mechanical engineering

renewable. rechargeable. remarkable.

Flow batteries can turn intermittent wind power from a utility manager's headache to a green and reliable energy source.

by Mark T. Kuntz
and Justin Dawe

It is sometimes harder to tell which is stronger: the public's love affair with clean energy, or the headaches that utility planners experience when they contemplate integrating these relatively new energy sources into their already-stressed grids.

On the one hand, customers and the popular press have made it exceedingly clear that they expect wind, solar, and other renewable energy sources to play an increasingly important role in generating the electricity that powers modern society. This desire is often driven by concerns about air quality, public health, and energy security, among other factors.

This 30 MW wind farm in Japan is augmented by a battery

system that can supply 4 MW of power for up to 90 minutes.

On the other hand, utility planners who are working to match instantaneous supply and load on their transmission and distribution infrastructure often wonder how they will handle 5 percent penetration by intermittent resources, much less the 20 percent or more that they are regularly told is just around the corner. Go to any power engineering conference these days, and you'll lose track of the number of times you hear seasoned planners asking each other, "But what about when there's no wind when you need it, or too much when you don't?"

As in so many cases where customers want something that providers are not used to delivering, the answer lies primarily in the development and application of new technologies. In this case, the technology family that promises to bridge the gap is grid-scale energy storage. Modern energy storage systems, capable of efficiently holding tens or even hundreds of megawatt-hours of energy, could well make intermittent renewable energy sources an attractive, reliable, and mainstream power option, even from the demanding perspective of a utility planner. One technology in particular, known as the flow battery, appears to have the combination of characteristics necessary to connect today's customer desires with tomorrow's integrated and clean energy system.

Before looking at how energy storage works, and what benefits it can provide, it is worth understanding the challenges that wind and other renewable energy sources create for utility planners. First, many renewables are what are known as "intermittent" energy sources, meaning that they aren't available all of the time or they cannot be called upon at the utility's discretion.

For a utility planner, any intermittent source is therefore not "dispatchable." A dispatchable energy source can be scheduled for use at the planner's convenience. Traditional energy sources, such as coal, natural gas, and nuclear-power thermal plants, are essentially completely dispatchable—with exceptions for system malfunctions or breakdowns. Among renewable energy sources, hydroelectric and geothermal facilities are also dispatchable, within the natural limits of the resource availability.

The reason that dispatchability matters is that the electric grid requires a constant and instantaneous match between the electric energy being generated and that being consumed. Outside of the electric sector, there is always a lag between supply and demand (think about grain in silos, the pipeline of goods in a warehouse, or any typical supply chain). In the electric sector, however, this buffer has traditionally been rarely available.

To make the balancing act work, utility planners lean on a mixture of energy resources. Baseload facilities are operated at or near their maximum capacity as much as possible, to serve the base of energy demand that is always present. Coal-fired and nuclear power plants are the classic baseload resources. Peaking plants are facilities that are then operated to follow the ups and downs of the electric load. In recent decades, facilities burning natural gas have been the fast-reacting power plant of choice for this peaking role.

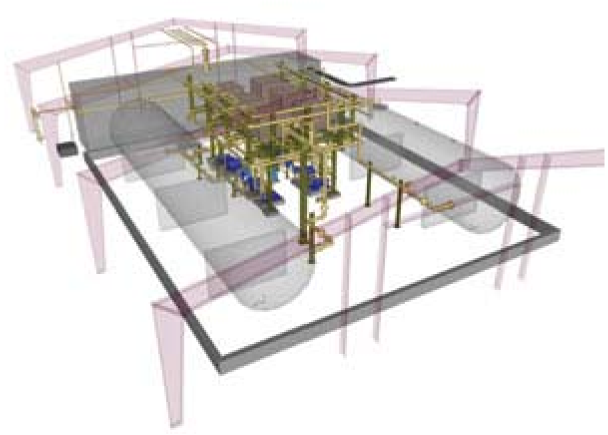
Customers on interruptible contracts, who agree to have their power turned off at periods of peak demand in exchange for lower rates, provide a demand-side option for balancing the equation.

fast rises and crashes

When you throw intermittent resources into the mix, matching energy supply and load gets more complicated. Now, instead of just the fairly predictable cycles of daily and seasonal load variations, there may be tens or hundreds of megawatts of power that can come and go in an unpredictable fashion. While there have been great strides made in forecasting methods, particularly for wind, the resource itself is still fundamentally outside the control of the utility planner. For the utility planner, these unpredictable changes in power output come in two flavors: fast rises and crashes.

