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Renewable Energy Systems: Enhanced Resilience, Lower Costs

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The enhanced resilience of today's renewable energy systems, comprising solar photovoltaic and wind electricity generators, coupled with the storage of electricity in Li-ion batteries and solar hydrogen, is a key attribute of current clean energy technology. Referring to selected recent examples, it is shown how families, companies, and entire regions can now safely rely on renewable energy to meet their energy needs.

1. Introduction

The production of power using utility-scale solar photovoltaic (PV) and wind energy has become largely competitive with conventional thermoelectric power generation.[1]

Yet, critics of renewable energy argue that energy production using PV modules and wind turbines cannot be planned to meet demand due to the intermittency of sunlight and wind. Furthermore, they insist that renewable energy systems lack resilience since extreme weather conditions can damage and even destroy solar cells, wind turbines, and hydroelectric dams. Hence, they conclude that modern society will never be able to shift to renewable energy.[2]

Is PV and wind energy power generation ("generation" in the engineering jargon, even though it is always energy conversion) truly less reliable and resilient than conventional power generation? Do extreme weather conditions such as, e.g., hurricanes or heat waves actually restrict or even impede renewable energy production and distribution?

Using selected recent examples, this study shows how, thanks to dramatic technology and industrial progress concerning both renewable energy generation and storage systems, renewable energy has become more reliable and "resilient" than centralized energy generation in thermoelectric power stations. Progress has been so rapid, and its scope so wide and encompassing, that not only families and companies but also entire regions can safely rely on renewable energy for their energy needs.

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2. Enhanced Resilience, Lower Costs

Although there is no consensus of resilience definition in the engineering community and at least four concepts for resilience could be identified by Woods in 2015,[3] resilience when dealing with today's energy generation, distribution, and utilization has largely to do with resilience as sustained adaptability.

With the emergence of renewable energy sources to generate electricity on a large ("utility") and small scale, in both centralized and distributed generation patterns, energy systems resilience translates into "network architectures that can sustain the ability to adapt to future surprises as conditions evolve."[3]

For example, during Australia's 2019 summer, a prolonged heat wave hit the Victoria state. A four-unit thermoelectric power station burning brown coal in Latrobe Valley suffered frequent outages, "putting the stability of the state's energy supply at risk."[4]

During the same days and weeks, the 60.23 MW Gannawarra Solar Farm (**Figure 1**) near the rural town of Kerang (northwest Victoria) continued to smoothly function, supplying up to 50.61 MW of electricity in the form of alternate current to the national grid at 66 kV, charging at the same time the batteries of the 25 MW/50 MWh lithium-ion battery energy storage system (ESS).[5]

The aforementioned ESS supplies power to the grid when required, even at nighttime, balancing the grid and responding to fall in the frequency of alternate current in the grid in milliseconds rather than in minutes as it happens with the fastest thermoelectric power plants. Digitally managed, the system releases or absorbs power from the electricity grid and the solar park depending on the grid requirements.

"Everyone will remember" commented, in June 2019, the Energy Minister of Australia's Victoria, "that in January we had extreme temperatures of 49 degrees. The solar energy powerhouse incorporating batteries was still producing and providing electricity while the coal powered station struggled to function."[6]

In the same country, in South Australia, another large 100 MW/129 MWh battery ESS connected to a large wind park (the Hornsdale Power Reserve) successfully has been participating since December 2017 in the profitable frequency control ancillary services (FCAS) market. The latter market, in Australia and in most world's industrialized countries, conventionally comprises large and costly gas generators connected to steam turbines ready to supply energy following the peaks in power demand.

Figure 1. The 25 MW/50 MWh energy storage system next to the Gannawarra Solar Farm, Australia. Reproduced with permission.[5] Copyright 2019, Edify Energy.

