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Perspective

Solar photovoltaics is ready to power a sustainable future

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SUMMARY

Thanks to fast learning and sustained growth, solar photovoltaics (PV) is today a highly cost-competitive technology, ready to contribute substantially to CO_2 emissions mitigation. However, many scenarios assessing global decarbonization pathways, either based on integrated assessment models or partial-equilibrium models, fail to identify the key role that this technology could play, including far lower future PV capacity than that projected by the PV community. In this perspective, we review the factors that lie behind the historical cost reductions of solar PV and identify innovations in the pipeline that could contribute to maintaining a high learning rate. We also aim at opening a constructive discussion among PV experts, modelers, and policymakers regarding how to improve the representation of this technology in the models and how to ensure that manufacturing and installation of solar PV- can ramp up on time, which will be crucial to remain in a decarbonization path compatible with the Paris Agreement.

Context & scale

Limiting global temperature increase to 1.5°C requires a rapid and profound transformation of our energy system. Solar photovoltaics (PV) is a mature technology ready to contribute to this challenge. Throughout the last decade, a higher capacity of solar PV was installed globally than any other power-generation technology and cumulative capacity at the end of 2019 accounted for more than 600 GW. However, many future low-carbon energy scenarios have failed to identify the potential of this technology.

In this perspective, we present arguments for anticipating that PVs could become our majority global energy source and argue for an improved representation of this technology in the models. New innovations, at both the solar cell and system levels, could contribute to keeping the high learning rate shown in the past. Neither materials nor land use will prevent PV expansion. The integration of strategies, both existing and under development, could enable solar PV to contribute not only to decarbonization of the power grid but also other sectors through direct or indirect electrification.

INTRODUCTION

Our ability to reduce greenhouse gas emissions by 2030 will determine whether we remain on a path compatible with the Paris Agreement or whether limiting temperature increase to 1.5°C above the preindustrial level is beyond our reach.[1] Solar photovoltaics (PV) is now a mature technology, which is ready to deploy at the multi-terawatt scale and contribute to emission reduction in the short term. Global electricity generation from solar PV is an order of magnitude lower than conventional technologies (it accounted for 2.8% at the end of 2019[2]), but it shows a very steep progression, see Figure 1. Several factors lie behind the plummeting cost and fast ramp up of this technology. One particularly interesting factor is the fact that PV is modular, also referred to as "granular."[3] Identical solar panels of hundreds of watts are combined, by the dozens in rooftop installations, or by the millions in utility-scale power plants. The small unit size and low unit investment have enabled a much faster scaling through replication compared with other technologies,[3] whereas several markets were addressed in parallel based on high modularity and access to solar resources in all countries. Today, solar provides the cheapest electricity in many parts of the world,[4,5] and the milestone of attaining a cumulative capacity higher than 1 TW is expected before 2023.[6,7] Despite the technological achievements, many of the analyses involving future energy scenarios have failed to identify the key role that solar PV could play in 2030 and in 2050 when net-zero emissions are required.[8–12]

Integrated assessment models (IAMs), which include a global representation of energy, economy, land, and climate, are typically used both to investigate transition

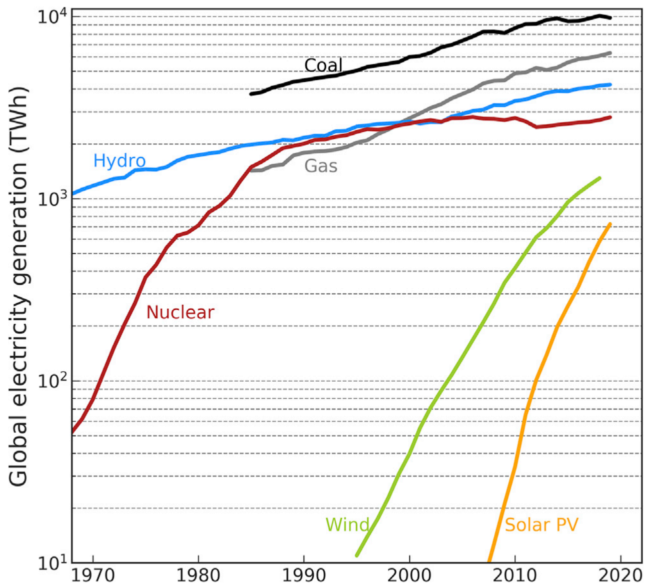

Figure 1. Historical expansion of electricity generation technologies
Original plot with data from BP, 2009.[2]

We identify the following challenges for a sustained scaling up of solar PV in the next decade: ensuring adequate regulatory frameworks that reduce soft costs, reducing capital expenditure via industrial innovations, untapping the demand for PV by enabling electrification of other energy sectors assisted by proper tax schemes, and strengthening research on improving efficiency and reliability of PV systems.

paths under stringent carbon budgets and to determine cost-optimal future scenarios.[8–12] Some IAMs include lower solar PV contributions to sustainable scenarios than those predicted by other analyses (Figure 2A.)[12,13] For instance, the 890 IAM scenarios included in the 5th Assessment Report (AR) of the Intergovernmental Panel on Climate Change (IPCC)[8] considered, on average, a global solar PV electricity generation of 4.9 PWh/year in 2050. For the 311 IAM scenarios covered in the IPCC 1.5°C special report,[9] the average is 12.5 PWh/year. Conversely, researchers in the PV community estimate that in 2050 solar electricity could contribute 41 to 96 PWh/year.[6,14] The main reasons that cause the outputs to downplay the role of solar PV in IAM results are cost assumptions and constraints that limit the maximum renewable penetration in the grid, together with low levels of direct and indirect electrification of other sectors. Those reasons will be examined in detail in the following sections.

Although the underestimation of the solar PV potential in IAMs was initially assessed by Creutzig et al.,[12] Breyer et al,[13] and Fraunhofer ISE,[16] expanding this discussion seems relevant because most of the limitations persist in some IAMs, and the evolution of PV technology in recent years has significantly reduced its costs. Furthermore, the outcomes of IAMs constitute the results included in the IPCC ARs[8,17] and influence the narratives on the energy transition.[18] As an example, the role of solar PV and wind is particularly understated in IAMs when technologies with uncertain development prospects, such as bioenergy with carbon capture and storage (BECCS), are considered. Reinforced by discount-rate effects, such technologies emerge in IAM results showing contributions to primary energy similar or higher than wind or solar PV by 2050[10,19,20] (Figure S1). There are also doubts as to whether the biomass for the assumed BECCS volumes would be sustainably available and whether a solar-PV-based CO_2 direct air capture and storage (DACCS) route would not be more attractive.[21,22] Some IAMs have recently made efforts to improve the representation of wind and solar PV,[12,20,23,24] but there are indications that they could be insufficient in many cases to capture the rapid evolution and critical role of sector coupling. Furthermore, the 7-year cycle for every new AR and the rapid evolution

