Scope: This article provides a brief overview of grid-scale electricity storage and its roles in the growth of intermittent renewable energy. This overview and its associated articles constitute an "energy technology distillate," a synopsis of challenge and opportunity at a specific frontier area of the energy system. For the full set of articles as well as information about the contributing authors, please visit http://acee.princeton.edu/distillates.

Article 1: Overview

Electricity is provided to most of the world's users through complex grids that connect large sources of electric power to millions of users through transmission and distribution power lines. Although demand for electricity from the grid varies throughout the day, many of the sources providing energy to the grid are controllable, allowing generation to be seamlessly matched to user demand. However, increasingly during the past 10 years, power produced from renewable sources, predominantly wind and solar, has begun to enter the grid, and the result has been greater intermittency and unpredictability.

Over the same period, new developments in electricity storage technology have brought forward the possibility that the very problems renewables introduce, storage may solve. Electricity storage devices differ fundamentally from traditional power plants. Storage systems are capable of both absorbing electricity *from* the grid and providing electricity *to* the grid. By contrast, power plants can only generate electricity. The promise of storage and the promise of renewables are intertwined.

This "energy technology distillate" is a collection of brief articles that introduce aspects of the interplay between intermittency and storage. Each article has the goal of providing the non-expert reader with the language and key concepts needed to ask informed questions – in this case, about energy storage in general and, particularly, about how energy storage might be integrated into the grid in ways that enhance the penetration of renewables. Each article is neither a detailed technical treatise nor a brief on behalf of any specific technological, political, or regulatory policy. The overall goal of the distillate is to provide a starting point where the reader can learn basic vocabulary, concepts, and principles.

Intermittent renewables

Renewable energy is, in effect, energy from the sun. It can be harvested either directly or indirectly. Direct collection occurs when sunlight produces electricity via special materials that sunlight can activate or when it heats water or another fluid. Indirect collection includes collection after the sun's heat evaporates water, the water falls as rain, and the rainwater is gathered by a river basin (hydropower). Other examples of indirect collection of solar energy produce electricity by harnessing the power in winds, waves, and currents. Biology provides still another version of indirect collection, after sunlight has been used by a leaf to create grass or a tree (biomass). Hydropower produces the most renewable electricity today; it is well matched to the assignment of providing electricity whenever it is wanted: it is "dispatchable." By contrast, solar and wind energy – the two sources that are growing most rapidly – are *intermittent*; that is, they are not available all the time, creating electricity only when the sun is shining or the wind is blowing above a certain speed.

Intermittent renewable energy 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, between them, these two intermittent sources produced 2.4 percent of total global electricity. In some areas, power generation from renewable sources has far exceeded this percentage; for example, in 2011 wind accounted for 28 percent of Denmark's total power production. However, even at significantly smaller wind penetration levels, such as in Germany and Texas (in both cases, 8 percent of total power production), the integration of wind and solar energy into the electricity grid is proving to be difficult.

These difficulties arise not only because wind and solar energy are intermittent but also because they are unpredictable. The grid is a dynamic system that must balance generation (supply) and load (demand) at all times to maintain reliability and stability. When a customer turns on a light, electricity must be available to meet this demand. The grid balances load with demand by turning "load-following" power plants on or off throughout the day and raising or lowering their output. Unpredictable variations in the output of renewables resemble unpredictable variations in user demand, both over the short term (minute to minute) and longer term (hour to hour or day to day). The unpredictability of renewables is gradually diminishing through advanced computational techniques that improve the forecasting of power generation from wind and solar facilities. Nonetheless the growing presence on the grid of unpredictable sources of power is already beginning to create larger challenges to grid management than have been presented by uncertain demand.

Electricity storage

One approach to addressing intermittency and unpredictability on the grid is to have resources online that are able to vary their output, or standing by and able to be brought online when needed, commonly called, respectively, spinning and non-spinning reserves. Today, these functions are provided largely by hydroelectric and natural gas-fired power plants varying their output. An alternative strategy is to use electricity storage systems, absorbing electricity when it is abundant and releasing it back to the grid when it is desired.