Fast rises in wind or solar power can be accommodated through power shedding—basically, the utility throwing away energy while it gets the system into balance. More challenging, though, is when an intermittent energy source crashes—when the wind suddenly dies or a cloud suddenly blocks the sun. In this case, the utility must have an energy source ready to pick up the slack; the alternative is customers losing power. Unfortunately, while traditional gas peaking plants can react quickly, even they generally need 15 minutes or more to ramp up their power output.

In recent years, a number of energy storage technologies have been proposed as a means of either making intermittent energy sources more dispatchable, or at least helping utility planners bridge the gap between the fall-off rate of renewables and the ramp-up rate of traditional peaking plants. Hydroelectric dams were the first, and in some ways are still the best, option under consideration. These facilities can react even more quickly than gas plants to changing load, making them excellent bridging resources.



A flow battery (shown here in a three-dimensional rendering) stores energy electrochemically in the form of vanadium ions suspended in a solution.

In places where a significant amount of wind power is being generated, that wind power can be used to pump water below the dam back up into a reservoir, essentially storing the power for later use. Better yet, this type of pumped hydro resource is relatively cheap, and the fact that it is renewable makes it an excellent complement to wind power, which is often developed in the first place to cut down on environmental impacts.

In places such as the Pacific Northwest, integration of wind and hydro has become relatively common. Unfortunately, there is a limited amount of hydropower, and it is not necessarily available in the same places where excellent wind resources can be found.

Another storage technology that has received attention is compressed air energy storage. In this case, wind power is used to compress air in an underground chamber; the compressed air is later released to help drive a turbine that generates electricity. Like pumped hydro, there are no technical limits to the implementation of large projects. Unfortunately, the geologic formations necessary for compressed air storage are relatively rare, meaning that it likely will never be a major contributor to the national energy system.

Traditional electrochemical batteries, including lead-acid batteries, are another option. For remote communities that have long needed energy storage, lead-acid batteries are viable but problematic tools. Due to cost and performance limitations, particularly their relatively short lifespans, large-scale lead-acid battery installations are not an adequate complement to intermittent renewable energy sources.

And, of course, no discussion about achieving a clean energy future would be complete without mention of fuel cells and the hydrogen economy. Fuel cells convert hydrogen (or other fuels) into electricity without combustion, and their successful mass commercialization could radically alter the way that power is generated in both stationary and mobile applications.

Some fuel cell proponents envision a day when wind farms and other clean energy sources power massive water electrolyzers, generating the hydrogen that fuel cells would use, in turn, to power the economy. While this type of arrangement would indeed represent a comprehensive energy system, it faces significant technological and economic hurdles.

juice in, juice out

All of this brings us to a novel type of battery known as a flow battery. Flow batteries essentially comprise two key elements: cell stacks, where power is converted from electrical form to chemical form, and tanks of electrolytes where energy is stored.

The most popular flow battery on the market uses a vanadium redox technology, using charged vanadium in a dilute sulfuric acid solution to store energy. The appeal of flow batteries is that for grid applications they combine the strengths of both conventional batteries and fuel cells.

Like a fuel cell, a flow battery has a long life and is both energy-efficient and environmentally friendly. Also, like a fuel cell, the energy rating of the system is a separate design variable from the power rating. Increasing the volume of the electrolyte tanks increases the amount of energy that the system can store and release; increasing the number of cell stacks increases the power that the system can generate.

Like traditional batteries, but unlike fuel cells, flow batteries are an "electricity in, electricity out" system. There is no external fuel source, such as hydrogen, that is added regularly to recharge the system. Instead, electric energy is supplied to the system at one time, and the system stores that electric energy in electrochemical form until it is needed later. For grid applications, this simpler arrangement avoids the need to create new fuel or distribution systems.

In addition, unlike fuel cells, flow batteries are not based on rare or valuable materials. Fuel cells typically use platinum or other expensive catalysts to speed the oxidation of their energy carrier. Instead, the material at the heart of a flow battery cell is vanadium, a plentiful, nontoxic metal.

While a flow battery using an electrolyte solution doesn't have the same energy density as a fuel cell using hydrogen as an energy carrier, for most grid applications high energy density is not a key design factor. Because of this lower energy density, you won't see a flow battery powering a car on the street, but the price and performance do create the potential for significant grid applications.