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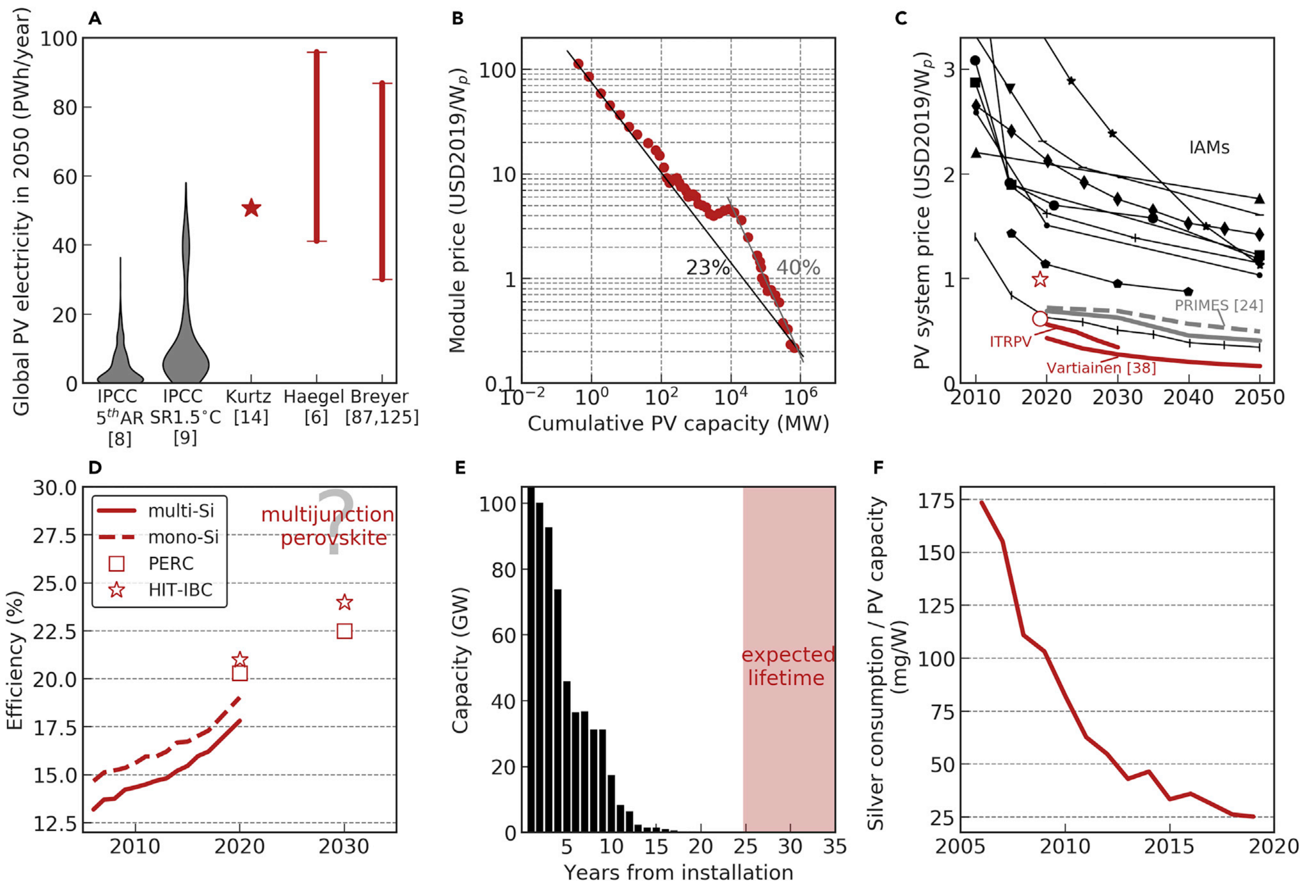

Figure 2. Historical evolution and projected tendencies for solar photovoltaics

(A) Global PV electricity in 2050. Violin plots represent the distribution of results included in IPCC 5th AR[8] and 1.5°C SR.[9]

(B) PV module price versus cumulative capacity.

(C) Cost assumptions for PV plants. The red star (circle) marks the average (minimum) cost in 2019.[15]

(D) Historical efficiency for multi and monocrystalline solar cells and efficiency targets included in the industry roadmap.

(E) Age distribution for existing power plants.

(F) Ratio of silver consumption to PV manufactured capacity. Data sources are listed in the supplemental experimental procedures.

See also Figure S1.

of the PV technology in recent years have widened the gap between the PV mitigation potential estimated by the mainstream IAMs (and included in the ARs) and that based on the technology's current achievements and trajectory.

Similarly, partial-equilibrium models using annual resolution also tend to result in low solar contributions. For example, the PRIMES model, which supports the analyses of policy options for the European Commission,[25,26] estimates that solar PV supplies less than 20% of electricity demand in all the cost-optimal 1.5°C and 2°C scenarios for 2050. This is well below the cost-optimal solar penetration obtained by other energy models including hourly resolution (Figure 3; Table S1). Cost assumptions and lack of proper modeling of the grid-integration challenges are again the key factors behind the underestimation of solar contribution.

In this perspective, we review assumptions and limitations that have prevented a major role of solar PV for some decarbonization scenarios and argue that most of them are too pessimistic in the light of current technology achievements. First, we discuss

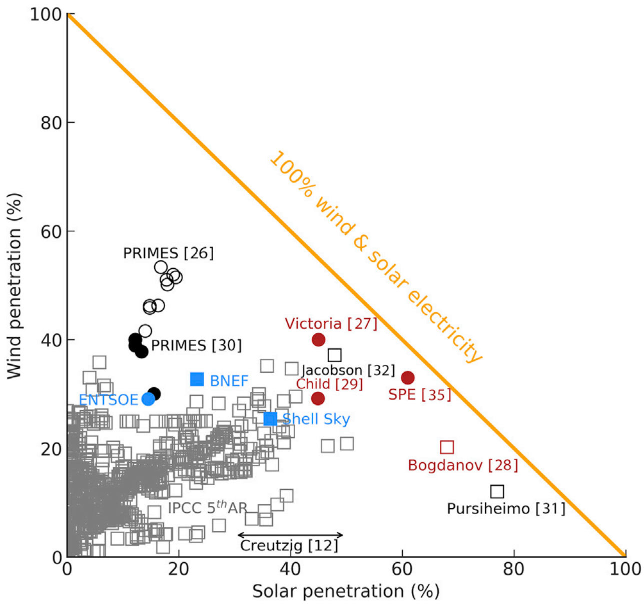

Figure 3. Solar and wind contribution to electricity supply in 2050 obtained with different models
The circles indicate models for Europe, and the squares indicate global models. Gray squares mark the IAM scenarios included in the IPCC 5th AR.[8] Red dots correspond to cost-optimal scenarios obtained with energy models that include sector coupling, uninterrupted hourly resolution, and network modeling.[27–29] The black line marks the range obtained by Creutzig et al. using an integrated assessment model with up-to-date PV cost.[12] Black dots indicate results obtained with the partial-equilibrium models PRIMES[26,30] and TIMES-VTT,[31] as well as results in Jacobson et al.[32] Scenarios, for Europe and globally, predicted by ENTSOE,[33] BNEF,[4] and Shell Sky[34] are also shown. The scenarios in Victoria et al.,[27] Bogdanov et al.,[28] and Ram et al.[35] include the cost assumptions for solar PVs from Vartiainen et al.,[36] as shown in Figure 2C.
See also Figures S2–S4.

cost and efficiency evolution, then materials and land limitation, and finally grid and energy system integration. The final section gathers the main conclusions.

Solar PV is cheap and still have room for learning and reducing costs

The rapid technological evolution of solar PV has made future-cost assumptions obsolete in most IAM models. Krey et al.[37] reviewed fifteen different global and national IAMs and found that all but one assume capital costs for solar PV plants close to or higher than 1€/W in 2050, whereas the average cost in 2019 was 0.995 €/W and the minimum was 0.618 €/W.[15,38] The partial-equilibrium model PRIMES also assumes higher future costs than those predicted by the industry[26,30] (see Figure 2C).

Solar PV modules have maintained a learning rate of 23% since 1976, i.e., their cost reduces by 23% every time the capacity doubles.[39] The main drivers for solar cost reductions include technological improvements, such as efficiency increase[40,41] and those described in Note S1, and high-level mechanisms,[41] including economies of scale, automation, and standardization in manufacturing[42,43] (Note S1), and the existence of a large body of knowledge on silicon materials and devices created by international research that has been gradually implemented by the industry.[42,44,45] The dominant high-level mechanism was different in the various phases of the learning curve.[41] Given that the learning rate is based on module prices, it also includes the elimination of big parts of the margins in PV manufacturing due to strong competition between suppliers.[45,46] Furthermore, the learning rate estimated with data from 2007 onward is even higher at 40% (Figure 2B). This recent learning acceleration is associated with the standardization of the material supply chain for silicon modules, once the silicon shortage was overcome, and the standardization of manufacturing tools being made in China, which has allowed higher throughputs and reduced capital expenditure on equipment.[42] Additional cost reductions in the balance of system (BoS) components,[36] reliability improvements, and lifetime extension further decreased the levelized cost of electricity (LCOE) (Note S2). Access to better financing conditions has also reduced solar LCOE.[47] It is noteworthy that all the previous mechanisms were catalyzed by policies that stimulated market growth through feed-in tariffs or renewable portfolio standards.[41] Looking ahead, those key drivers, together with further reductions in soft costs,[48] are expected to keep lowering the cost.