At the end of Australia's summer in May 2018, the Australian Energy Market Operator called the system "much more rapid, accurate and valuable than a conventional steam turbine,"[7] finding that the operation of the new ESS provides "a range of valuable power system services, including rapid, accurate frequency response and control."[7]

Contrary to what critics of renewable energy might argue, lamenting the large amount of public incentives earned by first-generation renewable energy parks, South Australia has been Australia's only state to record a decline in FCAS costs over the period, with savings exceeding $30 million in just a few months.[8]

In the first 4 months of operations of the Hornsdale Power Reserve, indeed, the FCAS in South Australia declined by 90%, and "with only 2% of the overall FCAS power capacity, the 100 MW Hornsdale Power Reserve achieved over 55% of the FCAS revenues in South Australia."[9]

3. Replacing Thermoelectric Generation

Originally designed to improve power dispatching, namely, managing energy flows along the grid so that offer and demand are always balanced, solar PV generation plus storage in large battery ESS has lately commenced to replace thermoelectric power generation altogether. For example, since early 2019, a local utility cooperative in Kaua'i island, Hawaii, has been paying $0.11 per kWh to the owner of the Lāwa'i Solar and Energy Storage Facility on the island's south shore.

The solar power station (**Figure 2**) consists of a 28 MW solar PV park and a 100 MWh battery storage system, employing lithium iron phosphate cathode technology. Alone, the new station delivers roughly 11% of Kaua'i's power demand and has cut the demand of diesel fuel for thermoelectric generation by about 1000 tonnes per year.[10]

Figure 2. The Lāwa'i Solar and ESS in Kaua'I island, Hawaii. Reproduced with permission.[10] Copyright 2018, AES Distributed Energy.

In this way, the intermittent renewable energy generation is converted into high-quality power whose reliability and overall quality are higher than thermoelectric power, and cost is lower. Showing the evidence of today's lower costs of solar PV generation coupled with electrochemical storage, indeed, the 11 cents per kWh price of energy paid by the utility is considerably lower than the cost faced to buy the electricity previously produced by burning diesel fuel.

The integrated solar power station either supplies the grid while charging the battery system or dispatches solar PV and battery power simultaneously to answer spikes in demand. Furthermore, it can supply the grid after a system-wide outage or a natural disaster.

From Nevada to Texas through Arizona, several other large ESSs have recently received approval from USA state governments, and many others will follow, driven by the high profitability of today's and tomorrow's solar PV + ESS solutions. What is relevant here is that some are already working, even in remote areas, where weather and geological conditions are even more demanding than that in mainland.

The technology is extremely versatile and can bear extreme weather conditions. For example, a China-based Li-ion battery manufacturer started to operate in early 2019 in Qinghai Province—a 100 MWh battery ESS coordinating and integrating three different types of renewable energies that feed into it: a 400 MW wind park, a 200 MW PV, and a 50 MW concentrated PV power park.

A three-layer relay protection system ensures protection of the batteries from damage caused by over-charging/discharging and over-current. Finally, since Golmud also lies in an active seismic zone, the whole ESS station was designed and tested to withstand a Richter magnitude 8 earthquake via vibration and shock absorption.[11]

Designed to last for 15 years prior to battery replacement, the ESS is capable of working at temperature from −33.6 to 35.5 °C. A battery management system ensures air passages and air flow to maintain a consistent cabinet temperature, whereas a battery cooling system starts as soon as it detects temperature anomalies, while stored electricity protects the battery from capacity loss or lithium plating caused by charging at a cold temperature.[11]

4. Resisting Hurricanes?

On September 2018, a hurricane ("Florence") struck the North Carolina coast as a Saffir–Simpson scale Category 1 hurricane (wind speeds between 33 and 42 $m\,s^{-1}$). Thousands of residents receiving power from coal-fired utilities remained without electricity for over 2 weeks. A dam breach at a retired coal-fired power plant in North Carolina sent coal ash (the toxic industrial waste obtained from burning coal) flowing into a nearby river. Another had three flooded ash basins, whereas in South Carolina, floodwaters threatened pits containing the same coal ash.[12]

Yet solar PV parks in North Carolina in the storm's path, roughly 1 GW out of 3 GW, suffered poor or no damage and functioned for a few days after the storm. In detail, ahead of the storm, the utility owning 40 solar parks in North Carolina disconnected the aforementioned arrays from the grid and stowed tracking panels in a horizontal position to avoid wind damage. In slightly more than a week, the utility remotely reconnected to the grid all the PV parks where the grid was no longer underwater.[13]

