POLICY FORUM

RENEWABLE ENERGY

Photovoltaics at multi-terawatt scale: Waiting is not an option

25% annual PV growth is possible over the next decade

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A major renewable-energy milestone occurred in 2022: Photovoltaics (PV) exceeded a global installed capacity of 1 TW_{dc}. But despite considerable growth and cost reduction over time, PV is still a small part of global electricity generation (4 to 5% for 2022), and the window is increasingly closing to take action at scale to cut greenhouse gas (GHG) emissions while meeting global energy needs for the future. PV is one of very few options that can be dispatched relatively quickly, but discussions of TW-scale growth at the global level may not be clearly communicating the needed size and speed for renewable-energy installation. A major global risk would be to make poor assumptions or mistakes in modeling and promoting the required PV deployment and industry growth and then realize by 2035 that we were profoundly wrong on the low side and need to ramp up manufacturing and deployment to unrealistic or unsustainable levels.

PV is increasingly recognized as a "no regrets option"—a deployment pathway for the critical next 10 years that is available, cost effective, and aligned with long-term sustainable development goals. A growing number of studies are converging on the realization that PV, with electrification and a strongly sector-coupled energy system, is key to decarbonization at scale. Electrification refers to direct [e.g., heat pumps or electric vehicles (EVs)] or indirect (e.g., producing hydrogen or synthetic fuels) replacement of today's fossil fuel use. Sector-coupling is the ability to address variable-generation limitation with flexible demand, storage, and interconnection among energy sectors, including transportation, buildings, and industrial use. The resulting transition could actually lead sustainable future with overall lower energy supply costs (*1*).

However, just as many earlier projections consistently underestimated PV growth because of outdated cost assumptions and limited vision, concerns are raised today about maximum industry growth rates and supply chains. The availability of very-low-cost electricity from PV, in a world that prioritizes global economic development and climate goals, calls for constant reassessment of long-held assumptions and acknowledgment of the rapid rate of growth and change in the field. Plans for 2025 and 2035 not only set the path to 2050 but also increasingly constrain future options if we are not on track.

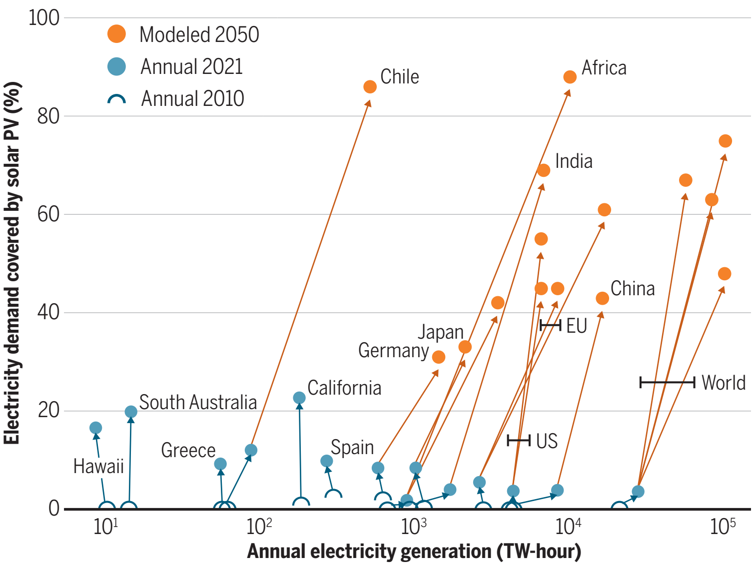
Based on a review of projections for global PV installation targets from various institutions and studies, projections of 2050 demand for PV range from 1.4 to 8 kW per capita, or 14 to 80 TW installed in the next 25 years, assuming a population of 10 billion (all PV installed or projected values are indicated in units of dc peak power). This is a large variation and does not provide clear direction to an evolving industry. Identifying a target range that is aligned with an achievable path to climate goals and economic development is critical for setting both manufacturing and policy goals.

The large variation in projections is associated with varying assumptions about future costs and preferred paths to decarbonization and often underestimates the sustained decrease in PV costs while anticipating decreased costs and rapid growth for other technologies (e.g., nuclear power and carbon capture and storage) that have yet to be realized or even begun. Low-end predictions for required PV by 2050 often also underestimate the increased energy consumption associated with development in the Global South, limit goals for broad electrification, or assume that countries, for various reasons, will adopt higher-cost technologies.

Integrating such large levels of renewable energy into the global energy system is a major challenge in such a relatively short period of time. In addition to the production capacity for PV, other renewable technologies, and storage, this will require a holistic approach that addresses transmission, grid integration, and interconnection. Infrastructure

Regional electricity demand supplied by solar PV

The data reflect annual percentages of historical regional demand (2010 and 2021) and modeled demand projections (2050). See supplementary materials for details.