The roadmaps for PV technologies[39,49] describe diverse strategies to increase efficiency that we briefly summarize here. Silicon solar cells comprise more than 95% of PV capacity installed in 2019. Passive emitter rear contact (PERC) technology[50] has been quickly adopted by the industry (65% of market share in 2019) reaching an average module efficiency of 20.3%, which is predicted to rise to 22.5% by 2030.[39] The record efficiency for silicon solar cells is 26.7% and was attained by using amorphous silicon-crystalline silicon heterojunction (HIT) and interdigitated back contacts (IBCs).[50,51] The latter increases efficiency by eliminating the shadow of the front contact. Average HIT module efficiency is at 21% and the industry roadmap predicts attaining 24% in 2030.[39] Tunnel-oxide passivated contact (TOPCon) could also provide an additional percentage increase in efficiency in the short term.[49] The quick learning of perovskite solar cells could enable an additional route for efficiency increase once the stability is improved.[52,53] When combined with silicon in a double-junction solar cell, 29.1% efficiency has been reported,[51] enabling a commercialization pathway toward 30% efficient perovskite/c-Si tandem modules.[53] Finally, multi-junction solar cells based on III-V semiconductors are the PV devices attaining the highest efficiency. The record six-junction solar cell achieves 47.1% efficiency at 143 suns by converting different parts of the spectrum into electricity.[51,54] Multijunction solar cells are used in space applications and can be combined with concentrating systems to generate electricity on the ground if significant cost reduction is achieved for such systems.[55]

Industrial innovations in the pipeline include pushing toward larger cells and modules, cutting them in half or more to reduce electrical losses,[42] and using multi-wire to reduce resistance and shadow losses, while at the same time reducing the use of silver.[56] Moreover, existing developments outside of standard PV modules show that there is additional room for innovation. Single-axis tracking, which accounts for 30% of the market today,[39] increases the energy yield by boosting electricity generation in the early morning and late evening when it matches electricity demand.[57] Bifacial solar cells,[58] which convert irradiance reaching both sides of the panel into electricity, account today for 20% of the market and are expected to gain market share.[39] Combined with single-axis tracking, they can achieve very competitive costs in most parts of the world.[59] On top of module cost, BoS and soft costs impact the total system cost (Note S2). BoS comprises wiring, mounting, and other area-dependent components, which will also benefit from an increase in module efficiency.[36,60] BoS also includes the inverter required to convert DC power generated by the solar panels into AC power and the grid connection. Inverters traditionally dimensioned with a DC/AC ratio of ~1.2 are shifting toward higher ratios, i.e., clipping part of the DC power in hours with high irradiance is worthwhile given that the utilization of the inverter and grid-connection capacity is increased. The cost-optimal DC/AC ratio can be as high as 1.7 for certain locations.[61,62]

As the module and BoS costs shrink, decreasing soft costs also becomes crucial. Soft costs, which include financing, planning, permitting, inspection, and interconnection (PPI), as well as land acquisition, installation labor, and profit, show a wide range among different regions[15,38,48] indicating that there is room for cost reductions as solar PV diffuses locally. The perception of solar PV as a mature technology and auctions, which have become the preferred method for governments to select new solar capacity worldwide,[38] decrease the risk and the financial costs, which in turn reduces the cost of solar electricity.[36] Improvements in maintenance and lifetime will also lower the cost. The efficiency of crystalline silicon modules degrades by ~0.5%/year.[63] This might enable lifetimes longer than the 25 years traditionally assumed. Because the average age of solar plants is still low (Figure 2E), research in degradation and maintenance strategies for solar modules and BoS materials[64] will be key to extending their lifetimes. Under low investment costs, operation and maintenance (O&M) become increasingly important and can account for 25% of the life cycle costs in solar power plants.[65] The existence of a high learning rate for O&M costs, estimated at 18% in Germany,[65] means that PV plants hold cost-reduction potential even after commissioning. Application of AI to diagnose operational status and failure of PV systems is expected to reduce O&M costs. The poor representation of policy-driven demand has also been identified as a potential limitation in IAMs.[12] Agent-based modeling has been proposed[66,67] to study PV diffusion and consumer choices, overcoming some of the limitations of IAMs and partial-equilibrium models.

We conclude this section by providing some suggestions. The previous experience and the innovations in the pipeline showed that solar PV is a dynamic, fast-evolving technology, and this should be reflected in the models. When modeling future energy scenarios, up-to-date cost assumptions must be included. The PV industry keeps up-to-date records on the learning rate and cost evolution of the technology.[15,38,39] We recommend including an endogenous learning curve that captures the learning effects and conducting sensitivity analyses to investigate the impact that the assumed learning and growth rates can have on the results. For instance, Creutzig et al.[12] found that implementing this strategy in REMIND, a specific IAM, resulted in solar PV covering 30%–50% of global electricity demand in 2050 (compared with 5%–17% share in previous results[68]).

Materials and land-use limitation

The availability of raw materials is not a real issue that limits the growth of PV manufacturing. Materials availability could be a constraint for thin-film technology[69,70] but not for silicon solar cells, which account for 95% of the market today.[71] Silicon is one of the most abundant materials on Earth. In 2019, the PV industry consumed 10% of global silver demand[72] which is used to manufacture the cell contacts. Thanks to the increase in efficiency and the use of thinner contact fingers, the use of silver per watt has significantly reduced in the last years (Figure 2F), and copper or aluminum could be used as a replacement if necessary.[39,43] The noncell materials in PV (glass, plastic, aluminum, concrete, and steel) are not expected to represent a limit either.[70] Fortunately, incorrect assumptions on material constraints are not common among IAMs, but there are some exceptions, e.g., an outdated silver consumption of 133 mg/W, which is more than five times higher than current value, is assumed in the analysis[73] associated with one IAM. The PV industry is already on the way to a circular economy. As a standard practice today, PV modules run through existing glass- or metal-recycling lines where the aluminum frame, external copper wire, and glass are recovered, which represents a mass-recovery rate that is higher than 75%.[74] Processes whose technical potential enable recovery rates of 94% for silver and 97% for silicon have been described.[74,75] The interest to industrialize those processes will increase as the large capacity installed in very recent years reaches its end of life (Figure 2E).

Supplying the current global electricity consumption with solar PV would imply covering 0.3% of the land area of the world (Note S3). PV modularity enables residential and commercial installations, as well as utility-scale power plants. In the former, solar panels can be installed on rooftops and facades potentially supplying more than 25% of electricity demand in most of the USA states[76] and Europe.[77] Utility-scale plants can be installed in dry areas that are not suitable for agriculture, although their ecological and social effects must be considered.[78] Furthermore, other strategies have recently emerged. In floating PV, solar panels are placed on water bodies, such as calm equatorial seas or hydro reservoirs,[79,80] enabling the reservoirs to act as virtual batteries.[81] Agrivoltaics, i.e., combining agriculture land and PV, can offer additional benefits.[82] In dry areas, soil humidity beneath the panel increases, reducing the need for irrigation.[83] In windy regions, vertical solar panels could act as artificial trees reducing the wind and increasing crop yields. Sparse strips of solar panels installed on agriculture land can serve as biodiversity reservoirs.[84] Other dual-use of infrastructures such as irrigation channels or sound barriers have also been proposed.[85] Of course, the forecasted PV development, land cover, and cost projections are not based on these PV configurations but on classic densely packed utility-scale power plants. Nevertheless, these embryonic applications show that there is still room for innovation at the system level. In summary, although available land can limit solar PV at local levels, it will not be a limitation at a larger scale, and therefore, we recommend that models include accurate and up-to-date constraints based on materials and land availability. The increase in efficiency and the strategies to improve annual energy yield described above will help to address the land-limitation issues in specific locations.

Grid and energy system integration of high shares of solar electricity

One of the main factors that hinders the role of solar PV in decarbonization pathways envisaged by IAMs, or partial-equilibrium models such as PRIMES (Figures 3 and S2–S4; Table S1), is related to the fact that such models use annual resolution. To circumvent the limitation of not modeling the supply and demand in every hour, additional constraints are imposed, which might be too pessimistic. Some models include integration costs, which are added on top of technology costs, and which can reach 23 $/MWh for solar and 37$/MWh for wind in low-penetration scenarios (<20% of demand)[68] and increase to above 100$/MWh for higher penetrations.[86] Assuming high integration costs, despite the existence of alternative, cheaper balancing strategies, hampers the role of solar PV in cost-optimized results. In other cases, an exogenous constraint limits the maximum share of wind and solar power in electricity generation, e.g., 30% limitation is used in some models.[12,68] Pietzcker et al.[24] have assessed different strategies to improve the representation of integration costs in IAM. The average electricity supplied by wind and solar PV increased from a model-averaged of 38% to 62%, but the new, simplified representations of integration cost might still be over constraining the results. Some IAMs have started to conduct harmonization exercises with hourly resolved models of the power sector[87,88] and investigated high electrification pathways,[89] which could provide useful insights. The trade-offs of reducing time resolution have been analyzed by the energy modeling community[90–93] and insights could be incorporated to IAMs.

