Future Energy Economics

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April 2019

1. Introduction

With continued technology improvements and cost declines, we expect that without incentives, wind is going to be a $0.02 to $0.025 per kilowatt hour product, and solar is going to be a $0.025 to $0.03 per kilowatt hour product early in the next decade. Combining these extremely low costs with a $0.005 to $0.0075 adder for a four-hour storage system will create a nearly firm renewable generation resource that is cheaper than the operating cost of coal, nuclear, and less fuel-efficient oil and gas-fired generation units. We continue to believe that this will be massively disruptive to the nation's generation fleet and create significant opportunities for renewable growth well into the next decade.[1]

- NextEra CEO James Robo

For the record, NextEra is one of the largest and most successful renewable energy firms in the U.S. For more information on them see the above reference and earlier paper linked below, section 3.4.

https://www.energycentral.com/c/cp/large-battery-energy-storage-systems

I occasionally start my papers with quotes, but these are usually short, philosophically intriguing quotes, not long, factual quotes like the above. This quote is quite frightening to anyone trying to invent some form of future power other than the above. This means they are chasing some extremely fast horses. And when these technologies reach the above benchmarks, they are not planning to slow down.

This is also bad news for those trying to save old generation technologies (read: any other than the above). This means they will need to subsidize these (in the short run) by at least 50% for them to be competitive. For the guys who depended on low-price coal-generated power to fund their high-energy industries – you are in deep trouble.

However there is one group (other than NextEra and their kind) that should be very happy: those who have been trying to to solve our current climate change crisis. Low-priced, very-low-carbon power is a big part of this solution. This power is not zero carbon yet because our economy and anything it makes have not evolved to net-zero carbon yet. Also, since the world does not take climate change seriously, improving renewable costs might let us mitigate some of the worst impacts of this challenge.

This paper will describe the basic underlying technologies and associated economics that support wind, photovoltaic (PV) and battery energy storage, and how currently evolving technologies might take a few pages out of their play-book.

[1] Matthew DiLallo, The Motley Fool, "NextEra Energy Continues to Bet Big on Battery Storage", March 30, 2019, https://www.fool.com/investing/2019/03/30/nextera-energy-continues-to-bet-big-on-battery-sto.aspx

2. Photovoltaic Projects

If you go through the link below and to the paper-PDF, section 2.1.1, you will see a detailed breakdown of the cost of various components in PV project. The "Modules" (PV panels) are the largest single component by cost at about 30%, this is followed by "Structural BOS" at about 15% (BOS = balance of system, Structural BOS mainly includes (1) mounting structures for PV panels and (2) trackers), Installation Labor and Equipment (about 14%), Electrical BOS (about 9%), and the inverter (about 5%).

https://www.energycentral.com/c/cp/photovoltaic-plus-storage-%E2%80%93-part-1-technology

2.1. PV Panels

The primary (and most expensive) component in photovoltaic (PV) projects are PV panels. The paragraphs below detail how typical PV panels are made:

The creation of metallurgical-grade (MG) silicon: A mixture of quartzite gravel and/or sand and carbon are heated to around 1500-2000 °C in an arc furnace. The SiO_2 (quartz in the sand/gravel) is reduced to around 98% pure silicon by the carbon taking the oxygen.[2]

Polysilicon production: There are three methods for the production of polysilicon that vary by the purity of the output. The Siemens process is most commonly used due to the high purity polysilicon (99.9999999% or 9N silicon) that is produced through the process. This is the current standard for the semiconductor industry, and is known as electronic grade polysilicon. After the MG silicon has been processed into trichlorosilane ($HSiCl_3$, a.k.a. "silane"), this is introduced to the Siemens deposition reactor. Each reactor contains two slim polysilicon rods. The reactor is heated to 1100°C and polycrystalline silicon deposits on the rods in columnar grains.[3]

The second process is the fluidized bed reactor (FBR) method of producing polysilicon produced medium grade silicon, 6-7N silicon. FBR operates at much lower temperatures than the Siemens process, and does not produce byproducts (Siemens process does). Instead of silicon-rods, the process uses silicon seed granules. These are fed into a chamber with heated silane gas, which fluidizes the silicon granules. As the silane gas breaks down, it deposits more silicon on the granules, which grow larger and exit the chamber once they have reached a sufficient weight. This process uses much less energy than the Siemens process and produces more silicon per cubic meter of reactor space.

The third method is upgraded metallic grade (UMG) silicon. This is produced by blowing gasses through the silicon melt, removing boron and phosphorous impurities. The material is then directionally solidified, creating an ingot of polysilicon. There is no one method for producing UMG silicon: Each company producing this product have their own processes and chemical mixtures that they use.

