life is reached, and so "cap-and-trade" regulation has been instituted (in the U.S. notably for nitrogen oxide (NOx) and sulfur oxide (SOx) emissions) to allow the pollution from older plants to be offset by newer and cleaner plants. A few jurisdictions (for example, the United Kingdom for a time) levied a pollution fee on all electric power sold, encouraging less use and thus less pollution. Other jurisdictions have subsidized the introduction of low-polluting power (for example, with a PTC, ITC or feed-in tariff), by an amount roughly equal to the externality costs. While this policy reduces pollution, its costs are borne by the taxpayers rather than by the users of electricity, and economists object that it artificially reduces the price of power leading to over-consumption.

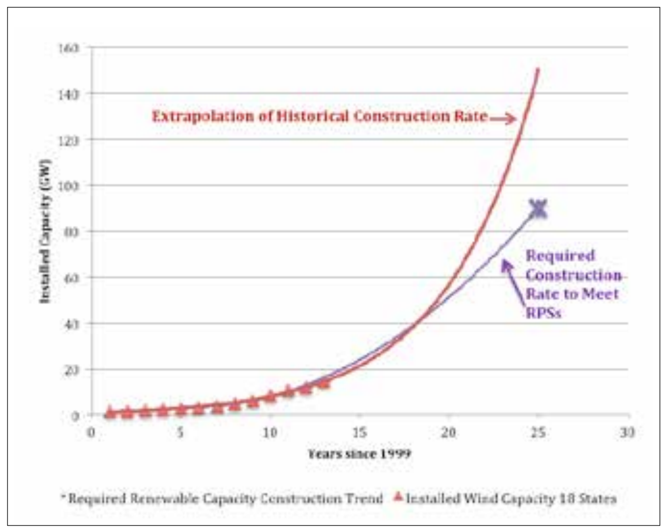


Figure 13: Wind capacity growth trends. The red line shows the observed growth rate in cumulative wind capacity in CA, CO, CT, DC, KS, ME, MD, MI, MO, MT, NJ, NM, NJ, NC, PA, RI, WA, WI extended to 2023. The purple line shows the trend required to meet the entire RPS target for these eighteen states by 2023.

Data Source: Wind Powering America, DOE at www.windpoweringamerica.gov/wind_installed_capacity.asp

An RPS, like command-and-control regulation, both lowers pollution and has costs that are borne by the electricity consumer, encouraging use of an economically efficient amount of electric power. However an RPS may not be efficient if the power sources included are restricted to those deemed "green" by its framers. "Renewable" and "low-carbon" or "low-pollution" are not synonyms, and the former generally does not permit low carbon generation from nuclear or large hydroelectric plants.

WHAT MIGHT BE THE POTENTIAL CONTRIBUTION OF RENEWABLE ENERGY TO TOTAL ELECTRICITY GENERATION?

The National Renewable Energy Laboratory (NREL) *Renewable Electricity Futures Study (RE Futures)*[26] investigated "the extent to which renewable energy supply can meet the electricity demands of the continental United States over the next several decades." Its key findings are that:

- Increased electric system flexibility, needed to enable electricity supply-demand balance with high levels of renewable generation, can come from a portfolio of supply-side and demand-side options, including flexible conventional generation, grid storage, new transmission, more responsive loads and changes in power system operations.
- The abundance and diversity of U.S. renewable energy resources can support multiple combinations of renewable technologies that result in deep reductions in electric sector greenhouse gas emissions and water use.
- The direct incremental cost associated with high renewable generation is comparable to published cost estimates of other clean energy scenarios.

Accurately assessing and preparing for the operational effects of renewable generation can ensure that renewables can play a much enlarged role.

A Personal Perspective…

"When considering adding renewable sources to the grid, it is critically important to take a systems-level perspective. Capacity factors, ramp rates, location, load profiles, life cycle costs and which fuel sources are being displaced all affect the ability of a renewable plant to deliver benefits. Understanding these complexities and tradeoffs is a challenge, but it is the only way to fairly evaluate the true potential of various technologies to reduce greenhouse gases and other pollutants in the electricity sector."