Table 1. Challenges and strategies for high solar PV penetration in the grid at different timescales

Timescale	Interannual	Seasonal	Hours	Minutes-sub seconds
Challenge	solar generation interannual variability is low. climate change impact on solar generation expected to be low.[101,102]	significant seasonal difference in PV generation only for high-latitude locations.[a] not significant for most of the world population living in the Sun Belt.	balancing the strong daily generation pattern.	lower inertia in the power system is a challenge, but it does not limit the maximum wind and solar penetration in the grid.
Strategy	robust design and operation of energy systems considering interannual variability	- balance with wind, which shows opposite seasonal dependence[103] - reinforce interconnections among neighboring countries - sector coupling provides higher demand flexibility and lower storage costs in other sectors - long-term storage (e.g., power-to-X)	- electric batteries - pumped hydro storage - demand-side management - additional flexibility brought by sector coupling - EVs with demand-side management and power-to-grid capabilities - high temporal correlation of cooling demand and solar generation - interconnections over large areas to smooth out local weather	- grid-forming inverters - synchronous condensers - batteries providing synthetic inertia - pumped hydro storage - PV and wind can contribute to upward regulation (if operated at reduced capacity) and downward regulation (if curtailed)

[a]This is the only challenge showing high complexity. The others show low complexity.

The share of global electricity supplied by solar PV in 2050 average to 10.6%/19.6% in IAM scenarios included in the IPCC 5thAR[8] / SR1.5[9] (Figures 3, S3, and S4). Although some scenarios include higher shares, historical growth rates, combined with the issues discussed above, suggest that significant underestimation might still be a concern. Another key factor is that most of those IAM scenarios include a limited direct or indirect electrification of other sectors. The contribution of solar electricity to primary energy in 2050 averages to 3.1%/6.8% in the IPCC 5thAR[8]/SR1.5[9] (Figures S2 and S4). Conversely, several analyses based on sector-coupled energy modeling approaches[27–29,94–96] found that deep electrification of other sectors (directly or indirectly by, e.g., synthetic fuels) is a cost-effective strategy to enable timely decarbonization.

Next, we first review the existing challenges and strategies to balance PV generation at different timescales. We then discuss how the proper modeling of all the existing strategies for balancing enables the emergence of solar PV as one of the main energy sources in cost-optimal decarbonized scenarios.

Matching variable renewable generation and demand entails challenges at different timescales. We focus here on those particularly relevant for solar PV (Table 1), but we keep in mind that onshore and offshore wind generation, and its associated variability, will also be a significant contributor in future power systems. We start by discussing seasonal variation. For high-latitude locations, solar generation in winter and in summer show large differences. Fortunately, wind generation typically shows the opposite seasonal trend.[97] Furthermore, most of the world's population lives in the Sun Belt close to the equator where the solar resource is abundant and seasonal variation is low (see Figure 4). Tropical locations, despite repeating weather patterns such as monsoon, show low seasonal variation in solar resources.[98] Moving now to the hourly balancing, the strong diurnal solar-generation pattern produces an excess of generation in the middle of the day and requires ramping up balancing technologies as solar generation vanishes after sunset. Power systems are already prepared to deal with hourly variation in electricity demand, so the initial solar deployment (demand being covered by solar <20%) can be easily integrated into the system without further modifications. For higher penetrations, short-term storage with

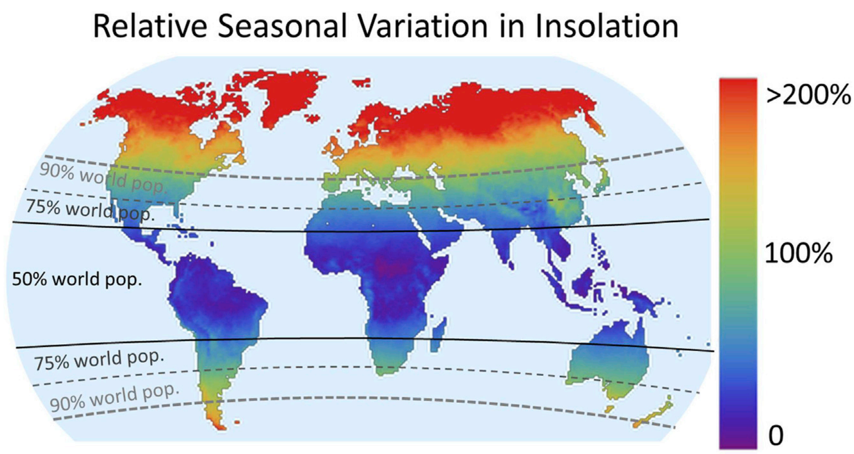

Figure 4. Relative seasonal variation in solar resource-
For every location, relative variation is calculated as the 80 percentile of daily insolation on the horizontal surface in the sunniest month minus the 80 percentile of daily insolation in the least sunny month, divided by the average daily insolation. Original plot with satellite data from NASA.[104] The depicted seasonal variation in solar resource is an upper limit for the variation that can be expected in solar power generation because of local variation in the utilization of direct and diffuse radiation.

high-efficiency, i.e., electric batteries, pumped hydro storage (PHS),[99] and demand-side management contribute to energy arbitrage to ease the intraday balancing of solar PV-.[100]

Finally, it is well understood that solar does not contribute mechanical inertia to the grid stability in the minute-subsecond timescale. Several strategies exist to deal with the reduced system inertia caused by increasing variable renewable penetration. First, grid-forming inverters can regulate the system voltages and frequency through local, decentralized control.[105] Second, the use of synchronous condensers to provide reactive power and inertia has been successfully implemented in Denmark and Australia, and conventional power plants can be retrofitted into synchronous condensers.[103] Solar can contribute to upward regulation (when operating at reduced capacity) and to downward regulation by curtailing. Batteries can also be operated to contribute to ensuring grid stability.[106–108] Pumped hydro can provide both mechanical inertia and rapid response (in tenths of seconds). It is interesting to note that South Australia recently operated for an hour with 100% PV electricity,[109] and already in 2015, Denmark's power system was operated without dispatching primary central power stations for several consecutive days in which wind supplied most of the electricity demand.[103] Frew et al.[110] showed that, with appropriate changes to grid operation, 55% PV penetration could be achieved in the US power system in 2050, while ensuring resource adequacy, addressing net-load variability, and providing sufficient operating reserves. In summary, the existing field experience and literature[105,111] do not indicate a maximum wind and solar penetration above which the system's operation is not feasible in the sub hourly timescale.

Besides the power system, solar PV can significantly contribute to decarbonizing other sectors while benefiting from the additional flexibility provided by sector coupling. Rooftop PV enables charging electric vehicles (EVs) reducing the need for distribution-grid reinforcement. The short-term storage provided by EV batteries synergizes with PV, easing the daily balancing of solar generation,[112] in particular when demand-side management and vehicle-to-grid capabilities are assumed for

EVs.[94,100] EVs can also be considered a granular technology[3]; their short renovation times enable mutual benefits from a fast PV deployment in the next decade. PV can also contribute to decarbonizing the residential and services sector by successfully competing with gas for low-temperature space heating and water heating with the assistance of electric heat pumps. Solar can also supply refrigeration demand, which is highly correlated in time with solar generation[113,114] and is expected to increase due to climate change. As solar becomes cheaper, it begins to compete with gas and coal for industrial heating through the use of high-efficiency electric furnaces. This can be coupled with low-cost on-site thermal storage in water, hot rocks, molten salts, molten silicon, and other materials to take advantage of low-cost daytime solar electricity.

Moreover, low-cost solar electricity could be used to produce electrolytic hydrogen that substitutes hydrogen from steam-methane reforming. This could reduce emissions associated with ammonia production and fertilizers in the agricultural sector and cover the entire chemical industry with related green methanol as the new bulk chemical.[115] Electrolytic hydrogen could also curb emissions in steel manufacturing by shifting to direct-reduced iron. Moreover, hydrogen can also be used as fuel for long-distance road transport and shipping[116,117] or used to supply high-temperature heat in the industry. In the Sabatier reaction, hydrogen can be combined with direct-air-captured CO_2[118] to produce synthetic methane, ensuring system operation in the critical weeks with low renewable generation and high heating demand.[94] It can also be combined with additional CO_2 in the Fischer-Tropsch reaction to produce synthetic hydrocarbons for aviation or to be used as feedstock in the chemicals industry. The flexibility provided by electrolyzers can not only stabilize the grid[119] but might also enable a most effective balancing of the entire energy system as indicated in the case of Europe.[94,100,35]

Before concluding this section, we should highlight that solar PV emerges as one of the main, if not the main, energy sources in cost-optimal future decarbonized scenarios when using models that include proper representation of all the aforementioned balancing strategies. i.e., when the models (1) use uninterrupted hourly modeling for a whole year, (2) use time series that represent solar generation at a country level by aggregating data with high spatial resolution (~40 km^2),[120] (3) allow the exchange of electricity among countries, (4) and include detailed coupling of the power system with other sectors such as heating, transport, or industry. For instance, Victoria et al.[27] and Child et al.[29] agree in estimating the share of solar electricity by ~45% in Europe in 2050. Energy models with high spatial resolutions (dozens of nodes per country) have also predicted a prominent role of solar PV.[121–124] Although the large seasonality in heating demand in Europe, opposed to solar seasonal variation, limits the solar PV penetration in that region, it is important to acknowledge that most of the global population, expected population growth, and energy demand growth are located at lower latitudes where the solar resource and energy demand show low seasonal variations (Figure 4). Bogdanov et al.[28] and Ram et al.[125] found that the optimal solar share increases to 68% for a global analysis not only for the power sector but also the entire energy system (Table S1).