Storage systems in various guises are capable of reducing and controlling the output variability across time periods as short as milliseconds and as long as days. The shortest periods are associated with controlling the voltage and frequency of grid electricity within a tight range (regulation). Fluctuations in voltage and frequency can be created in many ways, including by wind variability and cloud cover. Storage for a few minutes can remove bottlenecks from transmission and distribution lines. Storage that can reliably prevent the overloading of these lines may enable the deferral of expensive upgrades. Multi-hour storage systems allow nighttime wind to provide energy in the daytime, when it is more valuable. At small scale, they can enable a household to shift load away from times when electricity is particularly expensive. At all time scales, storage can provide emergency services.

To focus the discussion about storage in this distillate, batteries are highlighted. Batteries are indeed a prominent option, and the battery research frontier is particularly dynamic. However, several other storage technologies with grid applications are appearing at this time. One of these, flywheel storage, shares many features with battery storage. Others, including chemical storage, compressed-air energy storage, storage as high-temperature heat, and storage in water reservoirs ("pumped storage") have much less in common.

How important grid-scale electricity storage becomes, and how quickly it arrives, will depend upon the availability of cost-competitive technologies. Market competitiveness, in turn, requires lower storage costs and supportive policies. It also is strongly affected by the cost of natural gas, which today provides much of the grid's fine-tuning and load-following capability. In the U.S., policies that promote storage in its various grid-supportive roles are being introduced both by the federal government and by some states, notably California. These policies follow on the heels of federal and state policies to promote renewable energy and demonstrate many of the same difficulties of coherent implementation.

Subsequent articles

This distillate currently consists of this Overview (Article 1) and six supplementary articles with restricted focus. The articles are self-standing and can be read independently. The hierarchical structure is presented in Figure 1.1.

Article 1 is this Overview.

Article 2 introduces the concepts and vocabulary of energy storage. It may be useful for the reader to consult Article 2 when reading the other articles.

Article 3 introduces a simplified methodology for estimating costs and uses it to explore a three-way competition where intermittent wind supplemented by multi-hour storage competes with a) natural gas on its own and b) intermittent wind supplemented by natural gas but without storage.

Article 4 reviews the frontier of battery technology. Current approaches to improving the performance and cost of three battery systems are contrasted so as to highlight the most pressing challenges.

Article 5 adopts a systems perspective to introduce the challenge of improving the reliability of an electricity grid. Intermittency and unpredictability are contrasted, both of which become substantially more difficult to manage as the presence of intermittent renewables grows.

Article 6 examines the competition between fossil fuel-based and storage-based solutions to grid problems from the perspective of climate change mitigation and the low-carbon economy.

Article 7 explains how, in the U.S., new state and federal policies are being put in place to encourage investments in grid reliability and electricity storage. The complexities inherent in there being, in effect, two parallel electric utility industries, differing in how federal and state authority interact, are introduced.

The distillate process is open-ended. There may be additional articles and periodic revisions.

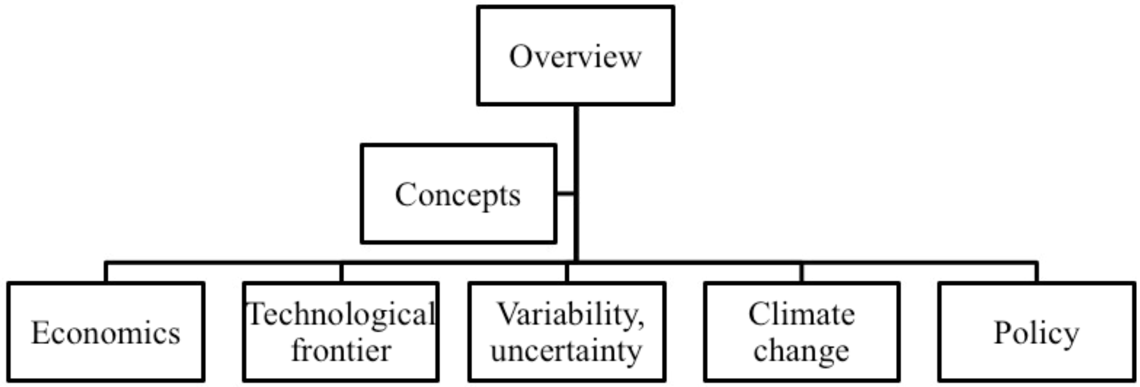

Figure 1.1 Hierarchical relationships among the seven articles in this distillate.