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PRINCETON UNIVERSITY

Grid-Scale Electricity Storage

Implications for Renewable Energy

Energy Technology Distillate No. 1

With this document and its affiliated website, Princeton University's Andlinger Center for Energy and the Environment introduces a series of publications called Energy Technology Distillates. Designed to provide succinct yet substantive information to policymakers, educators, students, and other citizens, these publications cover emerging topics in energy and the environment that combine technological, economic, and policy considerations.

This first Energy Technology Distillate is presented as an executive summary here and as a full report at **http://acee.princeton.edu/distillates.**

+Energy Storage

The future of renewable energy, primarily wind and solar, is intertwined with the development and deployment of energy storage technologies. This Energy Technology Distillate describes the fundamentals of energy storage, including leading technologies and their challenges, key costs, and important regulatory initiatives that are acting to drive commercial deployment.

Power produced from wind and solar has grown quickly over the past decade. Between 2001 and 2011, global wind capacity grew tenfold and solar electricity capacity grew forty-fold. In 2011, the two sources produced 2.4 percent of the total global supply of electricity. However, further integration of wind and solar into the grid will become increasingly difficult because these sources are both intermittent and unpredictable. Unpredictable sources of power present a challenge for the grid: when a customer turns on a light, high-quality electricity must be available to meet the demand.

This Distillate analyzes key issues associated with storing energy at a scale relevant to a regional electricity grid. It focuses specifically on batteries.

Energy storage systems offer a possible solution by absorbing electricity from the grid when it is plentiful and providing electricity to the grid at a later time.

Multi-hour energy storage systems could increase the renewable portion of electricity delivered to customers, and thus significantly reduce greenhouse gas emissions associated with power generation using fossil fuels. Storage also could help overall grid performance, allow better management of conventional power plants, and provide more options for providing power in emergencies.

Economics

Quick calculations of capital and operating costs offer an easy-to-use model for assessing economic viability of storage scenarios compared to burning fossil fuels. See page 2.

Technology

Research on batteries seeks to overcome trade-offs that prevent existing technologies from achieving all the needed characteristics of grid-scale storage. See page 2.

Uncertainty

Plans for deploying wind and solar must account for variations in wind and sun that are predictable and those that are not. See page 3.

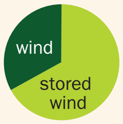
Climate

Storage could be critical to achieve the promise of wind and solar in reducing greenhouse gas emissions; otherwise fossil fuels must be deployed to fill gaps. See page 3.

Policy

Current regulatory frameworks have few direct measures to support energy storage, but regulations affecting renewable energy offer a beginning. See page 4.

Option I

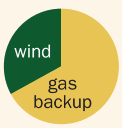


Three units of wind are collected and two are stored to provide baseload power during the other 16 hours.

Option II

Natural gas provides power at a constant rate throughout the day.

Option III



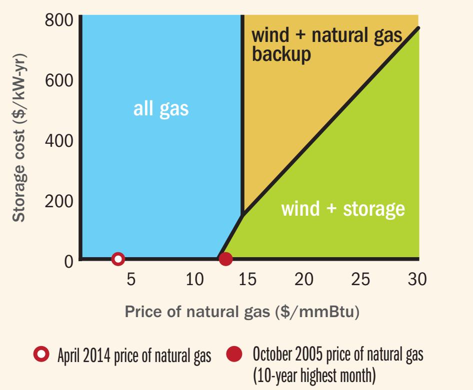
Wind provides power during the first eight hours and gas provides the "backup" power during the other 16 hours.

+ Economics

As a practical matter, the economic comparison of energy storage to other options currently comes down to the price of natural gas. Gas-fired turbines respond quickly to fluctuations in supply and demand, and are thus an obvious choice for pairing with wind and solar.

Lowest Cost for Baseload Power

Natural gas only vs. gas plus wind backup vs. wind and storage



For example, in developing a wind farm in a location where the wind blows mainly during eight night-time hours, it would make sense to compare several options:

I Build extra wind capacity so that the excess energy could be stored at night and released during the day;

II Forego wind altogether and just burn natural gas the whole time;

III Build only enough wind turbines to meet electricity demand when wind is available and use natural gas when wind is not available.

Using basic math to factor in both capital and operating costs reveals that the second option is cheapest even when natural gas prices are much higher than they are today. As natural gas prices rise, pairing wind and gas becomes economical; at even higher prices, replacing gas with storage becomes attractive. Adding a carbon tax or other incentives could make storage financially attractive at lower gas prices.

The math explained in this simple comparison could be used for more complex evaluations.

