Solar Photovoltaics in 100% Renewable Energy Systems

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Article Outline

Definition of the Subject

Solar photovoltaics has demonstrated the strongest long-term growth rates of all energy technologies since the 1950s. It has been recognized as the new "king" of energy markets, having emerged within the past few years as the least-cost source of electricity. Along with supporting energy system technologies, in particular batteries and electrolyzers, it can be anticipated that solar PV will emerge as the main source of primary energy for humankind within only a few decades. In parallel the research field of 100% renewable energy system analyses has developed strongly since the mid-2000s, with a growing number of research groups and organizations joining the 100% renewable energy community. The role of solar PV in these analyses has increased steadily, as the true potential role of solar PV in delivering 100% renewable energy supply has been identified in cutting-edge research in recent years. The results of the research, projections, and empirical statistics indicate the dawn of a Solar Age, which may be the key driving force to enable a rebalancing of human activities within the biogeochemical limits of planet Earth. Solar photovoltaic technology offers a crucial foundation for further progress toward a truly sustainable civilization of the highest technical, economic, and cultural standards, leaving no one behind.

Introduction

The history of solar photovoltaics (PV) traces back to Becquerel [10], who discovered the photoelectric effect in 1839. Einstein received the Nobel Prize for explaining the physical nature of the photoelectric effect in 1905 [52]. The first technical applications of solar photovoltaics were realized in the late nineteenth century [174] and the first half of the twentieth century [170]. The emergence of modern solar PV technology began with the invention of crystalline silicon (c-Si) PV technology at the Bell Labs in 1941 [138], which was undisclosed until a first scientific publication in 1954 [36], when the efficiency of converting sunlight into electricity reached about 6%. Solar PV had already achieved market dominance in a niche market, powering space satellites, by the late 1950s and early 1960s. Rapid conquest of markets is a key characteristic of solar PV, which has been observed several times in various markets since then.

Solar PV technologies have seen ongoing evolutionary development since the early days. New material classes exhibiting the photoelectric effect have been added over time, and technological barriers for continued increase in efficiencies have been overcome across all material classes. Year after year, lab-scale solar cell technologies surpass past efficiency records achieved by previous prototypes at cell and module levels [75] and advances are also observed in commercially marketed PV technologies [96].

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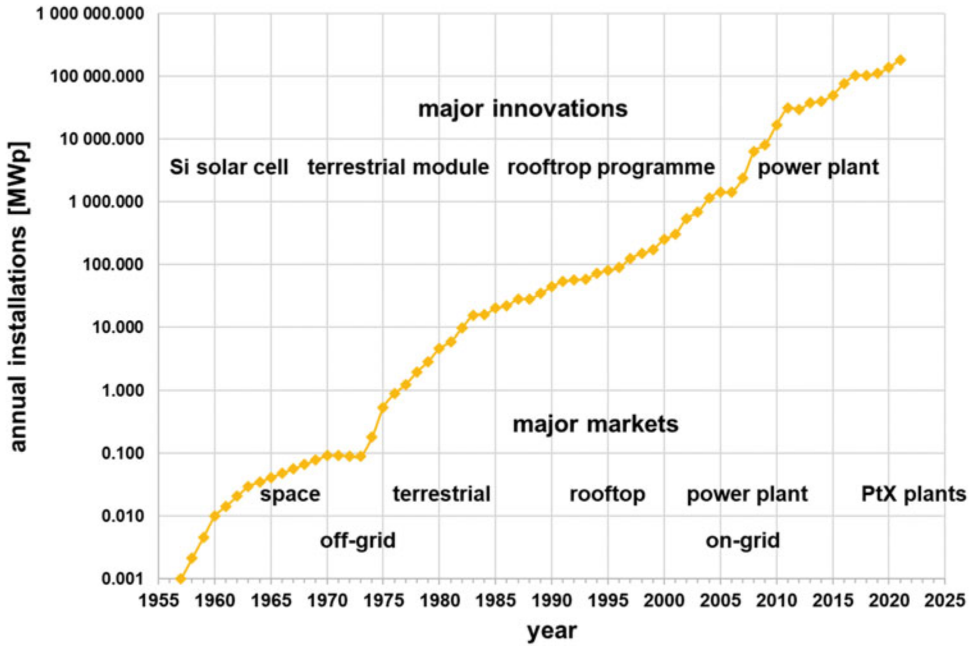
This record of strong technological development is mirrored in a continued unit cost decline. Solar PV costs have been documented since the mid-1950s [40]; the first cost analysis with learning rates was published as early as 1972 by Wolf [199], who documented a learning rate of 21–31% at PV cell level, based on data going back to the 1950s. In 2006, Swanson [182] assessed the learning rate at the PV module level using data for the period from the late 1970s to the early 2000s. He documented a 20% learning rate, a result which caught the attention of a wide public as well as that of the expert community. Kersten et al. [112] found that the learning rate has been roughly stable at about 20% from the mid-1950s until the late 2000s, a period of more than 50 years, but with a higher learning rate of about 30% until the late 1980s, slowing to about 17% for the 1990s and 2000s.

