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Terawatt-Scale Photovoltaics: Trajectories and Challenges

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The annual *potential* of solar energy significantly exceeds the world's total energy consumption. However, the vision of photovoltaics (PV) providing a significant fraction of global electricity generation and total energy demand is far from being realized. What technical, infrastructure, economic and policy barriers need to be overcome for PV solar energy to grow to the multi-terawatt (TW) scale? We assess realistic future scenarios and makes suggestions for a worldwide agenda to move toward PV at multi-terawatt (TW) scale.

Total renewable power capacity (not including hydroelectric) grew by a factor of 7.7 from 2000 to 2014, to 657 gigawatts (GW). Over this same period, solar PV capacity grew by a factor of 44, to 177 GW (*2, 3*). The relative growth rate of solar has been substantially greater than the growth in demand for electricity (Fig 1). Much progress to date has been enabled by a combination of policy initiatives coupled with technology advances. In Germany, the Renewable Energy Law of 2002 offered a generous feed-in tariff (FIT) without a cap on the number of installations. The resulting rapid expansion of the market in Germany encouraged rapid build-up of the PV supply-chain. Between 2007 and 2012, the global PV market expanded by an order of magnitude – from ~3 GW to ~30 GW (*1*). Global manufacturing capacity grew even more rapidly, mostly in China, with portions of the supply-chain growing to 60-100 GW per year (*11*).

Estimates point toward a 100 GW /year market in 2020. Even the most optimistic International Energy Agency (IEA) projections for an energy pathway consistent with limiting the global increase in temperature to 2°C by limiting the concentration of CO_2 in the atmosphere to ~450 parts per million have under-represented actual deployment of PV during the last decade (Fig 2). This tendency has been a general characteristic of many PV growth predictions.

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The majority of installations in 2009–2012 were in Europe, but PV markets are expanding in more regions of the globe (Fig 3). Most analysts project continued growth of deployment rates. However, the upfront cost can be high, so incentive programs and regionally-tailored project finance structures still drive primary markets (*13*).

With the extension of the Investment Tax Credit through the end of 2019, PV installations in the U.S. are projected to continue at ~10–11 GW per year through 2020. California has taken the unique approach of mandating installation of storage in parallel with renewable energy capacity. This, along with mandated time-of-use rates to motivate use of that storage capability, may enable PV to grow to a larger penetration than has been achieved elsewhere.

With generous FITs and streamlined interconnection, permitting and financing policies, the German PV market grew rapidly beginning in 2008, peaking at over 7 GW of annual installations in 2010, 2011, and 2012. Annual installations fell dramatically beginning in 2013 as challenges associated with continued support of generous incentive programs began to appear.

Japan has seen accelerated deployment of PV since the introduction of FITs and associated policies in 2012 (*15*). Booming PV markets led to severe grid constraints in specific utility companies' service areas and a rapid increase in surcharge (*16*). The government introduced an additional qualification scheme for PV projects and decided to implement a scheduled reduction of the FIT beginning in fiscal year 2017. These measures are expected to create a sustainable and stabilized market (*17*).

POTENTIAL COST REDUCTIONS

We consider two data-driven approaches to evaluate potential for PV price reduction: (i) extrapolating the historical experience curve; (ii) a bottom-up techno-economic analysis to identify how total lifecycle costs can be reduced.

Significant deviations from the historical price versus experience curve for PV modules have been driven by shortages (e.g., polysilicon in the mid-2000s) or oversupply (e.g., in recent years)(Fig 4). Recent analysis suggests it will be difficult to support manufacturing expansion and innovation at current profit margins (*7, 18, 19*), thus prices may return to the historical curve in coming years. Extrapolation of the linear curve suggests a $0.50/W and $0.25/W module price for cumulative deployment of 1 TW and 8 TW, respectively. Crystalline silicon (c-Si) PV may continue on a new trendline, which would result in lower module prices.

Recent techno-economic analysis has mapped potential paths to a levelized cost of electricity (LCOE; essentially the average inflation-adjusted cost over the generating technology's lifetime) of $0.03/kWh that could be achieved in the U.S. by lowering the module price to $0.30/W, increasing module efficiency to 25%, decreasing balance of systems costs (all components other than the PV panels) to $0.35/W and improving reliability (*21, 22*). Reaching an average module price of $0.30/W is consistent with Fig. 4, once cumulative installations are extrapolated to ~5 TW. Some manufacturers will likely meet this type of pricing earlier than others. For example, First Solar recently laid out a roadmap to reach $0.25/W module production cost by 2020 (*23*) and aggressive cost reduction targets are being pursued by most c-Si module manufacturers.