Even better, the state's first utility-scale wind farm (the 208 MW Amazon Wind Farm), consisting of 104 turbines that have been delivering power since late 2016, not only experienced no damage, but also even generated electricity during the storm.[12]

Similarly, 1 year before, the 380 MW Papalote Creek Wind Farm (196 turbines) near Corpus Christi, Texas, experienced no damage when hit by winds of another hurricane ("Harvey") hitting the coast of Texas with Category 1 winds.

In the latter case, the wind farm was back, producing power 1 week after the storm, with one section of the wind farm producing electricity 6 days after the storm and the other the subsequent day (with a 1 week delay in restarting chiefly due to the damage of power lines).[14]

Wind turbines have safety mechanisms designed to prevent damage during extreme winds. Beyond a threshold wind speed, the turbines feather their blades and start rotating around their hub. They will not resist Category 5 or Category 4 hurricanes,[15] as shown by the extensive damage suffered by a wind farm in southern China in 2013, when a Category 4 super typhoon ("Usagi") with wind speed exceeding 75.8 $m\,s^{-1}$ hit the wind farm.

Yet, these events are extremely rare, and even in the latter case, the tower collapse was later found to be influenced by shell-wall thickness reduction associated "with possible design defect... identified to be responsible for the tower collapse during Usagi impact."[16]

5. Enhanced Distributed Generation

At 1:45 a.m. of September 12, 2017, when the winds of "Irma" hurricane hit Gainesville, Florida, a major power outage occurred. The subsequent morning, even if it was a cloudy day, a Gainesville's resident was one of the few residents who had access to power. The 7 kW rooftop solar array installed 2 weeks before the storm smoothly fed electricity both to some of the home appliances and to the Li-ion batteries contained in the inverter. This allowed the resident to use power from the PV modules without being connected to the grid.[17] For comparison, residents in the neighborhood waited several days for grid power to come back.

In brief, adding storage in Li-ion batteries (or in solar hydrogen) to distributed generation via the global uptake of solar PV energy,[18] families and companies can realistically access levels of energy self-consumption until recently are considered out of technical and economic reach.

For instance, in Germany, two-thirds of all the customers of one of the largest utilities owning a PV array produce more electricity over the year than what they consume.[19]

Rather than switching to "virtual" options such as "virtual storage" in a "solar cloud working similar to a bank account,"[19] these families can realistically plan to become energy independent when complete renewable ESSs comprising home battery systems, hydrogen fuel cells, and water electrolyzers are available at affordable prices.

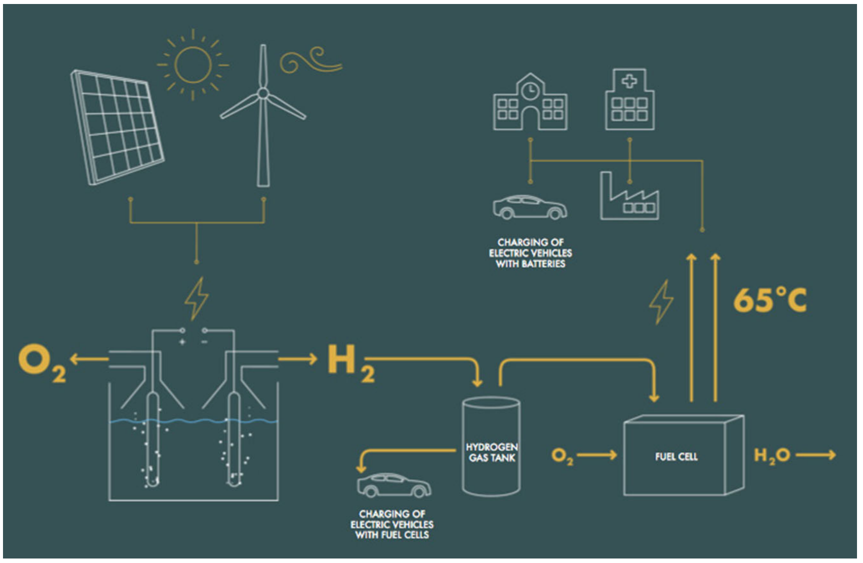

Figure 3. Renewable electricity stored in hydrogen via water electrolysis is then made available again via fuel cells to power (and heat) buildings and battery electric vehicles. Reproduced with permission.[21] Copyright 2019, Nilsson Energy.

