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The Mountain on the Horizon: Energy Storage

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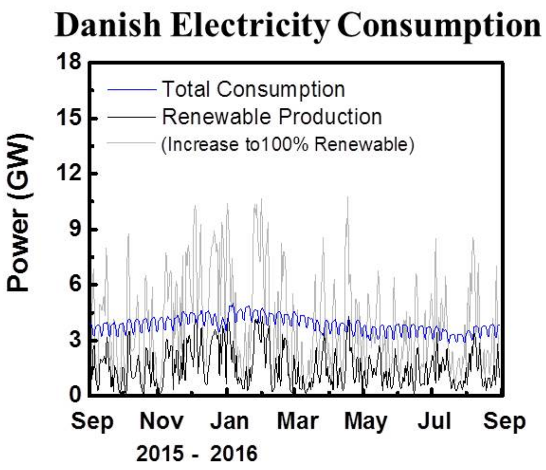
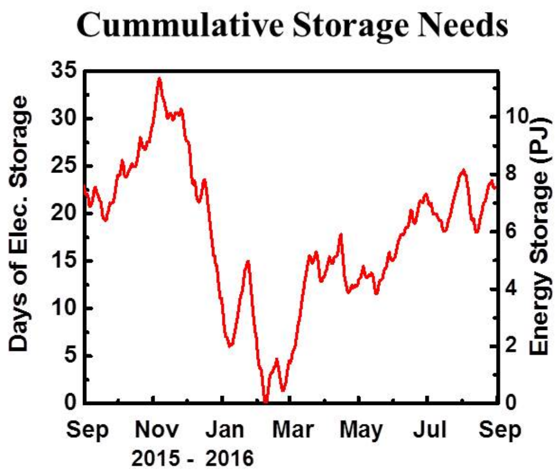
You can see a mountain much earlier than you reach it simply because it is so huge and potentially insurmountable. The same can be said about our energy storage needs for the impending transition to sustainable energy sources. Unfortunately, we are already at the base of mountains barrier of energy storage without a clear idea of how to conquer this or even how big this barrier is. Just like you can go over, go around, or tunnel through a mountain, there are many different options for energy storage. However let's look at the numbers to put these approaches into perspective.

The Demand

On average we use 17.4 TW of energy, thus to store just 1 second of the world's energy we would need 17.4 TJ. Clearly we know we will need storage much longer than that, but the question is how long. Fortunately, countries such as Denmark, Germany, and U.K. all record and publicly display their renewable electricity production as a function of time. While none of these countries achieve 100% renewable electricity throughout the year, they all achieve a very significant fraction of their electricity from renewables. Taking Denmark for example, by upscaling our wind and solar production by a factor of about 2.4 we would be able to achieve *on average* 100% renewable electricity as shown in the figure below. However if we did this for the last year, the fluctuations in renewable electricity production would mean that at one time in the year (Nov. 2015) we would need 34 days' worth of storage to account for underperforming renewables. If we could assume this electricity storage trend correlates to worldwide energy consumption 34 days of 17.4TW corresponds to 51 EJ (or 5.1 x 10^{19} J) worth of storage. This gives us at least an order magnitude number for our storage needs.





Let's look at that assumption though. While Denmark uses wind other countries may base their renewables on hydroelectric, geothermal, or solar. Hydroelectric and geothermal renewables have much less variability, and would need less storage. However, it is estimated that the maximum power hydroelectric and geothermal could produce is 3-4 TW, and 1 TW, respectively. Thus their contributions to meeting the 17.4 TW would be small.

Mountainous

While solar energy is great because the sun irradiates us with over 100,000 TW, the variability between summer and winter is huge compared to wind (60% difference in Denmark between summer and winter solstice). There are other issues that could increase our storage needs, such as increased global energy demand and conversion losses from renewable energy sources. On the other hand, we can easily decrease the need for storage by smart grids, electricity trade between nations, diversification of renewables and efficiency gains by further electrifying society (currently only ~1/3 of our energy goes towards electrical production). If we focus hard on storage optimization, 1-10 EJ seems like a reasonable estimate to base our analysis on.

How do we meet the demand?