In the second half of the 2000s, due to a shortage in electronic grade silicon production capacities and excess demand, market prices for solar PV did not reflect the true technology evolution-driven trend in PV unit costs. In the 2010s, the learning rate of solar PV modules reached the level well known from other silicon-based semiconductor products: 40% [88, 95, 112]. The key drivers for the sustained 40% learning rate have been identified to be enormous industrial production scaling, standardization of manufacturing, very strong competition, fast innovation cycles, practically unlimited access to capital for the PV industry, and continued growth in global demand [39, 192]. Some of these drivers had been identified earlier by Nemet [136]. To date, the bulk of international collaboration and main responsibility for research and development, market creation and industrial scaling has been shared between the US, Japan, Germany, and China [137].

The year-on-year market growth of solar PV in recent years has been extraordinary, as documented in Fig. 1. Major innovations have led to continuous increases in annual market sales. The four main innovations were the c-Si solar cell, the terrestrial PV module, rooftop programs, and large-scale modular utility-scale PV power plants. These innovations sequentially created major markets: the very first in powering satellites, the second in terrestrial off-grid applications, the third in grid-connected rooftop systems, and fourth, the recent explosion in large utility-scale solar PV power plants. The next major market, which is currently in its start-up phase, will be power-to-X applications for e-fuels and e-chemicals [59, 63].

The five largest PV power plants built in the world so far are Bhadla (India) with 2,245 GW, Huanghe (China) with 2,200 GW, Pavagada (India) with 2,050 GW, Benban (Egypt) with 1,650 GW, and Tengger (China) with 1,547 GW. In total, nine PV power plants have a capacity of at least 1,000 GW, with the four additional ones being located in United Arab Emirates, India, and China. PV systems are practically scale invariant from system sizes of a few watts up to multi-gigawatts. The 5-year average compound annual growth rate (CAGR) for capacity installations was higher than 40% for the entire decade of the 2000s, and declined to a 5-year average CAGR of not less than 20% in the 2010s. As a result, solar PV achieved a market share of 42% of all globally installed power generation capacity in the year 2020, by far the largest market share of all power generation technologies [94, 150]. In 2020 alone, an estimated 138.5 GW was installed, and cumulative capacity reached 756 GW [150], although the former figure may have to be updated to 147 GW [104]. Eighteen countries in the world achieved annual PV installations of at least 1 GW in the year 2020 [104]. The global market first achieved 1 GW of capacity installation in a single year in 2004; in 2007, just 3 years later, Germany became the first country to install over 1 GW in a single year [149]. The annual market outlook for the year 2021 ranges from 160 to 209 GW according to BNEF [154], in agreement with the expectations of Jäger-Waldau [104], which documents a CAGR of about 35% for the 17 years since 2004. Global PV manufacturing capacity is expected to reach around 400 GW by end of 2021 depending on the PV manufacturing value chain, with massive capacity expansions ongoing [172].

Practically all market analyses made during the 2000s and nearly all energy system scenario



Solar Photovoltaics in 100% Renewable Energy Systems, Fig. 1 Solar PV market development from the mid-1950s to the year 2021. Note the logarithmic y-axis scaling. Linear trend lines indicate stable annual market growth rates. The diagram is based on Sandén [165] and Breyer and Gerlach [19]. Data from Sandén [165], Kersten et al. [112], IEA-PVPS [149, 150], pv magazine [154]