EU, European Union; PV, photovoltaics.

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planning at this scale must look forward aggressively. Similarly, building and supporting supply chains for PV at the multi-TW scale requires planning and major lead times. Scenarios that substantially underestimate the required scale can limit planning and investment of governments, the PV industry, and other key stakeholders.

If climate, cost, and development goals are all kept in play, then independent modeling from multiple sources projects ambitious, but achievable, goals of 50 to 65 TW by 2050 (*2–4*), even before including future contributions from PV use for the chemical manufacturing sector. To identify what this total energy demand means for the PV industry and deployment, we take 75 TW as a target estimate for 2050 installed PV capacity.

PV FUTURE

This global estimate of 75 TW frames the challenge at hand. High PV growth rates from past decades must be continued. Rapid change has occurred in the past decade in the contribution of PV to the electric grid of various countries and regions (see the first figure). The fraction of electricity supplied by PV substantially increased from 2010, when it was negligible in all major power systems, to 2021, when it achieved a meaningful contribution in a growing number of power systems of different sizes. Local system records have been attained, for both annual average and instantaneous penetration of PV supply, that seemed impossible just a few years ago.

We also highlight the growth required to reach the targets identified in various 100% renewable models (see the first figure). Deployment and system flexibility and coupling challenges exist, especially for the largest power-grid systems (the United States and China), that are associated with technical challenges for high penetration of variable inverter-based energy sources. These are the focus of parallel R&D and investment, but multiple strategies exist to balance solar fluctuations. PV can be combined with wind power, which, in many world regions, shows complementary seasonal patterns. Also, dispatchable generation, such as hydropower, can accommodate operation to enable grids that have a high level of renewable power. Additionally, extended interconnections can be used to balance regional fluctuations, and storage can be used to balance fluctuations in time.

Whereas earlier discussions focused on narrowly matching PV and storage, more-recent approaches and modeling have moved to a focus on flexible demand response and broad sector coupling. The optimal required storage depends on the extent to which the other balancing strategies are used. For PV, electric batteries, which show high cost per energy capacity but also high efficiency, can effectively contribute to balancing intraday solar fluctuations. Pumped hydro storage or the conversion of solar electricity to hydrogen to be consumed in other sectors provides additional storage options. Heat pumps can be used to provide heating or cooling, with the latter having a good correlation with PV generation. Batteries can be both static and in EVs, providing an effective strategy to decarbonize land transport while bringing additional balancing options for smart charging or vehicle-to-grid operation. New battery chemistries, reduced use of critical metals such as cobalt, and increased R&D to identify alternative lithium sources, such as desalination or geothermal brines, are all moving forward to address battery materials and supply issues.

Energy system models and associated PV projections will continue to evolve. Key inputs to continuously assess include (i) up-to-date cost assumptions for PV and all other major components in the new energy system; (ii) high temporal resolution and modeling of balancing mechanisms, including storage and transmission networks; and (iii) modeling of technologies that enable direct electrification and indirect electrification of other sectors. When these requirements are fulfilled, future energy scenarios based on cost optimization project large shares of PV, regardless of the size of the energy system (see the first figure).

Organizations such as the International Energy Agency (IEA) and Intergovernmental Panel on Climate Change (IPCC), which have been and remain conservative regarding the future growth of PV, are now increasingly calling for more rapid scaling of wind and solar in the next decade. This "no regret" option can take us to major GHG emission reductions. Researching the best strategies for the final decarbonization steps, such as technologies to remove atmospheric carbon dioxide (CO_2), should be done in parallel with ambitious deployments of solar and wind to achieve a path that is compatible with the Paris Agreement.

PV MANUFACTURING AND R&D ON THE ROAD TO 2050

Reaching a target of 75 TW of globally installed PV by 2050 will place substantial demands on the manufacturing and R&D communities. Some question the ability of the PV and supporting industries to deliver components at the volume required, at low cost, and with the required quality and reliability while achieving the financial and material sustainability and production security that are expected from a critical manufacturing sector. Indeed, the PV industry over the past 50 years has shown a consistent ability to grow, with a demonstrated doubling of annual production and cumulative capacity every 3 years. At this rate, the next TW of installed capacity is expected to be reached around 2024, and planned build-out of polysilicon capacity suggests that a production rate of 1 TW per year could be reached by 2028 or sooner. The first half of 2022 saw an annual growth in production rate in the range of 45 to 137% of the Chinese PV industry across the entire supply chain of silicon PV, from polysilicon to deployment (*5*). The cost of manufacturing has followed a typical learning curve, with a 24% cost decrease for every doubling of cumulative production.