CARNEGIE MELLON UNIVERSITY RESEARCHER Nathaniel Horner

26 National Renewable Energy Laboratory, *Renewable Electricity Futures Study*, at www.nrel.gov/analysis/re_futures/

Managing Variable Energy Resources

Operations

prediction

planning

Carnegie Mellon University's RenewElec project, through an applied research approach that examines the engineering and economics issues raised by variable energy resource integration, has the goal of providing policymakers with actionable, relevant data to inform decision making. This section summarizes the empirically-based evidence from that project and provides a summary of major challenges and opportunities for integrating variable power generation sources and meeting the goals set forward in the state renewable portfolio standards.

WHAT ARE THE MAJOR CHALLENGES AND OPPORTUNITIES FOR INTEGRATING VARIABLE POWER GENERATION SOURCES INTO THE ELECTRICITY GRID?

Variability, described earlier, is the major challenge influencing the ability to incorporate variable renewable energy sources like wind and solar power into the electricity grid. Based on its research, the RenewElec project has found that the primary opportunities to respond to those challenges include:

- Better prediction of variability
- Changes in the operation of power plants, reserves, transmission systems and storage
- Improved planning of renewable capacity expansion
- Implementation of new regulatory paradigms, rate structures and standards

These opportunities will be discussed in the remainder of this section.

HOW CAN VARIABILITY PREDICTIONS BE IMPROVED AND WHAT STRATEGIES CAN REDUCE VARIABILITY?

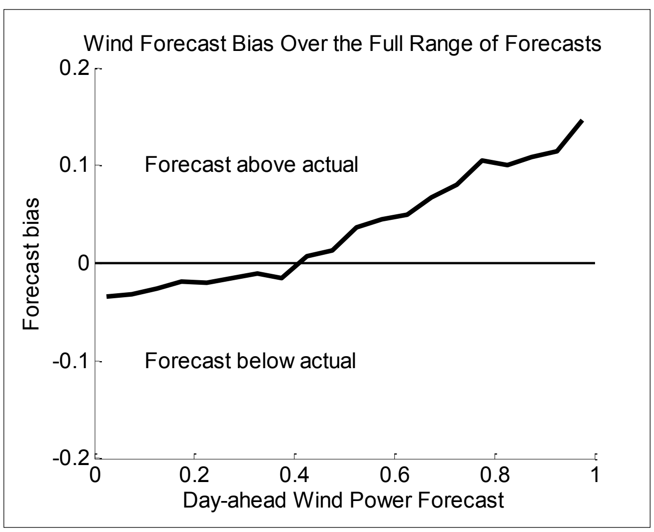


Figure 14: Wind forecast bias as a function of the day-ahead wind forecast in the Electric Reliability Council of Texas (ERCOT) for 2009 and 2010.

Source: Mauch, Apt, Carvalho and Small.[27]

The RenewElec project has identified two critical strategies for managing variability of generation: improved wind power forecasting and aggregating wind farm power within a region. It also has found that interconnecting large areas of the country with new transmission systems to integrate wind is not cost-effective as of now.

• Forecasts of wind power in the United States systematically underpredict wind during periods of light wind, and overpredict when there are strong winds (see Figure14). This is important for those who manage the electricity grid, which incorporates power from a number of sources, including wind power. It is the grid operators' responsibility to make sure power production instantaneously matches consumers' demand for electricity. In order to support large-scale wind and solar into the electricity system, these operators can improve integration by correcting for forecasting errors. In addition, we have found that there is a simple mathematical framework to incorporate forecast uncertainty so that other generation sources can be scheduled to match the variability of wind (and solar) power, and fill in the deficit that results from variability.

27 B. Mauch, J. Apt, P.M.S. Carvalho and M. Small, *An effective method for modeling wind power forecast uncertainty*, Carnegie Mellon Electricity Industry Center Working Paper CEIC-12-06, wpweb2.tepper.cmu.edu/electricity/papers/ceic-12-06.asp

• Aggregating power from wind farms within a region reduces variability; however, there are quickly diminishing returns as more plants are interconnected.[28]

• Aggregating wind power generated over large geographical areas is also beneficial for reducing variability and increasing economic efficiency, but the costs of interconnection are likely to be higher than building new natural gas combined cycle plants within each of the areas.[29] Thus, large new investments in transmission systems designed to interconnect large areas of the country are neither required nor desirable to integrate wind. Significantly decreased transmission costs could change this conclusion.

A Personal Perspective...