researchers failed to project the enormous success of solar PV, even though it was possible to roughly anticipate the enormous growth of solar PV that occurred over the past decade. In 2008, on the occasion of the largest PV conference that occurred in that year, the European Photovoltaic Industry Association (EPIA) published the first documentation revealing the true market potential of solar PV [56, 57], indicating that between 6% and 12% of all electricity demand could be supplied by solar PV by 2020, in a year when the solar PV share in electricity supply in the European Union was just 0.2% [91]. This was far beyond the projections even of very progressive European researchers [103]. By end of the year 2020, several European countries achieved this aim with a respective PV electricity generation potential: Germany (9.7%), Greece (9.3%), Spain (9.0%), Netherlands (8.9%), Italy (8.3%), and Belgium (6.6%), among others [150]. The EPIA findings were based on research at Q.Cells, the PV world market leader in that year; the method and finding were published as a paper in 2009 and as a peer-reviewed journal article in 2013 [19, 21]. The fundamental method for the EPIA findings was PV grid-parity, i.e., analyzing the point in time when end users benefit from lower PV electricity generation cost in comparison to what they would have to pay for electricity from the grid. In a following step, this analysis method was expanded to the so-called "fuel-parity," i.e., analyzing the point in time when power plant operators can financially benefit from lower power generation cost with PV compared to conventional thermal power plants in total cost, and even if only the fuel cost is substituted [17, 22]. Both parity analyses were established on PV system cost projections based on market growth and learning rates, so that PV system costs and electricity generation costs could be projected for the entire analysis period, typically until the year 2020. These two fundamental parity analysis methods were combined and published in 2011 in one of the very early terawatt PV papers [16, 17], indicating a cumulative market of 600–1000 GW for PV in the year 2020, a range well-matched by reality, with data showing that 756 GW were cumulatively installed by the end of 2020 [150]. As far as is known, no other long-term market projection from the early 2010s correctly projected the correct range of cumulative installed PV capacity.

One decade later, in the years 2019 to 2021, the latest methods and data have been applied to cutting edge energy system models, leading to the fundamental insight that the total installed solar PV capacity by the year 2050 may reach a level of around 70 TWp [83], covering about 70% of the total primary energy demand of humankind [14, 156]. The annual energy unit cost, i.e., total annualized energy system cost divided by the total final energy demand, can remain stable for the transition period from the present to mid-century during which a zero CO_2 emission global energy system must be built [14, 156], while the PV industry will be able to successfully manage this rapid growth phase [192]. Such a fast energy system transition means a historically unprecedented restructuring of the global energy system.

Several new insights were gained in the 2010s that led to a massive shift in the projected role of solar PV in the year 2050, rising from a projected 6–12% in electricity supply in 2020 [56, 57] to about 70% of total primary energy supply [14, 156]. These insights, captured in a new generation of energy system models, include future trends in low-cost solar PV, low-cost batteries, low-cost electrolyzers, and CO_2 direct air capture.

Battery technology has been identified as the first major PV supporting technology. Surpassing a 6–12% renewable electricity supply level without incurring substantial curtailment can be only realized in regions such as Europe, which have access to low-cost batteries. This became feasible in the second half of the 2010s. Very strong battery demand growth from the automotive industry was complemented by an increase in stationary battery storage deployment; together, these factors led to a huge decline in battery cost [169, 203]. This cost degression trend is projected to continue, leading to very low storage cost already by the end of the 2020s and further decline [191].

The second major PV supporting technology are electrolyzers, as they make it possible to apply low-cost electrons in the production of low-cost molecules for all applications that cannot be directly electrified. Nearly all energy demand applications that cannot be directly electrified, are based on hydrogen. These applications include green steel [15, 139], e-ammonia, and e-methanol for a sustainable chemical industry [15, 50, 63, 68, 108], and e-fuels for long-distance marine and aviation transportation [15, 50, 60, 89].

Accordingly, is can be expected that the inner core of sustainable energy systems established in the years and decades to come will be based on four central technologies: solar PV for least-cost electricity, batteries for overcoming the day-night cycle and mobile applications, electrolyzers for converting electrons to molecules, and finally CO_2 direct air capture for enabling e-hydrocarbons and net-negative CO_2 emissions [26, 62, 111]. The fundamental trend of steadily declining solar PV electricity generation cost will massively push solar PV dominance in global energy supply.

A new generation of energy system models has enabled the detailed analysis of energy system transition options given specified constraints, e.g., climate targets, societal preferences, energy resources availability, and energy services demand. Cutting edge energy system models show a high performance in temporal, spatial, and technological resolution and include sector coupling. Minimum standards of model documentation are of significance to ensure transparency of methods and data assumptions [152]. The two leading models in fulfilling the highest standards in all required fields are PyPSA and the LUT model [152]. PyPSA is validated best for energy transition analyses for Europe [193], but it is not yet available on a global scale; the LUT model is "global-local," i.e., can be implemented for energy system transition analyses at various scales, from global to regional to local [13, 14]. It is currently capable of analyzing a world divided into about 150 subregions. Most other models subdivide the world into only 20–30 regions [85], which makes them unable to analyze important details. Sophisticated energy system models like the LUT model reveal that linking least-cost solar PV electricity to low-cost batteries, low-cost electrolyzers, CO_2 direct air capture technology, and hydrogen-based synthesis routes can lead to a global average share of solar PV of about 70% of primary energy supply.

