RENEWABLE ENERGY

Terawatt-scale photovoltaics: Transform the global energy system

Improving costs and scale reflect looming opportunities

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Solar energy has the potential to play a central role in the future global energy system because of the scale of the solar resource, its predictability, and its ubiquitous nature. Global installed solar photovoltaic (PV) capacity exceeded 500 GW at the end of 2018, and an estimated additional 500 GW of PV capacity is projected to be installed by 2022–2023, bringing us into the era of TW-scale PV. Given the speed of change in the PV industry, both in terms of continued dramatic cost decreases and manufacturing-scale increases, the growth toward TW-scale PV has caught many observers, including many of us (*1*), by surprise. Two years ago, we focused on the challenges of achieving 3 to 10 TW of PV by 2030. Here, we envision a future with ~10 TW of PV by 2030 and 30 to 70 TW by 2050, providing a majority of global energy. PV would be not just a key contributor to electricity generation, but a central contributor to all segments of the global energy system. We discuss ramifications and challenges for complementary technologies (e.g., energy storage, power to gas/liquid fuels/chemicals, grid integration, and multiple sector electrification), and summarize what is needed in research in PV performance, reliability, manufacturing, and recycling.

DECREASING COSTS, INCREASING ELECTRIFICATION

Global average PV module selling prices have decreased by more than two orders of magnitude in a 40-year period (*1, 2*). Two years ago, we observed that if PV could continue on its historical learning curve, then PV module prices would reach \$0.50/W and \$0.25/W at a cumulative deployment of 1 and 8 TW, respectively (*1*). However, by the end of 2018, with only 500 GW of PV installed, the global average module selling price was already below \$0.25/W. Declining costs at the PV system level have translated into a dramatic decline in the price of PV-generated electricity relative to other forms of generation. Electricity prices, dominated by fossil fuel and nuclear generation, have remained relatively constant over a long period in Japan, Germany, and the United States (see the first figure). By contrast, PV prices have decreased sharply, whether tracked as unsubsidized levelized cost of energy (LCOE) (e.g., United States, Japan) or prices determined by changes in feed-in tariffs (Germany).

Various factors have played major regional roles—e.g., increased U.S. natural-gas production, national changes in feed-in tariffs for PV, and changes in the landscape for nuclear power in Japan and Europe following the incident at Fukushima. However, the recent rapid declines in PV system pricing illustrate that we are entering an era in which PV already is or will soon become cost-competitive with conventional electricity generation in many parts of the world.

In Germany, variable renewable electricity capacity (wind and solar) increased from 45 to 98 GW from 2010 to 2016, translating to an increase in grid penetration from 8 to almost 20% (*3*). In California, the fraction of electricity generated in-state from combined utility and residential PV increased from less than 1% in 2010 to ~18% in 2018 (*4*). These examples lead to questions about the next stages of growth, with critics focusing on challenges related to the variable nature of PV. Some research suggested that with current electricity generation operation practices, the value of PV will decrease as PV penetration increases. More recent analysis has identified how changes in operational practices of the existing generation fleet and PV systems themselves could enable much higher levels of PV in the electricity generation system. California is already implementing some of those operational practices, enabling annualized utility-scale PV plant curtailment to stabilize around 1 to 2%. However, if renewable electricity generation continues to increase rapidly without substantial storage and/or load shifting, then curtailment could increase. The challenge is to develop low-cost operational strategies and complementary technologies to accommodate the growing fraction of renewable generation.

Electricity demand could be increased through increased electrification (see the second figure, blue shaded area), including in heating, transportation, desalination, and industrial sectors. A growing body of research concludes that decarbonization of electricity followed by electrification of almost all parts of the energy system is a least-cost pathway for a low-carbon sustainable energy system, with many possible scenarios for PV growth (e.g., see the second figure, green curves). But there are multiple ways to transform the global energy system. For example, PV operates at a much lower fraction of the total generation mix in the World Energy Outlook 2018 Sustainable Development Scenario, in which power generation is largely decarbonized (see the second figure, green dashed line).

TARGET THE TOTAL ENERGY ECONOMY

Providing a majority share of solar in the total energy economy presents opportunities and challenges at the systems level and for research in technologies in related sectors.

Grid integration

Geographic and technology diversity and managing the supply-demand balance over larger geographic footprints could help smooth some of the variability of solar resources, especially in locations where nighttime wind electricity can complement daytime solar electricity and where high-voltage transmission lines can be available. Such approaches may be especially effective in managing short-term variability. Improved solar forecasting already helps to reduce uncertainty in predicting solar output (*5*).

Increasing the flexibility of the remaining generation portfolio would be helpful.

Flexibility in the grid can be provided by energy storage or coordinated demand response to help move energy from when it is produced to when it is consumed or to shift the load to when excess generation from PV is available (*6*). Both energy storage and demand response will be needed to a much greater degree than is used today.

