From workshop proceedings, “The 10-50 Solution: Technologies and Policies for a Low-Carbon Future.”
The Pew Center on Global Climate Change and the National Commission on Energy Policy.

Present and Future Electricity Storage for Intermittent Renewables

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Intermittent Renewables in the Context of Stabilizing Atmospheric CO_2

Stabilizing future atmospheric carbon dioxide (CO_2) levels at less than a doubling of pre-industrial levels will be a Herculean task, requiring a continuous flow of new carbon-free power 2-3 times greater than today’s energy supply to sustain economic development for a global population approaching 10 billion by the mid 21st Century. The sun and wind are the two largest sustainable sources of carbon-free power, but in spite of dramatic cost declines for solar and wind technologies, for the most part they remain more costly today than electric generation from fossil fuels, especially in the case of photovoltaics (solar cells). The costs of solar and wind power are partially offset by their potential benefits as distributed electricity generation sources. However, even if future development reduces their cost substantially, widespread deployment of solar and wind power in the future will face the fundamental difficulty that they are intermittent, requiring demand flexibility, backup power sources, and very likely enough electricity storage for days to perhaps a week.

Energy Storage Technologies

Electricity is not usually stored *per se*. Energy storage technologies instead convert electricity to other energy forms (gravitational, pneumatic, kinetic, chemical), with a characteristic turnaround efficiency usually driven by the simplicity or complexity of conversion and reconversion between electricity and the stored energy form. For example, it can be 90-95% efficient to convert electricity to kinetic energy and back again by speeding up or slowing down a spinning flywheel. Storing electricity by compressing and later re-expanding air is usually less efficient (75%), since rapid compression heats up a gas, increasing its pressure, making further compression difficult. The electric energy lost in energy storage drives up the overall cost of generating reliable electricity from wind or solar power. Another cost of energy storage is the capital investment required for the energy storage system. These costs are driven by the weight of material or volume of containment vessels needed to store a given amount of energy, termed energy density (kWh/kg or kWh/liter), again characteristic of each energy storage form.

Pumped hydroelectric and compressed air energy storage (CAES) are currently economic for utilities when relying on natural geologic formations and the cheapest, most abundant substances (i.e. elevated water and compressed air). In these situations the cost of energy storage capacity can be very low (<$5/kWh[1]) Unfortunately the scale and location-specific nature of energy storage in natural formations is likely to render it of limited benefit to small scale distributed renewables. Available pumped hydro and CAES capacities could prove small in relation to the overall amount of future global renewable electricity—and attendant storage requirements—necessary for massive reductions in greenhouse gases. If energy storage in existing natural formations turns out to be insufficient, then man-made energy storage systems will be needed to support massive deployment of intermittent renewables.

Among man-made energy storage systems, the most well-known is the battery, used today to store electricity from solar photovoltaic systems located where the grid is not available to back up solar power. Batteries are electrochemical energy storage devices which can be relatively efficient (~70-80%) if charged and discharged at moderate rates. Batteries are very modular and are therefore technically well-suited to use with small scale distributed renewables. The chief difficulty of battery technology is short life (~1000's of cycles equivalent to 3-5 years in daily use) which, given the their capital cost ($100-200/kWh of storage capacity), can make storing electricity in batteries at least as expensive as generating electricity. Additionally, in the context of deep greenhouse gas reductions, the sheer scale of raw material needed for batteries (billions of tonnes) would likely outstrip the known reserves of common battery materials (lead, nickel, cadmium), further increasing battery cost. Such huge quantities of battery materials might also need to be recycled nearly indefinitely to minimize disposal issues and environmental impacts.

An emerging alternative to batteries is the high-speed flywheel. Since there are no chemical reactions to reverse and little friction (flywheels are typically levitated by magnets in a vacuum chamber), flywheels have the technical strengths of high efficiency (~95%), high power, and long life. Dubbed "electromechanical batteries" by a chief early proponent, Richard Post, flywheels store kinetic energy in a cylindrical or ringed mass, spinning at very high speeds (~10,000-20,000 rpm), for high energy density (0.1-1 kWh/liter). Key issues for flywheels are safety and cost. Addressing the safety of deploying millions of flywheels would likely require underground use and/or stringent containment designed to withstand high-speed (~ 1000 miles per hour) fragments from a broken flywheel. This will likely place a lower limit on flywheel system capital costs. Flywheel capital costs are currently projected to be $200-500 per kWh of storage capacity at scales of 100-300 kWh of storage capacity, a size larger than appropriate for a single residence, but perhaps better scaled to a neighborhood grid or substation. The performance of flywheels depends critically on the materials of its construction with a significant premium on strength-to-weight ratio. Performance has improved dramatically over the last two decades with progress in ultra-high strength composite materials. If future developments reduce the cost of ultra-high strength materials, flywheels will be substantially more attractive. Currently, flywheels are just beginning commercialization for high-value uninterruptible power applications. If they become economic in a renewables context, flywheels, are likely to be best employed for routinely (i.e. daily) storing small amounts of energy delivered at high power for short times (1-2 hours), or perhaps to smooth out peaks in power demand into and out of a much larger battery storage system (improving battery life).