+ Technology

Battery technologies for grid-scale storage can be evaluated by six criteria: capacity, power, efficiency, cycle life, cost, and safety [see Key Concepts below]. No current technology excels at all six. With new applications, including electric vehicles and grid-scale storage, addressing trade-offs among these criteria becomes the focus of most battery research.

For example, among three common battery types:

- Lead-acid batteries (such as those found in automobiles to start engines) are low cost and relatively safe but require trade-offs between useful power, useful capacity, and the number of cycles before replacement.
- Lithium-ion batteries (found in cell phones) have high power density and high energy density, but would be very expensive at grid scale because extensive cooling is currently required for safety and long life.
- Sodium-sulfur batteries (under development primarily in Japan) achieve high power and long life but are at risk of extreme fires. The costs of monitoring and engineering to operate safely are too high at present to make this option competitive aside from a handful of applications.

Entirely new battery technologies are being developed but so far remain "beaker-scale" experiments. Their characteristics are not established sufficiently to extrapolate their potential performance at grid-scale deployment.

One such approach seeks to maximize the amount of material devoted to storing energy as opposed to providing structural support. This approach uses materials that naturally renew and restructure themselves each time the battery is charged, so that it can be cycled a very large number of times. Another approach to long cycle life seeks materials that incur only minimal disruption during charging and discharging. This second approach lowers costs by making cycling predictable and reducing failure rates.

Key Concepts

Four ways to measure the performance of a battery or other storage device:

Capacity — how much energy the battery can hold, measured in watt-hours (Wh). 100Wh would be enough energy to run a 100W lightbulb for an hour.

Power — how quickly a battery charges and discharges, measured in watts (W). A 100W battery could light a 100W lightbulb at full brightness but not drive a 1,500W hairdryer.

Round-Trip Efficiency — how much of the energy used to charge the battery is retrievable later, measured as a percentage.

Cycle life — the number of times the battery can be charged and discharged before the capacity is reduced below some useful level.

+ Climate

Use of fossil fuels is causing a rise in atmospheric carbon dioxide (CO_2) at a rate of one percent every two years. Coal and natural gas power plants contribute 40 percent of the world's CO_2 emissions. To what extent could those emissions be eliminated by wind and solar, for some specific region or grid? A substantial literature makes the case that an electricity system powered by 80 percent and even 100 percent renewables is potentially achievable. However, formidable challenges would need to be overcome for such an outcome to emerge.

Clearly, the whole job could not be done by wind and solar, both of which are not only intermittent, but partially unpredictable, even when multiple facilities are combined, each with its own time variation. The rest of the job could be done by some combination of a) renewable energy sources that can run all the time and are predictable ("dispatchable"), such as hydropower, biopower, and (in some locations) geothermal energy produced from heat deep underground; b) load shifting to match the intermittency (e.g., a clothes dryer can be set to run only on windy days), a key element of the emergent concept of the "smart grid"; c) additional wind and solar facilities that collect and store extra power for delivery when it can be used, typically many hours later. The high cost of multi-hour storage is one of the most serious detriments to an all-renewable power system.

Second-best, from the standpoint of CO_2 emissions, would be a system where energy from natural gas fills in when renewable energy supply falls below grid demand. A grid powered half by carbon-free renewables and half by natural gas would produce one-fourth as much carbon as a system producing the same amount of electricity entirely from coal (since natural gas power on its own emits half as much CO_2 as coal power and the use of renewable energy, in some guises, entails negligible CO_2 emissions). For many, "one-fourth of coal" is too high; for others, it's a victory.

Emissions from such a hybrid system could be further reduced by as much as 90 percent by adding CO_2 capture at the gas-fired plant and storing the CO_2 deep underground. But this is probably a mismatch, because the modified natural gas plant would be less nimble and better suited (in terms of technology and economics) for running at constant output.

+ Variability and Uncertainty

Some types of variation in the supply and demand of energy are predictable: people's tendency to use lights in the evening; seasonal patterns of sunlight; standard weather fronts. These can be used to plan energy generation. Energy from wind and solar introduces a much higher level of uncertainty due to unexpected fluctuations.

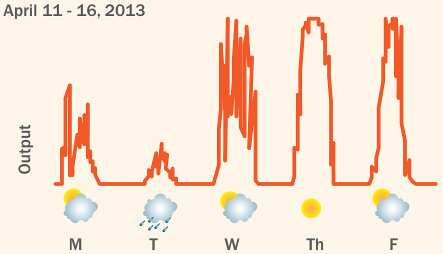
Many mechanisms exist to turn on or off (dispatch) conventional electricity sources – coal and gas – to meet predictable patterns of demand. But these mechanisms entail lags in both the planning process and the ability of the generators to respond. The advanced notice required to respond to unexpected change varies dramatically. At one extreme, automatic controllers tune generators based on signals every two to four seconds; at the other extreme, maintenance for nuclear power plants is planned a year in advance. Natural-gas-fired turbines can be turned on and off entirely in response to calculations forecasting 45 minutes ahead. By contrast, decisions to operate coal-fired steam generators must be made 12 to 36 hours in advance.