Most central station AC power plants (e.g., coal, nuclear, gas, and hydropower) use synchronous generators, creating a large virtual machine with specific inertial response characteristics. PV systems connect to the grid through inverters that usually synchronize to the nominal grid frequency to export power, but typically only produce real power and do not provide additional grid services necessary to ensure grid reliability. With increasing penetration of PV on the grid, advanced plant capabilities such as voltage regulation, active power controls, ramp-rate controls, fault ride through, and frequency control will become more important.

New installations of PV inverters have the ability to provide essential grid reliability services such as voltage and frequency regulation and synthetic inertia. Recent work examined how large PV plants could provide fast frequency regulation services both for islanded power systems such as Puerto Rico (*7*) and large 300-MW systems in California (*8*). At very high levels of PV deployment, PV systems will need to generate their own voltage reference waveforms and synchronize together. New techniques such as virtual oscillation controllers are being developed that can yield rapid response times and are capable of creating zero-inertia, inverter-based systems. PV is also being paired with battery storage to create more reliable and resilient systems and develop PV plants that can be used as dispatchable power.

Energy storage

At high penetration, increased PV installation is synergistic with increased storage. Tesla recently installed a 100-MW battery in South Australia and in the first 6 months recovered 14% of the capital cost. California is also setting aggressive targets for storage. The price of lithium-ion batteries has decreased by more than 80% in the past 8 years, and improvements are expected to continue through a combination of technological advances and increased manufacturing capacity. To achieve the U.S. Department of Energy battery storage target price of U.S. \$100/kWh, research should explore materials with higher energy density to further reduce costs, focusing on nickel-rich, critical-materials–free cathodes and advanced anodes for lithium-ion systems. With further research and cost reduction, flow batteries and sodium-ion and multivalent-ion or conversion systems could also hold the promise of long-term competitors to lithium ion.

An additional approach to battery-based storage is pumped-storage hydropower (pumped hydro). Recent research indicates that there is a substantial technical potential for untapped off-river (closed-loop) pumped hydro and other forms of gravity storage in many parts of the world (*9, 10*). Pumped hydro has the advantage of being able to provide short-term responsiveness and diurnal-scale storage potentially at low cost.

The biggest challenge may be to meet energy requirements during the winter at high latitudes. However, wind power tends to be more abundant in many of these locations, whereas most of the world's population lives closer to the equator. Economic development as well as population growth may be dominated by countries within 35° of the equator in the coming decades.

Transportation, heating, and industry

The transport sector consumes more than 39% of the fossil fuel components in global total final consumption (TFC) of energy. PV could play a critical role in electrifying the transport sector and providing fuels using renewably generated electrons. Global sale of passenger-car electric vehicles jumped by 63% in 2018 to top 2 million units for the first time, compared to global annual vehicle sales of ~100 million.

Coal, oil, and gas consumed to heat buildings corresponds to about 17% of the fossil fuels in global TFC. Increasing use of heat pumps would enable a dramatic increase in the global share of renewables and increase overall efficiency. Heat pumps with a coefficient of performance of 3 to 4 can reduce end-use energy consumption and enable thermal storage options that may have lower cost than battery storage.

Industrial processes, including huge consumers of fossil fuels such as cement, iron and steel, aluminum, pulp and paper, and chemicals, directly consume about 27% of the fossil fuel portion in global TFC. Very low-cost solar could be used to produce hydrogen and ammonia, which could provide a pathway to substantially reduce greenhouse gas emissions associated with the iron and steel and fertilizer industries and provide precursors for chemical and materials industries.

Power to fuels and chemicals

Very low-cost PV and wind electricity generation could be used to produce hydrogen, methane, or more complex hydrocarbons. Power-to-gas (PtG) or power-to-X (PtX) approaches could use many TWs of installed capacity of solar and wind generation. Storing solar electricity by electrolysis in chemical fuels would enable solar energy to impact many energy sectors beyond those that rely on electricity (*11*) and affect metals refining, biofuels upgrading, ammonia synthesis for fertilizer production, and synthetic fuel generation. Such fuels can be synthesized from hydrogen by combining with CO_2 through the industrial-scale reverse water-gas shift and Fischer-Tropsch reactions. In regions with high solar resource capable of producing electricity below U.S. \$30/MWh, cost-competitive production of ammonia below U.S. \$400/ metric ton (*12*) and of hydrogen below U.S. \$2/kg could be enabled if the capital cost of electrolyzers can be reduced to enable cost-effective intermittent operation (*11*).

In a similar process, methane can be produced from hydrogen using the Sabatier process or biochemical conversion. Methane can be used to heat homes and be distributed through and stored in existing natural-gas networks. Alternatively, reduced intermediates such as carbon monoxide, syngas, or formate can be used in biological or chemical production of chemicals and fuels. It is also possible to electrolyze CO_2 directly and produce feedstock chemicals that are projected to be competitive with production from fossil sources (*13*). There is still much work to be done to increase selectivity, efficiency, and cost-effectiveness.