Finally, historical field experience indicates that solar PV penetration is increasing rapidly. In 2010, no large power system existed in which solar PV supplied more than 3% of the annual demand. In 2019, solar PV supplied 9% of electricity demand in Germany and 19% in California (Figure 5). Existing plans contemplate penetration higher than 20% in several power systems by 2030.

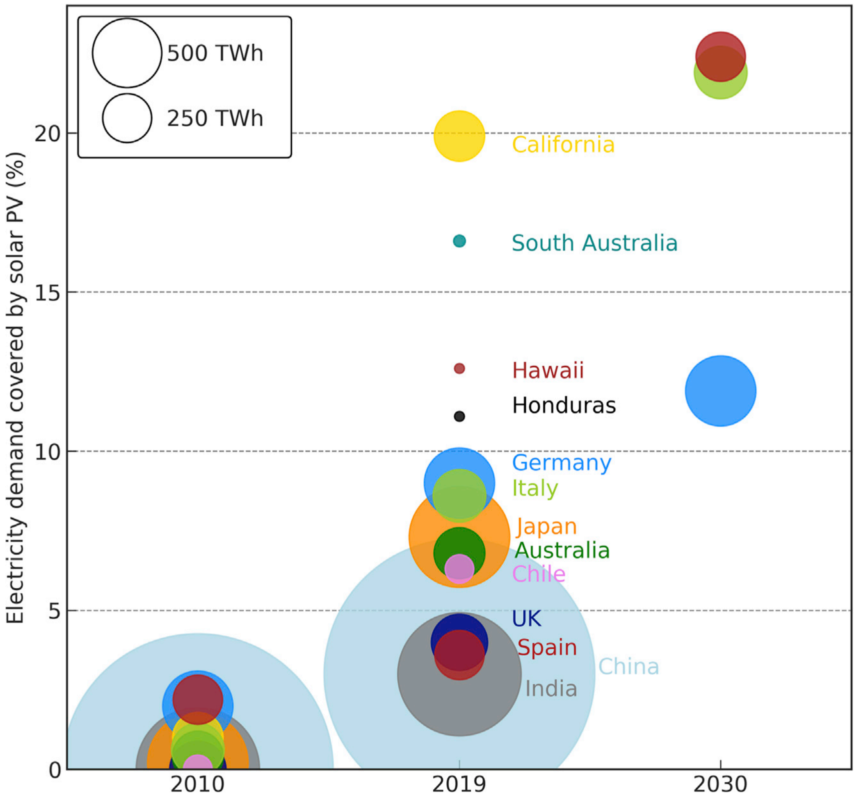

Figure 5. Percentage of electricity demand covered by solar PV in different markets worldwide
The circles' sizes are proportional to the annual electricity demand in 2019 in every region. Table S2 gathers references for historical values and planned expansion.

Conclusions

Solar PV is ready to become one of our main energy sources based on the arguments provided in this perspective: (1) learning and cost reductions are expected to continue, (2) neither materials nor land use will prevent PV expansion, and (3) existing integration strategies and those under development will allow large penetration of solar PV not only in the power grid but in the entire energy system. Some IAMs and partial-equilibrium models used to investigate alternative transition paths do not include proper representation of those strategies and use outdated technology costs. Consequently, they miss the large mitigation potential of solar PV and describe the 1.5°C-compatible scenarios that rely on a technology mix that will most likely be more expensive and over-reliant on far less mature technologies. A critical assessment of the results provided by those models needs to pay attention to cost assumptions, time resolution, and whether state-of-the-art modeling of sector coupling and renewable balancing strategies is used.

Failing to identify the prominent role that solar PV will play in a future climate-neutral energy system weakens the communication of an important message: PV technology is ready to ramp up fast and contribute to mitigating emissions by 2030, which will be key to remain on a path compatible with the Paris Agreement.[1] Installation times are shorter for solar PV than for other conventional technologies and PV modularity is again a benefit for ramping up. For developed countries, rooftop PV systems owned by citizens and small companies not only increase awareness, but they can raise additional investments for the energy transition. Proper policy interventions and business models can ensure that rooftop PV also diffuses among low- and moderate-income households.[126] For less developed countries, solar PV could be used in solar home systems or microgrids to provide electricity to the 860 million people who still live without it.[127,128] The modularity of the technology allows consumers to gradually climb the ladder of electricity access by extending their consumption as their income increases, from tier 1 (electricity for task lighting and phone charging) to tier 5 (use of high-power appliances).[129]

Throughout the last decade, global solar electricity generation maintained a 50% annual growth, rising from ~12 TWh in 2008 to ~880 TWh in 2018. Keeping a 50% annual growth for 9 additional years would mean producing ~34,000 TWh (more than the global electricity demand in 2019, which accounted for ~27,000TWh[2]). This highlights the large potential for solar PV expansion. Adequate policies are needed to ensure that high installation rates are maintained in the short term and that the potential environmental, social, and economic benefits of solar PV are effectively materialized. We identify the following challenges for sustained scaling up of solar PV in the next decade: ensuring adequate regulatory frameworks that reduce soft costs, reducing capital expenditure via industrial innovations,[130] untapping the demand for PV by enabling the electrification of other energy sectors assisted by proper tax schemes, and strengthening research on improving efficiency and reliability of PV systems. Certainly, developing PV is not the only action needed to limit temperature increase, but future scenarios must properly capture the mitigation potential of this technology.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information related to the data and code should be directed to the Lead Contact, Marta Victoria (mvp@mpe.au.dk).

Materials availability

No materials were used in this study.

Data and code availability

The data and code to produce the figures in the main paper and Supplemental Materials can be retrieved from the repository https://github.com/martavp/pv-is-ready.

SUPPLEMENTAL INFORMATION

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The responsibility for the contents lies solely with the authors.

AUTHOR CONTRIBUTIONS

Conceptualization, M.V., N.H., I.M.P., R.S., A.J.-W., C.d.C., C.B., M.S., and A.B; project administration, M.V.; visualization, M.V. and I.M.P.; writing–original draft, M.V.; writing–review & editing, M.V., N.H., I.M.P., R.S., A.J., C.d.C., C.B., M.S., A.B., I.K., K.K., and A.S.

DECLARATION OF INTERESTS

The authors declare no competing interests..