"Renewables such as wind and solar produce variable power output, but not all variability is created equal. We need a portfolio of resources to compensate for variability that operates at different time scales. While fast fluctuations must be balanced by quick-ramping resources such as batteries and natural gas plants, a large portion of the fluctuations from renewable generators are slower and can be balanced by slower-ramping resources such as coal."

CARNEGIE MELLON UNIVERSITY RESEARCHER Emily Fertig

HOW CAN THE OPERATIONS OF POWER PLANTS, RESERVES, TRANSMISSION SYSTEMS AND STORAGE BE CHANGED TO BETTER RESPOND TO VARIABILITY?

A number of changes can be made to the operation of the grid to better respond to the variability of VER sources. Among these are the use of both slow and fast responding generators, and the procurement of appropriate reserves on the day-ahead market. Several actions are not worth taking to manage wind variability issues, including establishing grid codes that incentivize wind turbines somewhat below their rated capacity, using compressed air energy storage, and large-scale deployment of storage resources at current costs.

Effective Actions

• The character of power fluctuations from wind and solar power is such that the strongest power fluctuations occur slowly over many hours or days (i.e., low frequency). Thus, slow-responding generators, such as coal and most combined cycle gas plants that take a long time to change their power output (slow ramping) can compensate for most of the variability.[30]

• Fast ramping sources—those that are able to reduce or increase their power output over short periods of times such as natural gas turbines, recently available combined cycle gas plants with a new design, and batteries—can play a role as they are better suited for balancing higher frequency variability. For example, a very small complement of batteries can reduce wind power variability to the electricity transmission grid and greatly increase the economic integration of wind power.[31]

• The use of fast-ramping gas plants can mitigate some of the high frequency variability of wind. Continuous ramping of gas plants, however, can increase the emissions from the power plants, and thus reduce the emission benefits generally associated with wind.[32] New gas plant technology, like Siemens H-Class and GE's Flex 50 combined cycle technology,

---

28 W. Katzenstein, E. Fertig and J. Apt, *The Variability of Interconnected Wind Plants*. Energy Policy, 2010. 38(8): 4400-4410

29 E. Fertig, W. Katzenstein, J. Apt and P. Jaramillo, *The effect of long-distance interconnection on wind power variability*. Environmental Research Letters, 2012. 7(3): 034017

30 J. Apt, *The spectrum of power from wind turbines,* Journal of Power Sources 2007, 169, 269–374

31 E. Hittinger, J.F. Whitacre and J. Apt, *Compensating for Wind Variability Using Co-Located Natural Gas Generation and Energy Storage*. Energy Systems, 2010. 1(4): 417-439

32 W. Katzenstein and J. Apt, *Air Emissions Due To Wind And Solar Power*. Environmental Science & Technology, 2009. 43(2): 253-258

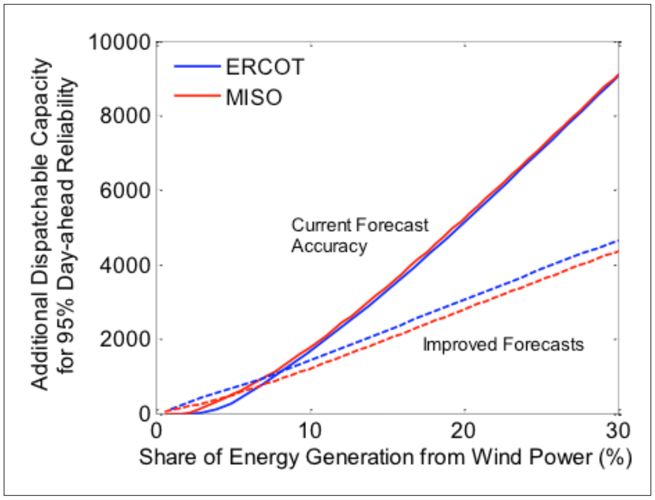


Figure 15: Additional reserve capacity for a range of wind penetration values in ERCOT and MISO. In this figure the horizontal axis is the percentage of load served by wind power. Solid lines assume no change in wind forecast accuracy. Dashed lines show the effect of improved forecasts.

Source: Mauch, Apt, Carvalho and Jaramillo.[33]

can mitigate this effect. Coal plants can be cycled to manage the low-frequency variability of wind while incurring minimal emission penalties. Incorporating the true cost of cycling these power plants would allow for the cost-effective use of coal plants to support wind and solar integration and reduce emissions.