Each of these processes have their own strengths and weaknesses. The Siemens process is the most expensive method of polysilicon production, but also produces the purest material. FBR polysilicon production is between the Siemens process and UMG silicon in price and quality, making it a potential replacement within the semiconductor

[2] WikiChip, "Metallurgical-Grade Silicon (MGS)", https://en.wikichip.org/wiki/metallurgical-grade_silicon
[3] The Quartz Corp., "Polysilicon Production", 2014, http://www.thequartzcorp.com/en/blog/2014/04/28/polysilicon-production/61

industry. UMG silicon cannot be used in semiconductor electronics manufacturing, but is becoming more popular in PV applications, due to reduced production cost and time.

Polysilicon wafers can be used directly to make PV cells, but they only produce cells that are about 15% efficient vs. about 20% efficient for monocrystalline silicon (mono-silicon). Since the PV panels represent 25% to 30% of the cost of a projects, using mono-silicon panels result in the best project economics. The process for mono-silicon is below.

Mono-silicon ingot production: There are potentially two process used. The Czochralski-technique, which is a method to pull a mono-crystal with the same crystallographic orientation out of melted silicon. First, polysilicon nuggets (optionally with dopants) are melted in a quartz crucible at a temperature greater than 1400°C in an inert gas atmosphere. The silicon melt temperature is kept constant just above the melting point. A monocrystalline silicon seed crystal with the desired crystal orientation is immersed into the melt and acts as a starting point for the crystal formation. The seed crystal is slowly (few cm/hour) pulled out of the melt, where the pull speed determines the crystal diameter. During crystal growth, the crystal as well as the crucible counter-rotate in order to improve the homogeneity of the crystal and its dopant concentration.[4]

With the float-zone technique a monocrystalline silicon seed crystal is brought into contact with one end of a polycrystalline silicon ingot. Starting from here, an RF coil melts a small region of the polysilicon which, after cooling down, forms monocrystalline silicon with the crystallographic orientation of the seed crystal. The RF coil and the melted zone move along the entire ingot. Since most impurities are less soluble in the crystal than in the melted silicon, the molten zone carries the impurities away with it. The impurities concentrate near the end of the crystal where they can simply be cut away. The ingot can be doped during crystal growth by adding dopant gases such as phosphine (PH_3), arsine (AsH_3) or diborane (B_2H_6) to the inert gas atmosphere.

Cutting Ingots into wafers: A diamond saw is used to cut ingots into wafers.

Manufacturing PV cells from wafers: The following are the major steps used to convert silicon (typically mono-silicon) wafers into solar cells.[5]

- The silicon wafers are textured to reduce reflection losses of the incident light.
- Diffusion is basically the process of adding dopant to the silicon wafer to make it more electrically conductive. There are basically two methods of diffusion: solid state diffusion and emitter diffusion. The former method basically involves the uniform doping of the mono-silicon ingots (as described above) with the p-type and n-type materials, the emitter diffusion refers to the placing of a thin dopant material-containing coating on the wafer by passing the wafers through a diffusion coating furnace.
- In addition to the surface texturing, anti-reflective coating is often applied on the surface to further reduce reflection and increase the amount of light absorbed into the cell.
- Metal inlines are printed on the wafer with the objective to create ohmic contacts. These metal inlines are printed on the rear side of the wafer, which is called

[4] MicroChemicals, "Silicon Ingot Production: Czochralski- and Float-Zone Technique", https://www.microchemicals.com/products/wafers/silicon_ingot_production.html
[5] Sino Voltaics, "Solar Cell Production: from silicon wafer to cell", 2015, https://sinovoltaics.com/solar-basics/solar-cell-production-from-silicon-wafer-to-cell/

backside printing. This is achieved by printing the metal pastes with special screen printing devices that place these metal inlines onto the backside. This process is followed by the printing of the front side contacts.

- The now ready-to-assemble solar cells are tested under simulated sunlight conditions and then classified and sorted according to their efficiencies.

Manufacturing PV panels from solar cells: The solar cells are placed on a glass substrate and wired in the designed configuration. Sealed into ethylene vinyl acetate, they are put into a frame that is sealed with silicon glue and covered with Mylar on the backside and a glass plate on the frontside. Finally, the structure is then supported with aluminum frames.

With the above process providing a context, note that photovoltaics are evolving to PERC technology. See the paper linked below, section 2.1.1 for description of how this technology extends the above.

https://www.energycentral.com/c/cp/photovoltaic-plus-storage-%E2%80%93-part-1-technology

2.2. Other Major PV Project Components

Most other major components in A PV project are commonly used in other applications. See the next subsection for synergies between these (including PV panels) and other major industries.