REFERENCES

1. Figueres, C., Schellnhuber, H.J., Whiteman, G., Rockström, J., Hobley, A., and Rahmstorf, S. (2017). Three years to safeguard our climate. Nature *546*, 593–595.
2. B Statistical review of world energy (2020). BP 2020. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.
3. Wilson, C., Grubler, A., Bento, N., Healey, S., De Stercke, S.D., and Zimm, C. (2020). Granular technologies to accelerate decarbonization. Science *368*, 36–39.
4. BNEF (2020). New energy outlook 2020. https://about.bnef.com/new-energy-outlook/.
5. IEA (2020). World energy outlook. https://www.iea.org/reports/world-energy-outlook-2020.
6. Haegel, N.M., Atwater, H., Barnes, T., Breyer, C., Burrell, A., Chiang, Y.M., De Wolf, S.D., Dimmler, B., Feldman, D., Glunz, S., et al. (2019). Terawatt-scale photovoltaics: transform global energy. Science *364*, 836–838.
7. International Energy Agency (IEA) (2020). Renewables 2020. https://www.iea.org/reports/renewables-2020/solar-pv#abstract.
8. IPCC (2020). IPCC Fifth Assessment Report, 2014, Data ensemble with scenarios results: https://www.ipcc.ch/assessment-report/ar5/ https://tntcat.iiasa.ac.at/AR5DB/.
9. IPCC (2019). Global warming of 1.5°C, intergovernmental panel on climate change (IPCC). https://www.ipcc.ch/sr15/ Data esemble with scenarios results. https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/.
10. Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., et al. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. Nat. Clim. Change *8*, 325–332.
11. van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., van den Berg, M., Bijl, D.L., de Boer, H.S., Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., et al. (2018). Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nat. Clim. Change *8*, 391–397.
12. Creutzig, F., Agoston, P., Goldschmidt, J.C., Luderer, G., Nemet, G., and Pietzcker, R.C. (2017). The underestimated potential of solar energy to mitigate climate change. Nat. Energy *2*, nenergy2017140.
13. Breyer, C., Bogdanov, D., Gulagi, A., Aghahosseini, A., Barbosa, L.S.N.S., Koskinen, O., Barasa, M., Caldera, U., Afanasyeva, S., Child, M., et al. (2017). On the role of solar photovoltaics in global energy transition scenarios. Prog. Photovolt.: Res. Appl. *25*, 727–745.
14. Kurtz, S.R., Leilaeioun, A.M., King, R.R., Peters, I.M., Heben, M.J., Metzger, W.K., and Haegel, N.M. (2020). Revisiting the terawatt challenge. MRS Bulletin *45*, 159–164.
15. IRENA (2020). Renewable power generation costs in 2019. https://www.iea.org/reports/renewables-2020/solar-pv#abstract.
16. Philipps, S., Kost, C., and Schlegl, T. (2014). Up-to-date levelised cost of electricity in photovoltaics. background from Fraunhofer ISE relating to IPCC WGIII 5th assessment report, final draft, September 2014. http://www.go100re.net/wp-content/uploads/2014/10/2014_10_24_Statement_LCOE_PV_Fraunhofer_ISE.pdf.
17. IPCC (2021). IPCC sixth assessment report. https://www.ipcc.ch/assessment-report/ar6/.
18. McLaren, D., and Markusson, N. (2020). The co-evolution of technological promises, modeling, policies and climate change targets. Nat. Clim. Chang. *10*, 392–397.
19. Gambhir, A. (2019). Planning a low-carbon energy transition: what can and can't the models tell us? Joule *3*, 1795–1798.
20. Gambhir, A., Butnar, I., Li, P.-H., Smith, P., and Strachan, N. (2019). A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS. Energies *12*, 1747.
21. Creutzig, F., Breyer, C., Hilaire, J., Minx, J., Peters, G.P., and Socolow, R. (2019). The mutual dependence of negative emission technologies and energy systems. Energy Environ. Sci. *12*, 1805–1817.
22. Breyer, C., Fasihi, M., Bajamundi, C., and Creutzig, F. (2019). Direct air capture of CO2:

a key technology for ambitious climate change mitigation. Joule 3, 2053–2057.

23. Luderer, G., Pietzcker, R.C., Carrara, S., de Boer, H.S., Fujimori, S., Johnson, N., Mima, S., and Arent, D. (2017). Assessment of wind and solar power in global low-carbon energy scenarios: an introduction. Energy Econ 64, 542–551.

24. Pietzcker, R.C., Ueckerdt, F., Carrara, S., de Boer, H.S., Després, J., Fujimori, S., Johnson, N., Kitous, A., Scholz, Y., Sullivan, P., and Luderer, G. (2017). System integration of wind and solar power in integrated assessment models: a cross-model evaluation of new approaches. Energy Econ 64, 583–599.

25. European Commission (2018). In-depth analysis in support on the COM(2018) 773: a clean planet for all - a european strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. https://knowledge4policy.ec.europa.eu/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en.

26. Impact Assessment Accompanying the EU Commission Communication Stepping up Europe's 2030 Climate Ambition. (2020). https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/impact_en.pdf.

27. Victoria, M., Zhu, K., Brown, T., Andresen, G.B., and Greiner, M. (2020). Early decarbonisation of the European energy system pays off. Nat. Commun. 11, 6223.

28. Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A., Oyewo, A.S., Barbosa, L.de S.N.S., and Breyer, C. (2019). Radical transformation pathway towards sustainable electricity via evolutionary steps. Nat. Commun. 10, 1077.

29. Child, M., Kemfert, C., Bogdanov, D., and Breyer, C. (2019). Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. Renew. Energy 139, 80–101.

30. European Commission (2018). In-depth analysis in support of the Commission Communication COM (2018) 773 A clean planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. https://knowledge4policy.ec.europa.eu/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en.

31. Pursiheimo, E., Holttinen, H., and Koljonen, T. (2019). Inter-sectoral effects of high renewable energy share in global energy system. Renew. Energy 136, 1119–1129.

32. Jacobson, M.Z., Delucchi, M.A., Bauer, Z.A.F., Goodman, S.C., Chapman, W.E., Cameron, M.A., Bozonnat, C., Chobadi, L., Clonts, H.A., Enevoldsen, P., et al. (2017). 100% Clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. Joule 1, 108–121.

33. ENTSOE (2019). Ten years network development plan (TYNDP) 2020, scenario report. https://www.entsos-tyndp2020-scenarios.eu/wp-content/uploads/2019/10/TYNDP_2020_Scenario_Report_entsog-entso-e.pdf.

34. Shell. (2020). Sky Scenarios. https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html.

35. Solar Power Europe (2020). 100% renewable Europe. https://www.solarpowereurope.org/100-renewable-europe/.

36. Vartiainen, E., Masson, G., Breyer, C., Moser, D., and Román Medina, E.R. (2020). Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. Prog. Photovolt.: Res. Appl. 28, 439–453.

37. Krey, V., Guo, F., Kolp, P., Zhou, W., Schaeffer, R., Awasthy, A., Bertram, C., de Boer, H.-S., Fragkos, P., Fujimori, S., et al. (2019). Looking under the hood: a comparison of techno-economic assumptions across national and global integrated assessment models. Energy 172, 1254–1267.

38. Masson, G., and Kaizuka, I. (2020). Trends in photovoltaic applications 2019 (IEA PVPS). https://iea-pvps.org/wp-content/uploads/2020/02/5319-iea-pvps-report-2019-08-lr.pdf.

39. International Technology Roadmap for Photovoltaic (ITRPV) 11th Ed. 2019 results. https://itrpv.vdma.org/documents/27094228/29066965/ITRPV%302020.pdf/ba3da187-3186-83de-784e-6e3b10d96f3f.

40. Nemet, G.F. (2006). Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy Policy 34, 3218–3232.

41. Kavlak, G., McNerney, J., and Trancik, J.E. (2018). Evaluating the causes of cost reduction in photovoltaic modules. Energy Policy 123, 700–710.

42. Chen, Y., Altermatt, P.P., Chen, D., Zhang, X., Xu, G., Yang, Y., Wang, Y., Feng, Z., Shen, H., and Verlinden, P.J. (2018). From laboratory to production: learning models of efficiency and manufacturing cost of industrial crystalline silicon and thin-film photovoltaic technologies. IEEE J. Photovoltaics 8, 1531–1538.

43. Verlinden, P.J. (2020). Future challenges for photovoltaic manufacturing at the terawatt level. J. Renew. Sustain. Energy 12, 053505.

44. Altermatt, P.P., Yang, Y., Chen, Y., Zhang, X., Chen, D., Xu, G., and Feng, Z. (2020). Requirements of the Paris climate agreement for the coming 10 years on investments, technical roadmap, and expansion of PV manufacturing (37th European Photovoltaic Solar Energy Conference and Exhibition), pp. 1999–2004.

45. Green, M.A. (2019). How did solar cells get so cheap? Joule 3, 631–633.

46. Chase, J. (2019). Solar Power Finance Without the Jargon (World Scientific).

47. Egli, F., Steffen, B., and Schmidt, T.S. (2018). A dynamic analysis of financing conditions for renewable energy technologies. Nat. Energy 3, 1084–1092.

48. O'Shaughnessy, E., Nemet, G.F., Pless, J., and Margolis, R. (2019). Addressing the soft cost challenge in U.S. small-scale solar PV system pricing. Energy Policy 134, 110956.

49. Wilson, G.M., Al-Jassim, M., Metzger, W.K., Glunz, S.W., Verlinden, P., Xiong, G., Mansfield, L.M., Stanbery, B.J., Zhu, K., Yan, Y., et al. (2020). The 2020 photovoltaic technologies roadmap. J. Phys. D: Appl. Phys. 53, 493001.

50. Blakers, A.W., Wang, A., Milne, A.M., Zhao, J., and Green, M.A. (1989). 22.8% efficient silicon solar cell. Appl. Phys. Lett. 55, 1363–1365.

51. Green, M.A., Dunlop, E.D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., and Hao, X. (2020). Solar cell efficiency tables, (version 56). Prog photovolt: Res Appl. 28, 629–638.

52. Jung, E.H., Jeon, N.J., Park, E.Y., Moon, C.S., Shin, T.J., Yang, T.Y., Noh, J.H., and Seo, J. (2019). Efficient, stable and scalable perovskite solar cells using poly(3-hexylthiophene). Nature 567, 511–515.