Increases of module efficiency to 25% are quite plausible. SunPower's X22 series is specified to have a minimum total-area module efficiency of 22%. In 2016, Panasonic and SunPower announced record aperture-area efficiencies of 23.8% and 24.1%, respectively, for full-sized modules (*24*). These analyses illustrate the significant impact of decreasing degradation rate to 0.2%/yr and increasing the system lifetime to 50 years. Degradation rates of < 0.2%/y and lifetimes over 30 years have been reported in a variety of locations and products (*25*). Realizing the benefits of longer lifetimes, however, will require innovation in business models and financing.

The bigger challenge will be to achieve improvements in all these areas simultaneously to achieve the greatest market impact. If we consider technologies that have demonstrated efficiency in excess of 20%, the pathway to $0.03/kWh is likely to differ for each approach. Silicon, the market leader, is on a path to $0.30/W module price, or $0.20/W if the price trajectory remains below the historical curve. Higher efficiencies are being demonstrated using HIT (heterojunction with intrinsic thin layer), PERC (passivated emitter real cell) and IBC (interdigitated back contact) structures, as well as shifts to n-type wafers, passivated contacts and other innovations. All indications are that the combination of > 20% efficiency at a price of $0.25/W is a plausible contributor to a $0.03/kWh target for silicon systems without subsidies.

First Solar has demonstrated record cell efficiency of 22% and is increasing module efficiency (record now is 18.6%), with a trajectory to surpass 20%. Recent research (*26, 27*) has demonstrated photovoltages > 1 V, significantly greater than the 0.88 V reported for the current 22% champion cell. If higher photovoltages can be realized, cadmium telluride (CdTe) efficiencies could rival gallium arsenide (GaAs), both with a bandgap that is close to optimal for the solar spectrum.

Copper indium gallium selenide (CIGS) efficiencies and cost have been comparable to those of CdTe (record cell efficiency now 22.3%), but multiple companies are implementing CIGS into lightweight products that could replace roofing material or address other markets for flexible products. Substantial research is needed to optimize deposition of CIGS on flexible substrates to achieve highest efficiencies and develop low cost, durable packages.

Concentrator PV (CPV) modules using multijunction, III-V cells have demonstrated efficiencies in the range of 36% - 39%, with further research likely to push above 40%. Substantial development cost is needed to optimize system design and reduce cost. The learning curve for CPV suggests it would eventually reach a lower price than silicon (*28*), but scaling to the needed volume will require large commercial investment and substantial research to understand critical design parameters.

III-V materials such as GaAs have achieved the highest efficiency of any technology (current champion is 28.8% for a single-junction cell) and have already demonstrated 24% efficiency for a 850 cm^2 module (*29*). Although these modules are very expensive, epitaxial liftoff techniques(*30*) enabling substrate reuse have been demonstrated. III-V modules have potential to reach very low costs with higher efficiency and lower weight than conventional modules.

Research on perovskites has highlighted how materials can be engineered to be defect tolerant, reducing requirements on material quality and enabling ultralow cost manufacturing technology for high-efficiency materials. These materials have caught the imagination of the PV community with their rapid rise in small cell efficiency, increasing from 14.1% in 2013 to 22.1% in 2016 (*31, 32*). Lessons from perovskites may identify a new class of solar cells that can achieve efficiencies comparable to GaAs, but with easily scalable manufacturing.

While the rapid drop in prices has enabled faster growth, these low prices make it challenging to attract investment for development, scale-up and market entry. While silicon is on a path to providing low-cost electricity, continued research and investment is needed in technologies that have potential to provide improved performance at competitive cost. Growth of manufacturing will be necessary to reach multi-terawatt scale over the next decade, and lower factory costs will enable faster growth (*7*).

The ultimate test of a technology is the market. For PV, as prices have dropped the market has grown substantially. PV power-purchase agreement (PPA) prices have dropped by nearly 75% in the last seven years (*33*). PPA prices below 5 cents/kWh are common in the US (*34*) and are believed to be economically sustainable in sunny locations with low-interest project financing and low construction costs, while record bids for new projects in multiple countries have recently gone as low as ~3 cents/kWh.

COMPLEMENTARY TECHNOLOGIES

Grid-integration and flexible technologies available today should enable integration of at least 25–40% variable renewable energy (VRE), i.e., solar and wind, with feasible cost and stability, even with limited use of energy-storage technologies (*36*). One major option for increasing flexibility of grids to accommodate VRE is demand-side management (DSM), which can shift load to times when there is excess electricity from VRE technologies. DSM could include pre-heating or cooling of water for buildings and leveraging their thermal mass to shift energy requirements to take advantage of electricity from renewables. Other methods that help grids accommodate more VRE include increased interconnected transmission, more flexible conventional generation, increased grid balancing-area cooperation, and better forecasting.