Electrolytic Hydrogen: A Future Technology for Energy Storage

In the future, predominantly solar or wind power systems will likely require energy storage for days to approximately a week, with or without connections to the electric grid. If so, conversion of electricity to chemical energy is potentially attractive, since chemicals are inexpensive to store and turnaround efficiency is less critical for storage periods of a week or more. The most attractive chemical for this process is likely to be hydrogen (H_2) generated locally by electrolysis of water using intermittent excess solar or wind power. Later, when combined with air or oxygen (O_2) in engines or fuel cells, H_2 can regenerate electricity on demand. Although H_2 electricity storage is less energy efficient (40-50%) than compressed air storage, H_2 has *far* lower costs of storage capacity, since H_2 is a chemical fuel and air is not. For example, a 250-liter pressure vessel designed to store 10-20 kWh of compressed air could store enough H_2 to provide 150-300 kWh of electricity, reducing the cost of storage capacity by more than a factor of 10. H_2 energy storage is therefore economically best suited to situations where the total amount of energy stored is more valuable than efficiency. This should be the case for electricity stored longer than 1-2 days. H_2 may also be stored cheaply without high pressure as a very low temperature (-453 ^{o}F) liquid (LH_2) or by absorption in powders of abundant metals (e.g. iron, titanium, aluminum, and sodium) that release H_2 upon moderate heating (<200 ^{o}F).

Energy Storage within a Hydrogen Transportation Fuel Infrastructure

A predominantly renewable electricity supply could be combined synergistically with a future carbon-free *electrolytic* H_2 transportation sector. Co-production of electricity and H_2 fuel would enable massive deployment of intermittent electric generation by making efficient use of otherwise almost unavoidable excess generation during some time periods. The reliability of solar and wind power could also be improved through intentional "oversizing" of generation capacity relative to demand, since the additional excess electricity could produce H_2 fuel. The energy stored in the H_2 infrastructure and/or onboard H_2 vehicles would be large enough to buffer H_2 demand on the time scale of days. When wind or sunshine were low, higher H_2 prices would temporarily reduce H_2 demand from vehicles. Later, when solar and wind electricity supplies returned to higher levels, accumulated demand for H_2 fuel could be easily met and H_2 prices could drop. Furthermore, if travel patterns and/or vehicle use were flexible over short periods (i.e. days), then the transportation sector could also vary transportation use in response to H_2 supply and cost levels.

Further integration of the electricity and H_2 transportation sectors could, in principle, include the very large latent energy storage capacity of H_2 vehicles as back-up power sources or even routine energy storage. A future H_2 hybrid-electric or fuel cell automobile with 5-10 kg of H_2 onboard (energy equivalent to 5-10 gallons of gasoline) could provide 75-150 kWh of electricity, enough to power a typical home for up to a week. The amount and efficiency of back-up power available from a H_2 automobile would actually *grow* with consumer demands for greater size, power, and driving range. This would turn what is otherwise an engineering challenge (designing a cost-competitive H_2 vehicle with range and performance comparable to or better than conventional gasoline vehicles), into a value-added benefit.

Conclusions/Recommendations

It appears that in the short term (through approximately 2020), intermittent renewables will either depend upon the grid for back-up power or use batteries for energy storage. Flywheels could potentially store energy on a daily basis, especially if flywheel materials improve. In the farther future (perhaps 2040), much larger greenhouse gas emission reductions will become necessary, and with it the need for greater use of intermittent renewables and significant electricity storage. For very large amounts of electricity storage, the availability of geologic formations for compressed air energy storage (CAES) and raw materials for batteries, as well as the need for recycling them, could become limiting factors. If the cost of high strength materials, underground installation, and/or safe containment of accidents limit the maximum deployment of flywheels as well, then electrolysis to produce hydrogen for routine storage for vast amounts of energy worldwide becomes attractive.

The storage needs of a predominantly (intermittent) renewable electricity supply may ultimately be best met in the future by increasing levels of integration with a hydrogen (H_2) fueled transportation sector. In addition to reducing greenhouse gases from transportation, this long-term option could have unique energy security, electricity reliability, and market-efficiency benefits which may be foregone if H_2 production, storage, and vehicle technologies are not developed and deployed in coordination with intermittent renewables.

It is therefore important that hydrogen research and development efforts focus on technologies enabling efficient integration of future carbon-free transportation *and* electricity generation. Examples would include much higher-efficiency electrolysis and fuel cells, and reversible systems that can produce H_2 from electricity as well as electricity using H_2, potentially in homes or on vehicles. In addition, policy attention should be paid to future regulations covering distributed electricity generation, hydrogen vehicles, fuel stations, and electricity systems for buildings to insure economic and efficient interaction between all these critical components of a future energy system powered predominantly by well-integrated intermittent renewables.

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[1] There can sometimes be confusion between the capital cost of electricity storage *capacity* (given throughout this paper in $/kWh of storage *capacity*) and the cost of electric power delivered from storage, usually given in $/kWh or cents/kWh). Generally, the cost of storage capacity ranges from ~ $5-500 $/kWh, and is amortized over many (i.e. thousands) charge-discharge cycles to determine its contribution to the price of electricity delivered from storage.