PV RESEARCH, DEPLOYMENT, AND MANUFACTURING

The "learning curve" in PV, which has demonstrated an average cost decrease for PV modules of ~23% per doubling of the installed capacity from 1976 to 2018, is expected to continue to drive costs down as the market grows to TW scale. Roadmaps for materials and device research for increased efficiency exist in all established technology areas. In silicon, by far the dominant technology with ~95% of the global market in 2018, there is a push for developing low-cost "passivating contact" solar cells, with higher efficiency thanks to a reduced carrier recombination at the metal contact areas. The highest efficiency achieved by a laboratory silicon solar cell has been 26.7%, using an n-type rear interdigitated back contact heterojunction.

Technology advances continue in thin-film and emerging technologies. Within the past year, there have been new record efficiencies in copper indium gallium selenide

(CIGS) (23.4%) and GaAs (29.1%); for CdTe, increased hole density in polycrystalline films by two to three orders of magnitude could provide a viable path to achieving higher efficiency with a cost structure based on polycrystalline starting material. Advances in organic-inorganic hybrid perovskite PV materials include record efficiencies at 20.9% for a ~1-cm^2 cell and 24.2% for a 0.0955-cm^2 cell. The combination of high external radiative efficiency, steep absorption edge, and a V_{oc} (open-circuit voltage) ratio to the bandgap at >90% (exceeded only by GaAs and GaInP among all PV materials), in a solution-processable system, continues to attract attention. Tandem structures also offer exciting opportunities. Mechanically stacked GaInP/GaAs/Si and monolithic perovskite/silicon tandem cells have achieved 35.9 and 28.0% efficiency, respectively.

Another critical research need is to advance the science of PV reliability. Cost reduction by minimizing materials usage and efficiency improvement by new solar cell designs will likely continue to introduce new failure modes. Increasingly accurate modeling of new designs relative to snow, wind, and other climate and application-specific mechanical stresses will be needed to address the different ranges of environment for PV around the world and in new configurations.

Increased production will bring a separate set of R&D challenges and raise the stakes for materials supply, sustainability, and recycling. For current manufacturing, silver consumption is 20 metric tons (±5 tons) per GW of production. At these levels, TW-scale production could exceed total worldwide silver production by 2030. Targeted R&D is needed to reduce Ag use, perhaps via replacement by Cu, coupled with recycling efforts. More broadly, reuse of primary semiconductor materials, addressing embedded energy in terms of extraction and purification, could be an important consideration for sustainability at TW scale. Reuse of both the semiconductor (in new modules) and the glass (in new products) has been demonstrated at a 90% level in CdTe PV recycling

Multi-terawatt capacity also raises questions about funding for manufacturing expansion. The cost of building new manufacturing capacity (CAPEX) is another area where costs have decreased faster than anticipated a few years ago. The typical CAPEX of an ingot-wafer-cell-module manufacturing plant can be as low as U.S. $120 million for a 1-GW/year production line for monocrystalline PERC (passivated emitter rear contact) silicon technology (*14*), and a 20% annual growth rate can be supported by the current gross margin that the PV industry generates.

The earliest PV R&D was driven largely by a need to power the first generation of satellites and launch a new era of space exploration. A subsequent global R&D effort—with major investments in the United States, Germany, Japan, Australia, and China— has brought the PV industry to a point of having greater than U.S. $100 billion/year revenue. Research spanning materials science, module design, systems reliability, product integration, and manufacturing will be required to address the challenges related to multi-TW–scale PV deployment. Addressing these challenges could enable PV to play a critical role in transforming the global energy system.

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Supplementary Materials

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Figure 1: Inflation-adjusted utility power price (black) and utility-scale PV prices (green). **United States**: Error bars for power price indicate the average price for the least-cost and highest-cost market in a given year (excluding Hawaii); error bars for PV indicate LCOE in New York, NY (high bar), and Phoenix, AZ (low bar). Prices are unavailable before 1990; therefore, we used the approximate ratio of high to average and low to average from 1990 to 2000. **Japan**: Utility power price (black) and PV LCOE (green/red) for varying system sizes. **Germany**: Industry power price (black) and feed in tariff prices (green) for freestanding PV. See supplementary materials for source data references.

Figure 2. Recent and anticipated growth of world total final consumption (TFC) (solid blue line) and world electricity (dotted blue line), according to the 2018 World Energy Outlook New Policies Scenario. The shaded blue area represents a possible scenario for an increase in electricity use, reflecting increased electrification. The four green lines provide four possible scenarios for growth of PV cumulative capacity (right axis) and electricity generation (left axis). A constant capacity factor of 1370 kWh/kWp is used to convert from annual energy demand to installed PV in TW. See supplementary materials for details.