2.3. Synergies

The development of photovoltaic cells and panels occurred in lock-step with silicon based electronic technologies, and these two technologies mutually accelerated high-volume production techniques. In response the price of both technologies declined rapidly. This was called Moore's Law for conventional silicon-based electronics. Gordon Moore, the co-founder of Fairchild Semiconductor and CEO of Intel, observed that the number of transistors in a dense integrated circuit doubles about every two years. Although photovoltaics do not follow Moore's Law per se, they benefit from a similar cost-curve because they share production technologies.

Structural BOS is mainly the structure (racking) that supports the PV panels, the trackers and related hardware. These are commonly used structural components, but trackers (that move the panels for optimum insolation (track the sun) throughout the day) do benefit from growth in automated positioning technology used in many types of production.

Reducing the labor content or skill level required by the workers will continue as more these projects use modular components produced in highly-automated factories. For instance, instead of manually wiring the components together (which requires highly skilled electricians), pre-fabricated, weather-proof cables with screw-on or snap-on connectors are increasingly used. These are also used in virtually all industries that that use electric power.

Although using prefabricated cables increases Electrical BOS slightly, a move to higher string-voltages reduces the gauge of wire required, reducing electrical cabling costs. Quick-disconnect cables and standard designs also facilitates the use of automated test equipment and quick replacement of faulty components on site.

The invertors in a project primarily use power-electronics which benefit from the synergies with other silicon electronics in a similar manner to PV panels.

3. Wind Turbines

The only really unique component in utility-scale wind turbines are the turbine blades. These have moderate synergies with aircraft lift and control surfaces. Adding to these synergies are those between the simulation software used to design aircraft and wind turbine aerodynamic components.

In the last five years as the largest wind-turbines grew to multi-megawatt monsters, it appeared that all of these would evolve away from turbines with gear-boxes to direct-drive designs. This does appear to be happening with off-shore turbines (these are at least twice the average size of on-shore turbines), but on-shore turbines have reversed course and appear to be retaining gear boxes. The trade-off here is that about 10 years ago gearboxes were identified as the least reliable components in a utility-scale wind turbine design, frequently requiring replacement every five years. Direct-drive utility-scale wind turbines have complex generators with a large number of poles so that they can provide 50 or 60 Hz power, while the turbine itself is turning at 10 to 15 RPM. Apparently the gear-boxes have reached a level of reliability to where it is less expensive to initially equip the turbines with gear-boxes, and perhaps periodically replace or refurbish these, than it would be to provide the much more expensive multi-pole generators, at least for on-shore turbines.

For off-shore turbines, the cost of any maintenance is much higher, thus the increased cost of direct drive designs are justified.

The gear boxes for (on-shore) turbines have synergies with marine drives and various industrial drives, however the latter are being displaced by variable frequency drives using power-electronics (like the inverters and dc/dc converters used in PV projects). Ultimately, power-electronics plus cost-optimized generators will probably displace both current on-shore and off-shore generation technology.

Other wind turbine components are mono-pole towers, bearings, nacelles, various instrumentation in the nacelles, and medium-voltage power-transmission components. Most of these have strong synergies with many other products or applications. The few specialized components represent a very small part of the overall cost and will generate relatively large volumes as designs of these are standardized.

4. Battery Energy Storage Systems

Although there are recent signs of life in flow batteries (see the recent paper linked below), a huge majority of battery energy storage systems (BESS) use Lithium Ion (LiIon) battery technology. Also, although there are other significant components in a BESS, the batteries represent (by far) the largest cost.