53. Sahli, F., Werner, J., Kamino, B.A., Bräuninger, M., Monnard, R., Paviet-Salomon, B., Barraud, L., Ding, L., Diaz Leon, J.J., Sacchetto, D., et al. (2018). Fully textured monolithic perovskite/silicon tandem solar cells with 25.2% power conversion efficiency. Nat. Mater. 17, 820–826.

54. Geisz, J.F., France, R.M., Schulte, K.L., Steiner, M.A., Norman, A.G., Guthrey, H.L., Young, M.R., Song, T., and Moriarty, T. (2020). Six-junction III–V solar cells with 47.1% conversion efficiency under 143 Suns concentration. Nat. Energy 5, 326–335.

55. Wiesenfarth, M., Philipps, S.P., and Bett, A.W. (2017). Current status of concentrator photovoltaic (CPV) technology. https://www.nrel.gov/docs/fy16osti/65130.pdf.

56. Ballif, C., Hessler-Wyser, A., Baumgartner, Y., Cattin, J., Cattaneo, B., Strahm, B., Papet, P., Ufheil, J., Gragert, M., Grischke, R., et al. (2014). SmartWire solar cell interconnection technology (29th European Photovoltaic Solar Energy Conference and Exhibition), pp. 2555–2561.

57. Afanasyeva, S., Bogdanov, D., and Breyer, C. (2018). Relevance of PV with single-axis tracking for energy scenarios. Sol. Energy 173, 173–191.

58. Luque, A., Eguren, J., and Del Alamo, J. (1978). Internal quantum efficiency of back illuminated n+ pp+ solar cells. Rev. Phys. Appl. (Paris) 13, 629–632.

59. Rodríguez-Gallegos, C.D., Liu, H., Gandhi, O., Singh, J.P., Krishnamurthy, V., Kumar, A., Stein, J.S., Wang, S., Li, L., Reindl, T., and Peters, I.M. (2020). Global techno-economic performance of bifacial and tracking photovoltaic systems. Joule 4, 1514–1541.

60. Peters, I.M., Rodriguez Gallegos, C.D., Sofia, S.E., and Buonassisi, T. (2019). The value of efficiency in photovoltaics. Joule 3, 2732–2747.

61. Oversizing White Paper, SMA. https://www.sma.de/fileadmin/content/global/specials/documents/oversizing/Whitepaper_Oversizing_EN_180530_01.pdf.

62. Fluence. (2018). How to optimize your inverter loading ratio for solar + energy storage

projects. https://blog.fluenceenergy.com/solar-energy-storage-how-to-optimize-your-inverter-loading-ratio.

63. Jordan, D.C., Kurtz, S.R., VanSant, K., and Newmiller, J. (2016). Compendium of photovoltaic degradation rates. Prog. Photovolt.: Res. Appl. *24*, 978–989.

64. DuraMAT (Durable Module Materials) Consortium https://www.duramat.org/.

65. Steffen, B., Beuse, M., Tautorat, P., and Schmidt, T.S. (2020). Experience curves for operations and maintenance costs of renewable energy technologies. Joule *4*, 359–375.

66. Rai, V., and Henry, A.D. (2016). Agent-based modeling of consumer energy choices. Nat. Clim. Change *6*, 556–562.

67. Lamperti, F., Bosetti, V., Roventini, A., and Tavoni, M. (2019). The public costs of climate-induced financial instability. Nat. Clim. Chang. *9*, 829–833.

68. Luderer, G., Krey, V., Calvin, K., Merrick, J., Mima, S., Pietzcker, R., Van Vliet, J., and Wada, K. (2014). The role of renewable energy in climate stabilization: results from the EMF27 scenarios. Clim. Change *123*, 427–441.

69. Kavlak, G., McNerney, J., Jaffe, R.L., and Trancik, J.E. (2015). Metal production requirements for rapid photovoltaics deployment. Energy Environ. Sci. *8*, 1651–1659.

70. Jean, J., Brown, P.R., Jaffe, R.L., Buonassisi, T., and Bulović, V. (2015). Pathways for solar photovoltaics. Energy Environ. Sci. *8*, 1200–1219.

71. Fraunhofer Institute for Solar Energy Systems, ISE (2019). Photovoltaics report. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf.

72. (2020) World Silver Survey.

73. Valero, A., Valero, A., Calvo, G., and Ortego, A. (2018). Material bottlenecks in the future development of green technologies. Renew. Sustain. Energy Rev. *93*, 178–200.

74. Heath, G.A., Silverman, T.J., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S., et al. (2020). Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nat. Energy *5*, 502–510.

75. Latunussa, C.E.L., Ardente, F., Blengini, G.A., and Mancini, L. (2016). Life cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Sol. Energy Mater. Sol. Cells *156*, 101–111.

76. Gagnon, P., Margolis, R., Melius, J., Philipps, C., and Elmore, R. (2016). Rooftop solar photovoltaic technical potential in the United States: a detailed assessment (NREL). https://www.nrel.gov/docs/fy16osti/65298.pdf.

77. Bódis, K., Kougias, I., Jäger-Waldau, A., Taylor, N., and Szabó, S. (2019). A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union. Renew. Sustain. Energy Rev. *114*, 109309.

78. Grodsky, S.M., and Hernandez, R.R. (2020). Reduced ecosystem services of desert plants from ground-mounted solar energy development. Nat. Sustainability *3*, 1036–1043.

79. Liu, H., Krishna, V., Lun Leung, J.L., Reindl, T., and Zhao, L. (2018). Field experience and performance analysis of floating PV technologies in the tropics. Prog. Photovolt.: Res. Appl. *26*, 957–967.

80. Lee, N., Grunwald, U., Rosenlieb, E., Mirletz, H., Aznar, A., Spencer, R., and Cox, S. (2020). Hybrid floating solar photovoltaics-hydropower systems: benefits and global assessment of technical potential. Renew. Energy *162*, 1415–1427.

81. Farfan, J., and Breyer, C. (2018). Combining floating solar photovoltaic power plants and hydropower reservoirs: a virtual battery of great global potential. Energy Procedia *155*, 403–411.

82. Schindele, S., Trommsdorff, M., Schlaak, A., Obergfell, T., Bopp, G., Reise, C., Braun, C., Weselek, A., Bauerle, A., Högy, P., et al. (2020). Implementation of agrophotovoltaics: techno-economic analysis of the price-performance ratio and its policy implications. Appl. Energy *265*, 114737.

83. Barron-Gafford, G.A., Pavao-Zuckerman, M.A., Minor, R.L., Sutter, L.F., Barnett-Moreno, I., Blackett, D.T., Thompson, M., Dimond, K., Gerlak, A.K., Nabhan, G.P., and Macknick, J.E. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nat. Sustainability *2*, 848–855.

84. Schneider, J., Pannicke, N., Haufe, N., Biger, J., Volz, B., Schmeichel, A., Zwosta, N., and Mattiza, M. (2020). Vertical bifacial solar module systems on wild flower strips combining energy and crops production with preservation of biodiversity (37th European Photovoltaic Solar Energy Conference and Exhibition).

85. Jäger-Waldau, A. (2020). The untapped area potential for photovoltaic power in the European Union. Clean. Technol. *2*, 440–446.

86. Pietzcker, R.C., Stetter, D., Manger, S., and Luderer, G. (2014). Using the sun to decarbonize the power sector: the economic potential of photovoltaics and concentrating solar power. Appl. Energy *135*, 704–720.

87. Eurek, K., Vimmerstedt, L., Lamers, P., Cohen, S., Podkaminer, K., Lyer, G., Binsted, M., Wise, M., and Graham, N. (2020). Challenges for modeling high-penetration renewable energy and energy efficiency technologies in integrated assessment models (Presented at the 13th IAMC).

88. IAMC (2020). Analyses presented at the 13th integrated assessment modeling consortium (IAMC) annual meeting. https://www.iamconsortium.org/event/thirteenth-annual-meeting-of-the-iamc-2020/.

89. Luderer, G., Madeddu, S., Ueckerdt, F., Pietzcker, R.C., Levesque, A., Pehl, M., Rottoli, M., Dirnaichner, A., and Kriegler, E. (2020). When the most valuable becomes the cheapest: increasing electrification of global energy use on the road to climate neutral energy systems.

90. Pfenninger, S. (2017). Dealing with multiple decades of hourly wind and PV time series in energy models: a comparison of methods to reduce time resolution and the planning implications of inter-annual variability. Appl. Energy *197*, 1–13.

91. Kotzur, L., Markewitz, P., Robinius, M., and Stolten, D. (2018). Impact of different time series aggregation methods on optimal energy system design. Renew. Energy *117*, 474–487.

92. Frew, B.A., and Jacobson, M.Z. (2016). Temporal and spatial tradeoffs in power system modeling with assumptions about storage: an application of the POWER model. Energy *117*, 198–213.