• It is now possible to use accurate statistical methods to procure an economically efficient amount of generation a day ahead as a reserve for net load (load-wind) variability (see Figure15). As the figure shows, at low wind levels, the amount of reserve power currently scheduled is sufficient. As the amount of wind power in the system increases, operators should also increase the amount of reserve available.

Less Effective Actions

• Some grid codes allow grid operators to curtail the power output of wind turbines (e.g., Denmark, Ireland, Great Britain and Germany[34]) to create a reserve of power for regulating the grid frequency. This practice is less economically efficient than regulating with a natural gas turbine. In cases where it is required (perhaps when natural gas prices are very high), the requirement should not be uniformly spread across all wind turbines, but instead placed on the fewest number required to achieve the desired reserve.[35]

• Compressed air energy storage (CAES) does not appear likely to be profitable in the U.S. unless the market price differentials more than double or capital costs substantially decrease. One large CAES project in Ohio and another in Iowa have been put on indefinite hold. Better wind forecasting will not help CAES profitability. Subsidies to make a wind+CAES plant break even (i.e., have a net present value of zero) are ~$100/tonne of avoided CO_2. Portugal is expanding pumped hydro capacity to support wind by building 636 MW of new pumped hydropower storage (PHS), a 60% increase, for a system with a peak load of 9-10 GW. Wind provided 18% of Portugal's 2011 electric energy. PHS in Portugal and in Norway (the latter to support German wind) is unprofitable based on energy arbitrage, i.e., storing electricity when prices are low and selling it when prices are high.[36]

• Grid-scale storage can provide substantial benefits for VER integration and can directly benefit consumers by avoiding the need to keep expensive and rarely-used plants on retainer. However, large-scale deployment of storage for energy arbitrage is likely uneconomical under current electricity market designs. Even with capital costs as low as $150/kWh, large scale storage may not be profitable in the world's largest electricity market, PJM, where storage capacity of 4% of peak load already exists. Increasing efficiency or reducing O&M costs is not sufficient to make arbitrage profitable. However, storage can provide other services to the grid not currently captured in the energy markets.

33 B. Mauch, J. Apt, P.M.S. Carvalho and P. Jaramillo, *What day-ahead reserves are needed in electric grids with high levels of wind power?,* Carnegie Mellon Electricity Industry Center Working Paper CEIC-13-02, wpweb2.tepper.cmu.edu/electricity/papers/ceic-13-04.asp

34 S. Rose and J. Apt *The Cost of Curtailing Wind Turbines for Secondary Frequency Regulation Capacity*, Carnegie Mellon Electricity Industry Center Working Paper CEIC-12-05, wpweb2.tepper.cmu.edu/electricity/papers/ceic-12-05.asp

35 Ibid.

36 E. Fertig and J. Apt, *Economics of Compressed Air Energy Storage to Intergrate Wind Power: A Case Study in ERCOT,* Energy Policy, vol. 39, no. 5, pp. 2330-2342, May 2011

A Personal Perspective…

"The hurricane risk to offshore wind turbines in the Gulf of Mexico is not an engineering problem—it's a money problem. Turbines can be built stronger, but the added cost may make the power they generate uncompetitive in electricity markets."

CARNEGIE MELLON UNIVERSITY RESEARCHER **Stephen Rose**

HOW CAN THE SITING OF RENEWABLE ENERGY PROJECTS BE IMPROVED?

When renewable energy siting decisions are being made, they can be aided by taking into account the need for emergency power in the case of hurricanes, locating facilities in the Mid-Atlantic states if pollution reduction is a goal, and taking into account the potential for small earthquakes in siting enhanced geothermal systems. Each of these results is discussed further below.