In parallel, there has been a substantial increase in the speed of translational innovation. Since 2010, the PV industry has gone from a somewhat slow-moving and conservative industry focused on the cost of individual components, where new technologies took considerable time to replace old technologies because of cost, to a very dynamic industry that is more focused on levelized cost of electricity (LCOE, or the estimated

PHOTO: PATRICK HERTZOG/AFP/GETTY IMAGES

Double-usage of land is demonstrated at this Agrivoltaic site in Amance, France, where the simultaneous use of land for power production and agriculture can also reduce irrigation needs in arid lands.

revenue needed to build and operate a generator over a certain period), where innovations are quickly introduced to the market and where technology transitions happen in months to a few years. Examples of these include hydrogenation for defect control, diamond wire sawing, multibusbars, half-cut cells, and increases in wafer size. The latest tunnel oxide passivated contact silicon (Si) PV technology (commonly known as TOPCON) advanced in 5 years from an industrially relevant laboratory design to commercialization and mass production. Fundamental advances in materials chemistry for cadmium telluride (CdTe) PV have recently also made their way into production in record time. Recent analysis shows that it now takes about 3 years for the average cell efficiency in mass production to reach the efficiency of the champion cell fabricated in the industrial laboratory (*6*).

Rapid growth in Si PV has been enabled in part by a clustered industry, first in the United States and then in Japan, Germany, and now China, with major collaboration between industry players and research laboratories (*7–9*). Standardization throughout the supply chain has been an important factor to reduce cost. Over the past 10 years, the cost of building new Si PV production lines has decreased by 50% every 3 years, driven primarily by typical machine throughput doubling every 3 years. During the past 20 years, Si wafer size has increased from 125-mm pseudo-square wafers to 210-mm fully square wafers. With an efficiency increase of 0.5% absolute per year on average, this corresponds to an increase of power output per cell from 2.5 to 10 W. Module power output has increased from 150 to 400 W for residential modules and up to 700 W for large utility panels.

The PV industry, however, is at an important juncture. It needs to demonstrate that it can sustainably and reliably deploy multi-TW of PV systems every year. Supply constraints could have serious impacts on cost and the ability to grow. It is important to differentiate supply chain issues related to volume demands for components such as Si and glass from issues related to potential scarcity of materials. For the current leading Si technology, the main material sustainability issue is silver. Current industrial use is ~15 mg/W. To be sustainable at multi-TW scale, this needs to be reduced to less than 5 mg/W because today's silver consumption for PV is already 10% of worldwide production. Research to replace silver with copper or aluminum is advancing. Other scarce materials, such as indium used for Si heterojunction technologies that combine crystalline and amorphous Si layers, must be assessed in the context of TW-scale demands. Techniques to address the use of scarce materials should be approached from an ecodesign perspective and analyzed by life-cycle assessment to confirm resulting impacts, evaluating metrics such as resource depletion and GHG emissions.

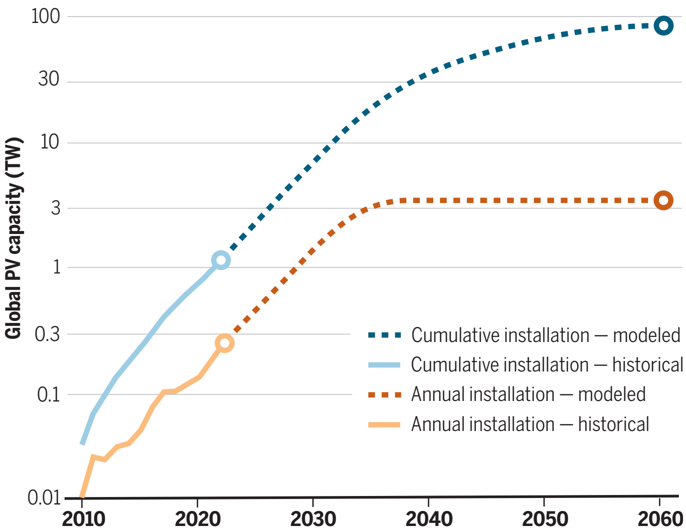
Major PV manufacturers have been reducing their energy, water usage, and CO_2 emissions. Efficiency improvement, larger wafer size, increased batch size, and multilane tools have contributed to this improved footprint, but the main factor has been the reduced use of Si feedstock per unit of power, from about 14 tonnes/MW in 2000 down to less than 4 tonnes/MW in 2021, which is due to a fourfold reduction in the diameter of the steel wires used to slice the wafers. At the same time, improved high-efficiency cell architectures allow the use of thinner Si wafers without performance loss.