Such systems enable providing electricity and heat for 8760 h, comprising the solar year (**Figure 3**). For example, the 172 flats (in six different houses) belonging to the public housing company Vårgårda Bostäder, in Sweden, are currently undergoing refurbishment to become energy efficient, adding a third floor to accommodate more apartments and new roofs optimized for integrating the PV modules.[20]

When phase 1 of the renovation works will be complete in autumn 2019, the first off-grid house of 30 flats equipped with 109 kW PV rooftop modules (conservatively expected to produce 87 000 kWh year^{-1}, essentially between April and September) will start using electricity stored both in Li-ion batteries and in 10 400 Nm^3 H_2 produced via water electrolysis and stored at 300 bar in a centralized solar hydrogen tank.[21]

To understand progress in hydrogen fuel cell technology, it is enough to consider that the previous generation of the fuel cell to be installed at the aforementioned Sweden's homes had a target durability of 5000 h. Yet, the proven durability found by testing the fuel cell under real-life conditions exceeds 12 000 h, with the fuel cell still running and showing no sign of membrane electrode assembly (MEA, the fuel cell core) pitting, corrosion, or other degradation effects.[22]

6. Economic Aspects

The only reason for which in Germany—where the aforementioned two-thirds customers of Germany-based utility produce via rooftop PV more electricity than they consume—the shift to off-grid homes has not yet taken place is due to the ongoing high price of both Li-ion batteries and hydrogen fuel cells in Europe.

The production of Li-ion batteries, indeed, is mostly concentrated in two countries only: China and Japan (followed by South Korea and the United States of America). All other world's countries have a negligible share of the global output.

Accordingly, the price of a large home battery ESS in Germany was around $34 000 by early 2019.[23] Yet, Germany is one of the world's wealthiest countries, and in 4 years between 2015 and 2018, some 120 000 German households and small-business owners purchased and installed a solar PV array with battery storage.[23]

Numerous large Li-ion battery factories are currently under construction across the world. An increase in the lithium-ion battery production capacity is forecast to about 400% by 2028, to surpass the 1 TWh threshold.[24] A similar growth rate is observed for lithium battery recycling plants.[25]

Under these circumstances, when the current shortage of affordable Li-ion batteries and hydrogen fuel cells in Europe is over, home owners will quickly switch to solar PV power plus storage.

Underestimating China's political and industrial commitment to lead the closely related renewable electricity and electric vehicle global industries, most energy experts and government researchers failed in forecasting the dramatic global growth of solar PV first[26] and Li-ion battery and battery electric vehicles later.[27]

The exceptional price decline of both PV modules and lithium batteries has been (and is) driven by reduction in production costs due to booming production,[28] similarly to the trend identified by Wright studying airplane production costs during the 1920s.[29]

Expanding the production of Li-ion batteries in countries beyond China will take time and significant capital investment, whereas the global demand of batteries is booming. Indeed, regardless of forecasts for 2018 of an energy research firm projecting that battery pack prices would decline 14%, "prices actually fell just 6%, due to tight supply,"[30] with solar PV and battery system installation firms in the United States claiming "a shortage in battery supplies is a major drag on the ESS market."[30]

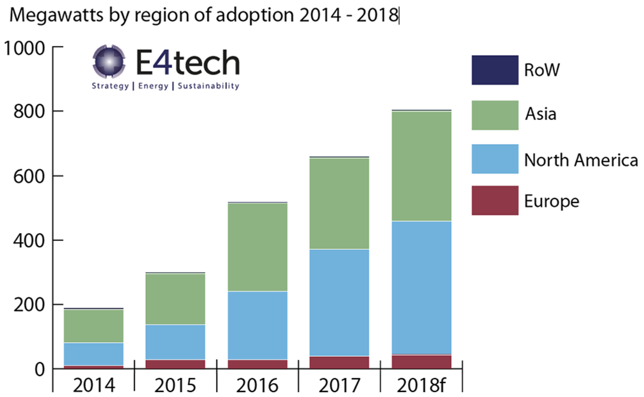

Figure 4. Fuel cell shipments in MW by world's region (2014–2018). RoW stands for "Rest of the World". Reproduced with permission.[31] Copyright 2018, E4tech.