Taken together such decisions create complex interactions, but provide a powerful hedging mechanism that allows the grid to handle even unpredicted variations as large as a few percent.

However, a wind energy source can quickly drop to zero, and even when wind power from many sources is combined, total electricity from these sources still fluctuates unpredictably. If wind were powering even 20 percent of the grid, new strategies would be required to adapt to such volatility.

Princeton Solar Field

April 11 - 16, 2013



In one week, the output of a solar field was predictably low on Tuesday and high on Thursday, but was unpredictably variable on Monday and Wednesday.

For individual homeowners and businesses trying to supply their own electricity via solar, the grid acts like a big backup battery. But at high penetration levels, the increased variability places significant stresses on the power electronics and the planning processes.

Even in regions such as Denmark and Spain or Iowa and South Dakota, known for deriving a substantial amount of power from wind, smooth operations require reliance on grid connections to a broader geographic area and other types of power.

+ Policy

Federal and state policies have contributed to the falling costs of wind and solar installations and might contribute similarly to energy storage, although public policy support for storage has been limited so far.

About half of the states – mainly in the Southeast and West – have a conventional regulatory scheme in which a state commission regulates utilities in exchange for granting a monopoly over a vertically integrated set of roles: generating, transmitting, and distributing power.

The rest of the states have undergone partial deregulation, separating these roles and creating competition in the electricity generation segment. Responsibility for transmitting electricity falls to independent grid operators called Regional Transmission Organizations, which operate across state lines and are federally regulated.

These two regulatory models affect investment in new technologies. Under conventional regulation, a Public Utility Commission could mandate use of storage and allow the utility to charge ratepayers for the extra costs of early deployment. In deregulated states, federal rule-making can promote innovative deployment of storage technology by rewarding its special features.

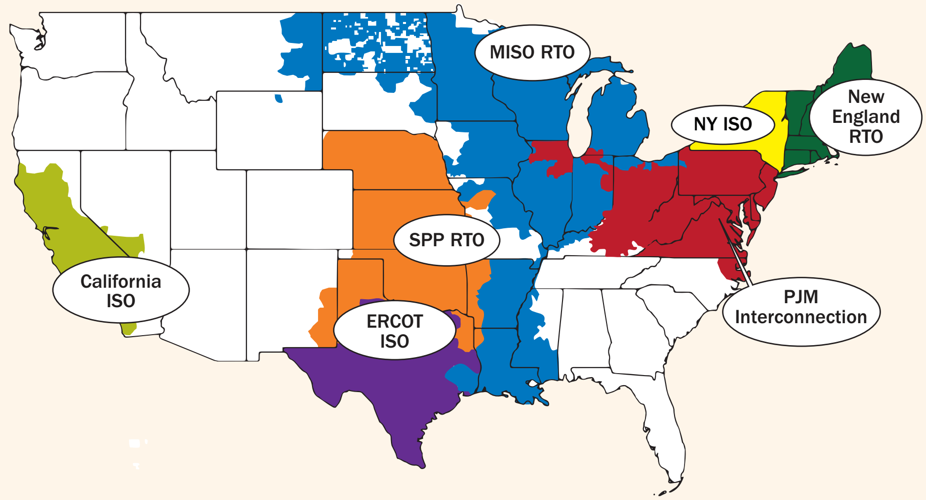
In both models, utilities must meet reliability standards, which storage could help achieve.

Storage also could help address unintended consequences of state and federal regulations designed to promote wind and solar power. Current incentives do not specify what time of day the electricity is provided, meaning that subsidized wind power, which tends to be available at night, may be abundant when not needed. Coal-fired plants are best run at constant power, because they are expensive to ramp up and down. Therefore, when wind power is abundant and inexpensive, a coal plant can be forced to sell electricity below its cost of production, while wind energy that could have been put on the grid is thrown away ("spilled").

Other recent federal regulations are more specifically targeted at promoting storage. For example, one regulation rewards faster response in controlling the frequency of alternating current, which storage systems are well suited to providing.

California recently established the nation's first targets for procuring energy storage and also forbids utilities from owning a majority of storage operations, encouraging independent operation of storage systems.

The Seven US Regional Transmission Organizations



Colored regions of this map show states that have undergone partial deregulation of electric utilities, opening the generation of electricity to competition and assigning transmission to regional organizations.

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