• The U.S. Department of Energy has estimated that over 50 GW of offshore wind power will be required for the United States to generate 20% of its electricity from wind.[37] Although hurricanes can pose a risk to offshore wind turbines, making small changes such as having emergency power to yaw the turbine nacelle rapidly into the wind can improve survivability. In addition, it is possible to predict which offshore areas are the least risky for wind turbines prior to construction.[38, 39]

• When wind or solar energy displaces conventional generation, the reduction in emissions varies dramatically across the U.S. If the goal of renewable power is pollution reduction (including displacing CO_2 from power plants), it is much better to locate the facilities in the Mid-Atlantic States than in the Southwest or West. While the Southwest has the greatest solar resource, a solar panel in New Jersey displaces significantly more criteria pollutants than a panel in Arizona, resulting in 14 times more health and environmental benefits. A wind turbine in West Virginia displaces twice as much carbon dioxide as the same turbine in California. Depending on location, the combined health, environmental, and climate benefits from wind or solar range from $10 to $100 per megawatt-hour, and the sites with the highest energy output do not yield the greatest social benefits in many cases. As a result, national production-based subsidies for wind and solar energy are poorly aligned with health, environmental and climate benefits.[40]

• Traditional geothermal power systems are focused on areas where there is sufficient naturally-occurring heat, water and rock permeability to extract energy (e.g., a geyser). A new type of geothermal energy, called enhanced geothermal systems, uses a process called "hydraulic stimulation" to generate energy from dry and impermeable rock. The challenge of this process is that small earthquakes may occur as the rock is stimulated causing public concern. This concern needs to be taken into account in the siting process for these facilities.[41]

---

37 U.S. Department of Energy, *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply,* July 2008 at www.nrel.goc/docs/fy08osti/41869.pdf

38 S. Rose, P. Jaramillo, M. Small, I. Grossmann and J. Apt, *Quantifying the Hurricane Risk to Offshore Wind Turbines.* Proceedings of the National Academy of Sciences of the United States of America, 2012. 109(9): 3247-3252

39 S. Rose, P. Jaramillo, M. Small and J. Apt, *Quantifying the Hurricane Catastrophic Risk to Offshore Wind Power.* Carnegie Mellon Electricity Industry Center Working Paper CEIC-12-07 wpweb2.tepper.cmu.edu/electricity/papers/ceic-12-07.asp

40 K. Siler-Evans, *Evaluating Interventions in the U.S. Electricity System: Assessments of Energy Efficiency, Renewable Energy, and Small-Scale Cogeneration*, Dissertation, August 2012 at wpweb2.tepper.cmu.edu/electricity/theses/Kyle_Siler-Evans_PhD_Thesis_2012.pdf

41 E. Hoşgör, J. Apt and B. Fischhoff, *Incorporating Seismic Concerns in Site Selection for Enhanced Geothermal Power Generation.* The Journal of Risk Research, in press wpweb2.tepper.cmu.edu/electricity/papers/ceic-11-05.asp

WHAT NEW REGULATORY, RATE STRUCTURES AND STANDARDS MIGHT BE PUT INTO PLACE TO SUPPORT THE INTEGRATION OF VARIABLE POWER?

A number of new regulatory, rate structures and standards might be put into place to address variability, including facilitating transmission infrastructure, requiring five-minute scheduling (when possible) instead of intra-hour scheduling, enhancing decommissioning requirements, and considering the effects of "wind droughts" when reviewing wind generation proposals. Each of these is described in more depth below.

• One of the most significant barriers to the widespread adoption of renewable electricity is the extensive transmission infrastructure required to carry wind resources from their geographically isolated locations to major load centers. The previous regulatory landscape governing transmission has not adequately provided measures to facilitate the transmission infrastructure needed to implement renewable energy. However, the recently promulgated FERC Order No. 1000 is expected to significantly alter transmission planning processes and cost allocation—potentially producing significant implications for renewable electricity. Note though, as mentioned earlier, additional transmission is not a major factor in managing variability, but it is necessary if wind projects continue to be developed far from load centers.

• The availability of forecasts that can be used to support the scheduling of resources to be dispatched to meet load is one of the challenges of integrating variable energy resources. Forecasting methods are still undergoing substantial development. In addition, there is a need to improve the integration of such data into the minute-to-minute operations of the power system. In particular, rules standardizing the time frame used in the dispatch process should be evaluated so to make use of the best available forecasts.

In 2011, RenewElec expressed support for FERC's proposed rule requiring operators to implement intra-hour scheduling, but urged FERC to require five-minute scheduling in areas with significant VER integration needs, instead of stopping at 15 minutes. This is because 15-minute dispatch intervals may not be sufficiently refined for public utility transmission providers aiming to achieve very high levels of VER intergration. Five-minute intervals, on the other hand, are already common in organized market regions, are technically feasible, and will ensure that VER dispatch is conducted at maximum achievable accuracy and efficiency.[42] In the final rule, FERC adopted its 15-minute scheduling proposal.