We provide one simple scenario for current industry growth to reach a cumulative installation of ~75 TW by 2050, with a steady-state production of ~3.4 TW/year reached in 2037 (see the second figure). Cumulative totals are estimated by adding new installation and subtracting the installation from 25 years earlier, assuming a 25-year module warranty. This means that steady-state cumulative installation, in this case ~85 TW, is not reached until close to 2060, when retirements become comparable to installation.

To reach a target of this order of magnitude in a realistic way, the PV industry must continue to grow over the next critical years at rates of ~25% per year. A 25% per year growth rate, however, is consistent with what PV has achieved in past decades. This simple model could be modified in a myriad of ways but makes clear the order of magnitude of growth that is required over the next 10 years.

PV installations and growth toward 75 TW by 2050

Modeled cumulative capacity going forward is based on sustaining 25% production rate growth over the next 7 years and then reducing slowly to steady state. Replacement needs are included by simple subtraction of installations 25 years before the modeled date.



INNOVATION, DEPLOYMENT, AND SECTOR COUPLING: RAPIDLY AND TOGETHER

Solar PV has become a strategic technology to fight climate change and enable global development. This suggests that its supply chain must be delocalized, not only to reduce logistics costs and embedded emissions but also to ensure uninterrupted component supply. IEA and other institutions have observed that overly concentrated production in a single country or region can limit supply and increase the risk of supply chain disruptions.

R&D for ecodesign and recycling must be ramped up now to support rapid and sustainable scaling of PV. Recycling is not a short-term solution for materials availability issues through 2035, given the relatively low current installation levels and long lifetimes compared with the demands of the next two decades. Product lifetime, reliability, and detailed life-cycle analysis are key levers in minimizing virgin materials needs, waste, carbon footprint, and environmental impact, particularly at the TW scale (*10*, *11*).

As we enter the TW scale of annual global production, the PV industry must continuously innovate to improve material sustainability and reduce the embedded carbon and energy required to manufacture and deploy PV. Increasing material circularity through many different pathways is one way to reduce the emissions, energy, and environmental impacts associated with mining, refining, and upstream manufacturing processes. Responsible scaling requires that the industry reduce embedded energy and carbon at every step (*12*). Because the energy mix used in PV production is a critical factor, increased PV installation will help decarbonize an already green technology.

Improved module efficiency will continue to be important to reduce both cost and space demands. The asymptotic approach to fundamental efficiency limits for single-junction Si solar cells is driving accelerated R&D of potential low-cost tandem structures, both for established (e.g., CdTe-Si) or emerging (perovskite-Si) material combinations. Production of thin-film modules, including CdTe, requires less energy input and produces fewer GHG emissions because they do not require individual wafers. Given the multi-TW need, there is room for a mix of technologies going forward, and thin-film PV, which is competitive for both embedded energy and GHG emissions (*12*), could increasingly contribute as it scales.

To deliver on the promise of PV at this scale, there must be comparable scaling in energy storage and electrolyzers, and PV itself should be able to provide added flexibility to the grid. Building integrated PV can help meet electricity needs in the building sector as well as contribute to heating and cooling requirements. Direct charging of EVs during times of high PV electricity generation is an efficient and sustainable means for transforming large parts of the transportation sector (*13*). Agrivoltaics, the simultaneous use of land for power production and agriculture, can integrate land use while reducing irrigation needs in arid lands (*14*). As emerging economies greatly increase their energy and electricity consumption in the coming years, PV should become the natural choice for energy system expansion. Finally, global attention to the development of hydrogen and hydrogen-based e-fuels and e-chemicals at scale as carbon-free fuels and feedstocks is only possible in a sustainable way if low-cost electricity from PV and wind are available at large scale.

The next decade will be decisive. The path to 2050 needs to include continuing policy support that addresses the real costs of climate change and air pollution and encourages a transition to broad electrification, on-going communication to address rapid change and outdated assumptions, and continued PV R&D and innovation. Of particular importance is attention to global PV supply chains to ensure support for multiple sources at all component levels, as befits a critical and strategic energy supply. Acceleration of permitting, incentives for daytime charging of EVs, and standards and net-zero goals for buildings are all examples of supportive local actions. Multiple countries and regions—including India, the United States, and Europe—have acted in recent years to focus on the complete PV supply chain, encourage distributed production, and create a broader global playing field, though selection of the highest-impact actions depends on regional and national circumstances. Policies that demonstrate long-term commitments to achieve climate change mitigation can provide a market security to support the major capital investments that are required.

Recent history and the current trajectory suggest that sustained global growth in PV of 25% per year over the next decade toward 75 TW of installed PV by 2050 can be achieved. Waiting is not an option. ■

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