When the share of VREs rises above 30-40%, or the grid is non-existent or weak (e.g., isolated areas such as islands), then additional system-level factors must be addressed. In large grids, system inertia is provided by the rotating momentum of large synchronous generators, allowing the grid to ride through short-term system disturbances. VRE will need to provide "synthetic inertia" through fast-reacting power-electronic inverters. They will need to operate at slightly off-peak power to provide both up and down regulation. Inverters cannot provide the same level of short-circuit current as synchronous generators, which will require changing how the grid is protected for short circuits. Solutions include adding synchronous condensers or completely revising the approach to system protection (*38*).

At high levels of VRE penetration, storage technologies will be required to bridge the gap between generation and demand. Electrochemical batteries have attracted considerable attention. The market for lithium(Li)-ion batteries has grown rapidly with the growth of the portable consumer-electronic device market. Reduction in Li-ion battery manufacturing costs is expected to continue (*40*).

The amount of storage needed at a particular price point is a function of the flexibility of the local grid, the value of PV electricity to the off-taker, and the value of other services that energy storage can provide. These determine the energy-storage demand curve for each market—but at a high level, the $150/kWh price target (Fig. 6) is viewed as sufficient to enable significant market growth (*41*). Assuming the $150/kWh battery price is met by 2030, and the number of charge/discharge cycles meets a target of 6,000 by 2020 (*42*), a first-order approximation would suggest a round-trip stored-electricity price of less than 2.5¢/kWh by 2030. Even if one doubles or triples that to account for additional financing, installation and power conditioning costs, dispatchable solar electricity (PV LCOE of 3c/kWh plus 5 c/kWh associated storage) could be economically competitive for a range of markets by 2030. Near-term, there may be other low-cost storage options, including pumped hydro. Longer term prices of storage technologies will likely be set by the battery market leader, which today is Li-ion; we use the Li-ion learning curve as a proxy for storage, as all other options would need to meet or exceed this curve. New market structures that monetize the value of storage will need to be considered to realize the full potential of storage.

In markets such as California, relatively small amounts of energy storage can compete with the cost of peak generating capacity and measurably increase PV penetration (*43*). In areas with high insolation and high electricity costs, energy-storage systems are becoming attractive for households—the current cost-payback time is about 10 years for Australia (*44*). For off-grid small applications in Kenya and India (*45*), the payback can be less than a year.

With new controls and innovative market structures, batteries in electric vehicles (EVs) and plug-in hybrid electric vehicles (PHVs) could act as a flexible load, but also feed power back when connected to the grid, which can further ease VRE grid integration. Some forecasts suggest that EVs will become economically feasible in the 2020s and predict ~400 million EVs on the road by 2040 (*46*). Terawatts of storage capacity could thus be available by EVs alone.

PV must provide electricity, but also a path to fuels for transportation as well as process heat. Power-to-gas can use renewable energy to create hydrogen via electrolysis. To become feasible as storage, power-to-gas technologies need significant cost reductions (*48*). Energy storage in the form of gas or fuel is expected to play a substantial role in future energy systems (*49, 50*).

DEPLOYMENT

PV shipments in 2015 were about 57 GW (*53*). Using this starting value and assuming a 25-year lifetime we estimate challenging but feasible growth rates to reach 2030 target capacities (Table 1). The growth rates are substantially below what the industry has achieved over the past decade, but combine with the challenge of transforming energy systems to accommodate this level of PV generation and the need for a sustainable industry at these levels of production.

Three TW of cumulative PV installations by 2030 should be achievable with continuation of current policies. Increased policy stimulus, continued cost reductions, and technology advances could combine for 5–10 TW of deployment by 2030. 25%/yr growth to reach 10 TW of deployment will require major investment. This requires confidence in a profit margin that is sustainable, which is linked to addressing grid integration and dispatchability issues. Research leading to lower capital cost for manufacturing equipment could reduce the investment needed.

To reach 5 TW by 2030, we identified the following research requirements and priorities: continued innovation and investment to improve reliability and efficiency and to drive module and manufacturing cost reductions; minimize or substitute for use of higher cost or critical materials (e.g., Te, In, Ag, Ga); sustained efforts to advance functionality and reliability of inverters; attention to reducing soiling effects; land-use issues; testing and standards. Public investment in transmission and grid modernization will be required.

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Figure 1. Total world electricity generating capacity (black, solid line), and annual expansions of world generating capacity (black, dashed line) since 1980 (*2, 6*). Solar data (red) are from (3, 7).

Figure 2. Projected (labeled by year of publication) vs actual (labeled as "historical") PV cumulative installations. Historical data are from (*1*). Projections are from World Energy Outlook 450 scenarios in multiple years, as labeled. The 2002 projection was an earlier IEA scenario before the 450 scenario was developed. .

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Figure 4. PV module experience curve showing decreasing module prices as a function of cumulative production (*20*).

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Table 1: Estimated compound annual growth rate (CAGR) to reach TW-scale deployment in 2030 with annual loss fractions per year of 0.02 (past capacity) and 0.04 (newly installed capacity) See SM.