93. Kannan, R., Turton, H., and Panos, E. (2015). Methodological significance of temporal granularity in energy-economic models—insights from the MARKAL/TIMES framework. In Informing Energy and Climate Policies Using Energy Systems Models (Springer International Publishing), pp. 185–200.

94. Brown, T., Schlachtberger, D., Kies, A., Schramm, S., and Greiner, M. (2018). Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. Energy *160*, 720–739.

95. Kwok, G., Farbes, J., and Jones, R. (2020). Low-carbon transition strategies for the southeast united states (Evolved Energy Research/Sustainable Development Solutions Network). https://www.unsdsn.org/low-carbon-transition-for-the-southeast-united-states.

96. Bogdanov, D., Gulagi, A., Fasihi, M., and Breyer, C. (2020). Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination. Appl. Energy, 116273.

97. Heide, D., Greiner, M., von Bremen, L., and Hoffmann, C. (2011). Reduced storage and balancing needs in a fully renewable European power system with excess wind and solar power generation. Renew. Energy *36*, 2515–2523.

98. World Bank (2017). Solar resource and photovoltaic potential of indonesia, Energy Sector Management Assistance Program (World Bank Group). http://documents.worldbank.org/curated/en/729411496240730378/Solar-resource-and-photovoltaic-potential-of-Indonesia.

99. Stocks, M., Stocks, R., Lu, B., Cheng, C., and Blakers, A. (2021). Global atlas of closed-loop pumped hydro energy storage. Joule *5*, 270–284.

100. Victoria, M., Zhu, K., Brown, T., Andresen, G.B., and Greiner, M. (2019). The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system. Energy Convers. Manag. *201*, 111977.

101. Jerez, S., Tobin, I., Vautard, R., Montávez, J.P., López-Romero, J.M., Thais, F., Bartok, B.,

Christensen, O.B., Colette, A., Déqué, M., et al. (2015). The impact of climate change on photovoltaic power generation in Europe. Nat. Commun. *6*, 10014.

102. Schlott, M., Kies, A., Brown, T., Schramm, S., and Greiner, M. (2018). The impact of climate change on a cost-optimal highly renewable European electricity network. Appl. Energy *230*, 1645–1659.

103. Orths, A., and Eriksen, P.B. (2016). The future has come: the 100% RES driven power system is reality. Revue de l Electricité et de l Electronique *5*, 84–86.

104. Doelling, D.R., Loeb, N.G., Keyes, D.F., Nordeen, M.L., Morstad, D., Nguyen, C., Wielicki, B.A., Young, D.F., and Sun, M. (2013). Geostationary enhanced temporal interpolation for Ceres flux products. J. Atmos. Oceanic Technol. *30*, 1072–1090.

105. Kroposki, B., Johnson, B., Zhang, Y., Gevorgian, V., Denholm, P., Hodge, B.-M., and Hannegan, B. (2017). Achieving a 100% renewable grid: operating electric power systems with extremely high levels of variable renewable energy. IEEE Power and Energy Mag *15*, 61–73.

106. Garralaga Rojas, E.G., Sadri, H., and Krueger, W. (2020). Case study of MW-sized power generation at St. Eustatius island combining photovoltaics, battery storage, and gensets. Prog. Photovolt.: Res. Appl. *28*, 562–568.

107. AURECON. (2018). Hornsdale power reserve, year 1 technical and market impact case study. https://www.aurecongroup.com/markets/energy/hornsdale-power-reserve-impact-study.

108. Oyewo, A.S., Farfan, J., Peltoniemi, P., and Breyer, C. (2018). Repercussion of large scale hydro dam deployment: the case of Congo grand Inga hydro project. Energies *11*, 972.

109. Parkinson, G. (2020). Solar meets 100 per cent of South Australia demand for first time. Renew Economy. https://reneweconomy.com.au/solar-meets-100-per-cent-of-south-australia-demand-for-first-time-78279/.

110. Frew, B., Cole, W., Denholm, P., Frazier, A.W., Vincent, N., and Margolis, R. (2019). Sunny with a chance of curtailment: operating the us grid with very high levels of solar photovoltaics. iScience *21*, 436–447.

111. Brown, T.W., Bischof-Niemz, T., Blok, K., Breyer, C., Lund, H., and Mathiesen, B.V. (2018). Response to 'burden of proof: a comprehensive review of the feasibility of 100% renewable-electricity systems. Renew. Sustain. Energy Rev. *92*, 834–847.

112. Kaufmann, R.K., Newberry, D., Xin, C., and Gopal, S. (2021). Feedbacks among electric vehicle adoption, charging, and the cost and installation of rooftop solar photovoltaics. Nat. Energy *6*, 143–149.

113. Zhu, K., Victoria, M., Andresen, G.B., and Greiner, M. (2020). Impact of climatic, technical and economic uncertainties on the optimal design of a coupled fossil-free electricity, heating and cooling system in Europe. Appl. Energy *262*, 114500.

114. Laine, H.S., Salpakari, J., Looney, E.E., Savin, H., Peters, I.M., and Buonassisi, T. (2019). Meeting global cooling demand with photovoltaics during the 21st century. Energy Environ. Sci.. *12*, 2706–2716.

115. Kätelhön, A., Meys, R., Deutz, S., Suh, S., and Bardow, A. (2019). Climate change mitigation potential of carbon capture and utilization in the chemical industry. Proc Natl Acad Sci USA *116*, 11187–11194.

116. Horvath, S., Fasihi, M., and Breyer, C. (2018). Techno-economic analysis of a decarbonized shipping sector: technology suggestions for a fleet in 2030 and 2040. Energy Convers. Manag. *164*, 230–241.

117. Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J., and Jäger-Waldau, A. (2020). Green hydrogen in Europe – a regional assessment: substituting existing production with electrolysis powered by renewables. Energy Convers. Manag. *228*, 113649.

118. Fasihi, M., Efimova, O., and Breyer, C. (2019). Techno-economic assessment of CO2 direct air capture plants. J. Cleaner Prod. *224*, 957–980.

119. Breyer, C., Tsupari, E., Tikka, V., and Vainikka, P. (2015). Power-to-gas as an emerging profitable business Through creating an integrated value chain. Energy Procedia *73*, 182–189.

120. Victoria, M., and Andresen, G.B. (2019). Using validated reanalysis data to investigate the impact of the PV system configurations at high penetration levels in European countries. Prog. Photovolt.: Res. Appl. *27*, 576–592.

121. Hörsch, J., and Brown, T. (2017). The role of spatial scale in joint optimisations of generation and transmission for European highly renewable scenarios. In 14th International Conference on the European Energy Market (EEM), pp. 1–7.

122. Sasse, J.P., and Trutnevyte, E. (2020). Regional impacts of electricity system transition in Central Europe until 2035. Nat. Commun. *11*, 4972.

123. Tröndle, T., Lilliestam, J., Marelli, S., and Pfenninger, S. (2020). Trade-offs between geographic scale, cost, and infrastructure requirements for fully renewable electricity in Europe. Joule *4*, 1929–1948.

124. Lombardi, F., Pickering, B., Colombo, E., and Pfenninger, S. (2020). Policy decision support for renewables deployment through spatially explicit practically optimal alternatives. Joule *4*, 2185–2207.

125. Ram, M., Bogdanov, D., Aghahosseini, A., Gulagi, A., Oyewo, A.S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., Barbosa, L.S.N.S., et al. (2019). Global energy system based on 100% renewable energy – power, heat, transport and desalination sectors (Study by Lappeenranta university of technology and energy watch group). http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf.

126. O'Shaughnessy, E., Barbose, G., Wiser, R., Forrester, S., and Darghouth, N. (2021). The impact of policies and business models on income equity in rooftop solar adoption. Nat. Energy *6*, 84–91.

127. IEA Sustainable Development Goal 7. Data and Projections. https://www.iea.org/reports/sdg7-data-and-projections.

128. Szabó, S., Pinedo Pascua, I., Puig, D., Moner-Girona, M., Negre, M., Huld, T., Mulugetta, Y., Kougias, I., Szabó, L., and Kammen, D. (2021). Mapping of affordability levels for photovoltaic-based electricity generation in the solar belt of sub-Saharan Africa, East Asia and South Asia. Sci. Rep. *11*, 3226.

129. Bhatia, M., and Niki, A. (2015). Beyond Connections. Energy Access Redefined (World Bank)).

130. Needleman, D.B., Poindexter, J.R., Kurchin, R.C., Marius Peters, I.M., Wilson, G., and Buonassisi, T. (2016). Economically sustainable scaling of photovoltaics to meet climate targets. Energy Environ. Sci. *9*, 2122–2129.