• Existing decommissioning requirements for wind plants are likely to be insufficient and appropriate bonding requirements may need to be established to guarantee the proper decommissioning of wind turbines at the end of their life. While some municipalities have established bonding requirements for wind plants, these have generally been at the very low end of projected decommissioning costs and should be revised.[43]

• "Wind droughts" and other long-term weather phenomena are quite likely to occur, and should be considered in regulatory agency review of wind generation proposals.[44]

A Personal Perspective...

"The use of better power forecasts in the operating decision-making process may be one of the largest opportunities for more efficiently managing the variability of wind and solar power."

CARNEGIE MELLON UNIVERSITY RESEARCHER **Paulina Jaramillo**

---

42 P. Jaramillo, J. Apt and P. Hines, *Comments of the RenewElec Project of the Intergration of Variable Energy Resources Notice of Proposed Rulemaking.* Submitted to the United States Federal Energy Regulatory Commision (FERC). Docket No. RM10-11-000. March 2, 2011.

43 D. Changala, M. Dworkin, J. Apt and P. Jaramillo, *Comparative Analysis of Conventional Oil and Gas and Wind Project Decommissioning Regulations on Federal, State, and County Lands.* The Electricity Journal, 2012. 25(1): 29-45

44 W. Katzenstein, E. Fertig and J. Apt, *The Variability of Interconnected Wind Plants.* Energy Policy, 2010 38(8): 4400-4410

Recommendation

wind

management

Regulation

RECOMMENDATIONS FOR REACHING 20-30% RENEWABLE PORTFOLIO STANDARD

Based on the results of the RenewElec Project, Carnegie Mellon University researchers believe that reaching a 20-30% renewable portfolio standard goal is possible, but not without changes in the management and regulation of the power system. Accurately assessing and preparing for the operational impacts of renewable generation can ensure that renewables can play a much enlarged role. The actions outlined in Figure 16 can help reach the goal of increasing renewable energy's contribution to the grid.

Wind and solar power's contribution to power generation can increase by about 10-fold, from 3% to 20-30%. California provides evidence to support the goals of the renewable portfolio standards. In 2012, its three major utilities, Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E), were each able to meet a required mandate of supplying their customers with 20% of their energy from renewable sources.[45]

Successful deployment of the variable energy resources expected to be the major contributors to renewable power, however, requires improved planning and operations, advanced technologies and infrastructure, and appropriate public policies.

Short Term Strategies

- **Forecasters and grid operators** should correct for forecast biases before using the data for unit commitment and dispatch.
- **Grid operators** should incorporate forecast uncertainty in unit commitment and dispatch decisions.
- **Independent system operators/regional transmission organizations (ISOs/RTOs)** should not uniformly curtail wind turbine power output to create a reserve of power for regulating grid frequency, but instead curtail power from gas turbines or a small subset of wind turbines to achieve the desired reserve.
- **Legislative bodies and regulatory agencies** should provide incentives to site wind and solar power plants in the Mid-Atlantic region, where emission benefits are highest.
- **ISO/RTOs** should allow coal plant operators to incorporate cycling costs in their bids so they can limit excessive cycling of coal units.
- **Local, state and federal governments** should establish appropriate decommissioning requirements for wind and solar power plants.
- **Regulatory agencies and insurers** should provide incentives for the development of renewable resources in areas with lowest risks of hazards like earthquakes and hurricanes.

Long Term Strategies

- **ISO/RTOs and planning agencies** should recognize that large-scale geographic aggregation is not necessary to mitigate the variability of wind.
- **ISO/RTOs** should develop strategies to compensate energy storage operators for the benefit they provide to electricity customers.

Figure 16: Short and long-term strategies to reach wind renewable portfolio standard targets

45 California Public Utilities Commission, *Renewable Energy Portfolio Standard, Quarterly Report, 1st and 2nd Quarter, 2012* at www.cpuc.ca.gov/NR/rdonlyres/2060A18B-CB42-4B4B-A426-E3BDC01BDCA2/0/2012_Q1Q2_RPSReport.pdf

Wilton E. Scott Institute
for Energy Innovation

5000 Forbes Avenue
Pittsburgh, PA 15213
412-268-2000

May 2013

cmu.edu/energy