Pipes and pumps carry the vanadium solution to stacks of proton exchange membranes, which transfer electrical charge and create a current.

One early application of flow battery technology in the United States was a project developed in a partnership between the large western utility, PacifiCorp, and VRB Power Systems, a Vancouver, British Columbia, developer of vanadium-based flow battery energy storage systems. The project, located in Castle Valley, Utah, involves a 250 kW installation with an eight-hour storage capacity. In energy terms, this is a 2 MWh system.

Installed in 2003, the Castle Valley system is charged overnight by baseload resources, and supplements the supply of power to a small community during the hottest part of the day, when the distribution feeder is overloading. This arrangement helped PacifiCorp avoid having to install a new transmission line to Castle Valley, and increased the utilization of existing infrastructure. Nearly two-dozen other flow battery systems are in place around the world, with tens of thousands of reliable charge-discharge cycles on record.

Flow batteries also appear to match up quite well with the needs of utility-scale wind farms. In Japan, where utilities are required to generate a portion of their energy from renewable sources such as wind, the utility J-Power added a 4 MW, 90-minute (6 MWh) vanadium-based flow battery to an existing 30 MW wind farm.

The wind farm charges the storage system, and the storage system serves to level the output of the wind farm to the broader distribution grid. When the wind rises or falls over the course of a few seconds, the storage system smooths the frequency variations that would normally arise. This protects energy consumers from deviations in their expected power quality.

When the wind suddenly cuts out more than that, though, the flow batteries really earn their keep. In those cases, the flow batteries can provide burst power up to 6 MW, creating the power bridge that gives utility operators the chance to bring peaking plants or other generation resources online.

The additional layer of equipment adds perhaps 15 percent to the cost of a stand-alone wind farm, but more than makes up for the additional cost by increasing the value of the electricity that's generated.

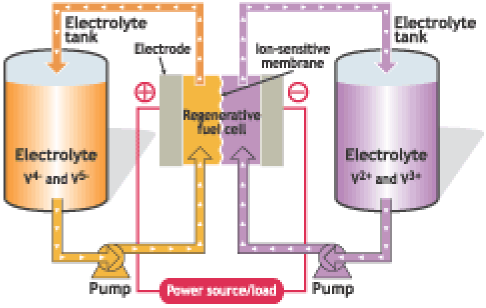
As with any relatively new technology, there are a few chasms that must be crossed before widespread development of wind-integrated flow battery systems occurs. VRB Power Systems and others are working to build the capacity to supply products in volume to the market, as well as to build market awareness of the technology and to continue to drive down the cost of manufacturing the energy storage systems. Just as importantly, utilities are beginning to understand how energy storage can increase the value of their existing system resources, and how it can help them reshape their resource base over time, if necessary.

The notion of complementary ramp rates—of flow batteries and peaking plants matching the falloff from wind farms—is beginning to be discussed and fine-tuned by utility planners. Utilities such as J-Power and PacifiCorp, by installing flow batteries on their grids, are providing invaluable real-world proving grounds and racking up years of performance records that will ultimately make or break the market.

In short, energy storage technologies are rapidly being commercialized to enable the widespread integration of intermittent renewable energy sources into the grid. Hydropower, compressed air, flow batteries, and other technologies continue to be fine-tuned as tools for the utility planner's tool belt. The increasing understanding of how storage can build a bridge from wind power to dispatchable resources creates options that were not available even a few years ago. And, as the months go by, these technologies make it more feasible for an increasingly reliable, clean, and secure electric energy system to emerge.

How Flow Batteries Work

Working like a cross between a standard lead-acid battery and a fuel cell, flow batteries have been around since the 1880s, when one was used to power an airship. After decades of neglect, the concept of the flow battery was picked up by research groups in Australia and Japan in the mid-1980s.



Derived from a patented vanadium-based redox regenerative fuel cell, VRB's flow batteries convert chemical energy into electrical energy. Energy is stored chemically in different ionic forms of vanadium within a dilute sulfuric acid electrolyte. The electrolyte is pumped from separate plastic storage tanks into flow cells across a proton exchange membrane where one form of electrolyte is electrochemically oxidized and the other is electrochemically reduced. This creates a current that is collected by electrodes and made available to an external ciurcuit. The reaction is reversible, allowing the battery to be charged, discharged, and recharged.

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