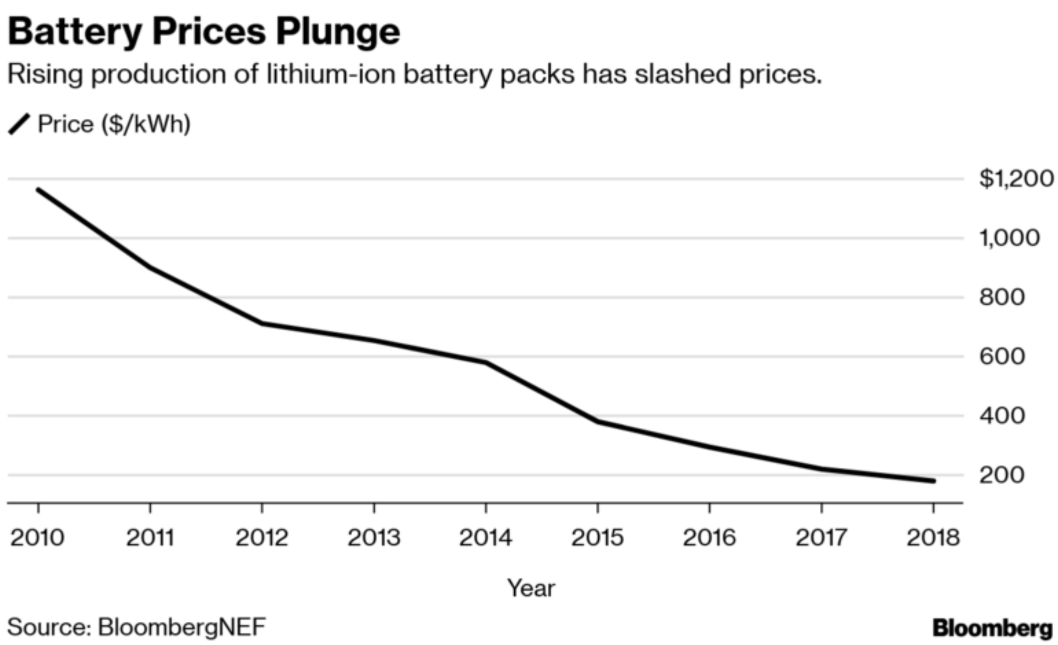
https://www.energycentral.com/c/cp/advances-battery-energy-storage

The source of the strongest synergies for BESS batteries are electric vehicles (EVs). Although LiIon batteries for EVs typically use different chemistry and protective systems than those used for BESS, their configuration, production techniques and materials are basically the same. Thus the economies of scale of EVs and BESS are largely additive. And what is their scale? The U.S. deployed Battery installations for 2018 totaled 311 megawatts and 777 megawatt-hours, according to energy research firm Wood Mackenzie and the Energy Storage Association. But the new achievement for the young industry pales compared to what's to come: an expected doubling in 2019, followed by a tripling in 2020.[6]

Recent history for U.S. EV sales (battery electric vehicles (BEV) plus plug-in hybrids) is 2018: 361,307 vehicles, 2017: 199,826 vehicles, 2016: 158,614 vehicles and 2015: 116,090 vehicles.[7] So far Tesla, Chevrolet and Nissan are the only volume BEV manufacturers offering these in the U.S. Their combined production in 2018 was 224,361 BEVs. The only recent new market entrant is Jaguar (I-Pace SUV) which entered the U.S. Market late last year and have only produced about 1,000 BEVs.

Regarding materials for LiIon batteries, Lithium itself is not rare. It's the 25th most abundant material in earth's crust. It is present in production-quantities in a number of minerals, including spodumene, petalite polylithionite, trilithionite and hectorite clay. There is no doubt the price of elemental lithium will rise with increased consumption, but even a slight rise will bring additional supplies on-line, including in the U.S.

The above paragraph also applies to other materials used in LiIon batteries. Although there has been some concern about cobalt, a relatively rare metal used in the cathode of these batteries, there have been several advancements: less cobalt in the cathode alloy and better recycling of old batteries, extracting the cobalt. The price of LiIon batteries, continue to drop (see chart below), and this could drop below $100 in 2024.[8]



The only other major components in a BESS are the invertor/charger, and the control software. The batteries and inverter (and a few other minor components) either use

[6] Julian Spector, Greentech Media, " US Energy Storage Broke Records in 2018, but the Best Is Yet to Come", March 5, 2019, https://www.greentechmedia.com/articles/read/us-energy-storage-broke-records-in-2018-but-the-best-is-yet-to-come

[7] Inside EVs Monthly Plug-In EV Sales Scorecard, https://insideevs.com/monthly-plug-in-sales-scorecard/

[8] David R Baker, Bloomberg, 2019, "Battery Reality: There's Nothing Better Than Lithium-Ion Coming Soon" https://www.bloomberg.com/news/articles/2019-04-03/battery-reality-there-s-nothing-better-than-lithium-ion-coming-soon

weatherproof enclosures or lighter-weight enclosures (NEMA 1 or NEMA 12) mounted in standard weatherproof shipping containers that include space for the required access.

5. Future Technologies

The keys to success demonstrated by Wind, PV and BESS are:

- Raw materials should be inexpensive.
- Manufacturing processes should quickly evolve to reach mass production.
- Each major component should be built on a foundation of synergies with similar components used by other industries, and
- Synergistic industries should be growing rapidly.

So what future power generation technologies might achieve reasonably rapid growth? Only two come to mind: small modular nuclear reactors (like NuScale) and ocean wave power. I believe the former has a good base to scale up, but not to the extent that it can compete directly with the above economics. However, it will have niches where wind, PV and storage have difficulty. Although I have seen some very limited success for ocean wave power, I believe, at best, it might find some niches where it can be competitive.