Similar arguments hold for the hydrogen energy industry. After three decades of stagnation and limited production of hydrogen fuel cells and water electrolyzers, in 4 years only (2015–2018), the hydrogen energy industry experienced its first global boom.[31]

Even though mostly limited to Japan and South Korea in Asia, and Canada and the United States in North America, the number of fuel cells shipped in 2018 exceeded 70 000 units and power exceeded the 800 MW threshold (**Figure 4**).

These figures are almost negligible, when compared with battery and battery-electric vehicle production. Yet, aware of the delay accumulated in Li-ion battery industrial production (80% of the world's existing battery production in Asia, with China accounting for 69% of capacity, the United States 15%, and the EU <4%),[32] in 2017, Germany's government started to invest in the hydrogen energy industry: first ordering and deploying the world's first H_2-powered trains, followed by about one new hydrogen refueling station installed each week in the course of 2018 and in the first semester of 2019.

Hydrogen and H_2 fuel cells are ideally suited to power heavy vehicles such as buses, trains, and ships. Furthermore, showing synergy rather than competing with fuel cells, Li-ion battery packs are always incorporated in both today's fuel cell electric vehicles and fuel cell-powered buildings.[33]

7. Conclusions and Recommendations

Dramatic technical and industrial progress in clean energy generation (PV modules and wind turbines), storage (Li-ion battery and solar hydrogen),[33] and energy digital management[34] technologies has opened the route to renewable energy systems of enhanced resilience, reliability, and lower costs compared with conventional energy systems based on burning fossil fuels.

This study refers to selected recent examples to show that families, companies, and entire regions can actually rely on renewable energy for their energy needs on par and with even better reliability than when using energy produced from fossil energy sources.

Originally designed to improve grid stability in aging grids and aging thermoelectric plants causing unstable power supply, solar PV parks and wind farms coupled with battery ESSs lately have started to entirely replace thermoelectric power plants in several regions. As the production of Li-ion batteries scales up, further lowering prices and increasing availability, the number and scope of these applications will continue to grow at a fast pace.

In this context of accelerated change, three main recommendations aimed at policymakers will aid efforts to strengthen local economic growth based on newly available, no longer intermittent, renewable energy.

First, aimed at promoting the progressive replacement of centralized conventional generation with decentralized generation via both large PV and wind parks and rooftop PV arrays, policymakers will support the generalized adoption of battery and hydrogen fuel cell energy storage systems.

Second, aware of the social and economic relevance of solar energy and related new clean energy technologies, policymakers will ask university and research centers to deploy renewed courses and education in solar energy[35] and energy management.[36]

Bezdek, e.g., has lately identified 42 emerging occupations (from hydrogen plant operations manager to director of hydrogen energy development) in the hydrogen and fuel cell industries alone, calling for a rapid review of university and vocational programs so as to incorporate changes "in science and engineering education... to prepare students for hydrogen and fuel cell careers, to understand where opportunities lie and what additional curricula may be needed."[37]

Third, learning from China's exceptional achievements in the field of the clean energy industry,[38] policymakers should promote public and private investments to establish new and crucially important solar cells, Li-ion batteries, hydrogen fuel cells, and water electrolyser factories.

There are many ways to promote and attract national and foreign investments in technologically advanced industries, and each country will identify what it is most suited to its needs, including joint ventures and partnerships with existing companies.

Conflict of Interest

The authors declare no conflict of interest.

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energy storage systems, hydrogen, lithium batteries, renewable energy, resilience

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