Let's look at our options. The most obvious option is batteries with a short-term round trip efficiency of 85-90%. In 2015, we produced somewhere on the order of 400 GW-hr (1440 TJ) of batteries. This corresponds to 83 seconds of energy storage of our 17.4 TW. While there are many different types of batteries (Li-ion, lead acid, nickel-metal hydride, etc.), scalability is the real issue here. Below is a table showing how much material we would need to mine to produce 1 EJ of storage versus global annual production rates. You would basically have to scale up global production 100-1000 times of materials that are already being produced in huge quantities. Flow batteries, normally based on vanadium, are another interesting approach, but they also run into the same scalability issues as traditional batteries.

Battery Material	Amount needed for 1 EJ (megatons)	Annual Production (mega-tons)
Lithium (for Li-ion)	20	0.03
Nickel (for Ni-metal hydride)	510	2.5
Lead (for Pb-acid)	1,584	4.7
Vanadium (for flow batteries)	577	0.08

Table 1: Amount of material for 1 EJ of energy assuming perfect storage.

The second major option is molecular fuels. This can be done via photosynthesis and biofuel production, but photosynthesis is only 1-3% efficient in the best cases, whereas solar cells are typically 15-20% efficient. Thus land management can become an issue with photosynthesis/biomass. Another approach would be to take solar cell electricity and produce fuels via electrolysis. Using electrolysis to turn CO_2 to fuels such as gasoline seems like a brilliant idea, but currently both the selectivity and efficiency for this process is very low. Additionally if we burn this fuel in internal combustion engines, the CO_2 we produce is dispersed throughout the atmosphere at a concentration of 0.04%. Re-concentrating this for electrolysis would be a major practical issue. Producing hydrogen via water (H_2O) splitting may be a more viable approach because water is abundant, self-concentrates into a liquid (i.e. rain) and the oxygen by-product is harmless. However, this process is hampered by a round trip efficiency of ~35% due to inefficient catalysis. With this efficiency we would need to completely electrolyze a lake corresponding to 5 km by 5 km, and 10 meters deep to achieve 1EJ. Since the hydrogen we produce is much less dense than water, even if we compress it to 10 MPa (1500 psi), we would still need 100 times larger volume than the aforementioned lake just to store it. Fortunately, underground salt caverns and old oil wells could provide tremendous amount of storage whereas storing it in steel vessels allows for flexibility and mobility in storage.

Alternatively we could store energy by compressing air into a cavern, and then decompressing it when we need energy. In theory, this approach would need 25 times more storage space than storing hydrogen. However the round-trip efficiencies of compressed air are relatively high (54% now, and 70-80% in the future) compared to hydrogen (30%), thus the actual storage needs would be closer to 10-15 times more storage than hydrogen.

Another storage technique that is already in use is pumping water to elevated locations (like hydroelectric power in reverse). While this can work for small scale situations, as Tom Murphy has pointed out in his blog this would be impractical to scale to the exa-joule scale.

A very simple technique is simply to store the energy by heating rocks, and then retrieving the energy at a later time. The energy can be extracted by boiling water, in a similar manner to how a coal fired power plant works, and thus the infrastructure is already in place. While we have plenty of rocks to store 1EJ of energy, the efficiencies will probably be the same as a coal fired power plant (40%), the storage cannot be mobilized, and this approach would only be viable as a large power plant. Nevertheless, this seems to be a greatly undervalued/underinvestigated storage technique.

Another approach would be to have natural gas fired power plants as an alternative to energy storage. By using sequestration we can pipe the used CO_2 back into the underground caverns they came from thus mitigating any greenhouse gas effects. It costs about 10% of the energy to capture and sequester CO_2, which is notable, but not a show-stopper. A larger issue would be that the capitol costs of building a power plant could never be recouped if its only purpose was to act to fill in the time intervals when renewables lagged. The only way this could work economically would be if the renewable energy producers subsidized the fossil fuels power plant… That's a weird thought.

A brute force approach is to simply build an excess of renewable energy sources. By using the Danish example again, if Denmark would produce 10% excess in renewables annually, this would decrease storage needs by 60% to only 14 days. This simple example shows that one realistic option to consider may be simply to have a slight excess of renewables and just shut them off when not needed.

The front runners in renewable electricity generation are already at the base of this mountainous energy storage barrier. When you are just starting to climb the mountain many paths may look promising especially when clouded by excitement. Hopefully this article has made it clear that that no path comes without its difficulties and this truly is a mountainous barrier we must overcome. Nevertheless by making smart, well-thought out decisions now, we can prevent the need for backtracking and overcome this barrier as fast as possible.