The highest reported present-day solar PV electricity supply values for countries and states are from Tokelau (99%), California (19.9%), Honduras (12.9%), Hawaii (12.6%), and Australia (10.7%); as of 2020, these are the countries and states with a greater than 10% share of annual PV electricity supply [150, 183, 194].

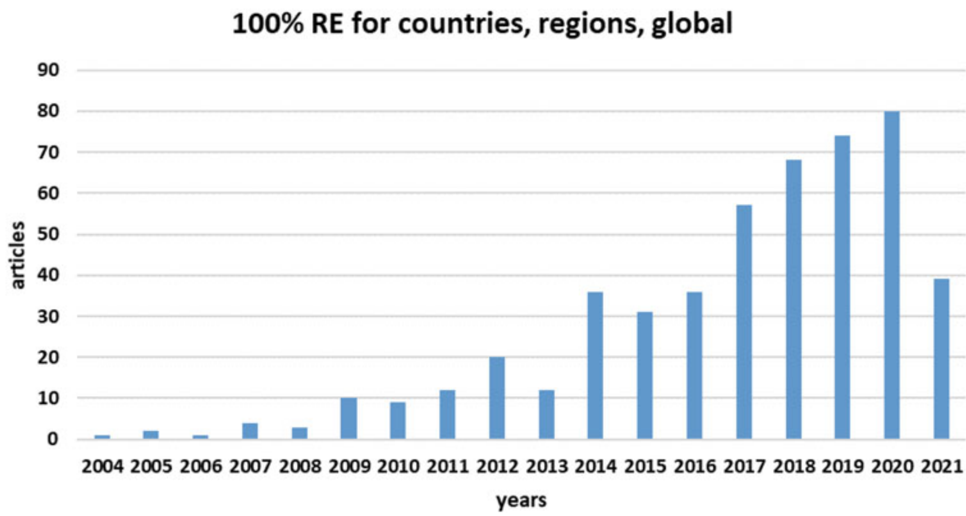
The history and status of 100% renewable energy system analyses are detailed in the following sections. First it will outline the role of solar PV in scenarios, and demonstrate why many scenarios still show substantial deficits in describing the real role of solar PV. Next, details of the solar PV share in 100% renewable energy supply scenarios are discussed. The phenomenon of puzzlingly low levels of solar PV in conventional energy scenarios, and even in some 100% renewable energy scenarios, recently stimulated the publication of a number of scientific assessments exploring limitations in scenarios design; their findings are discussed in the following section. The implications for how barriers incorrectly limiting the projected role of solar PV in energy scenarios might be removed are discussed after that. In the final section, we attempt a brief outlook at what the dawn of the Solar Age may mean for civilization.

History and Status of 100% Renewable Energy System Analyses

The historically first 100% renewable energy system analysis was published in 1975 by Sørensen [177] focusing on Denmark as a case study. Remarkably, that first article was published in the high-prestige journal *Science*, yet not a single second article exploring 100% renewable scenarios has since been published in *Science*, which may indicate a lack of interest of its editors in highly sustainable energy systems. At nearly the same time Lovins [129] published the second article on 100% renewables, calling it "the soft energy path." Since then, more than 500 known peer-reviewed articles on 100% renewable energy systems analyzing a specific geographic scope have been published, plus about 30 articles discussing generic questions and about 35 articles reviewing the field of 100% renewable energy system analyses. The development of the research field since the mid-2000s is presented in Fig. 2. The CAGR of annually published articles between the year 2010 and 2020 was 24%, which indicates a strong growth of this research field. The number of articles already published in the first few months of 2021 (as of early April) indicates that it will be another record year. Additional analysis on the sectoral resolution and journals that publish research papers, encompassing data up to the year 2018, can be found in Hansen et al. [85]. The five leading teams in the world, according to number of published articles, are Breyer et al., Lund/Mathiesen/Østergaard et al., Greiner et al., DLR and Jacobson et al., with 14%, 8%, 5%, 5%, and 4% of all known 100% renewable energy system analysis articles, respectively. Their rank order according to number of annual citations, as of the year 2020, is Lund/Mathiesen/Østergaard et al., Breyer et al., Jacobson et al., Greiner et al., and DLR. The two most used energy system models for 100% renewable energy system analyses are EnergyPLAN and the LUT model [127], with 69 and 60, respectively, known articles as of April 2021; all other models were used for less than 20 articles each.

The historically first global 100% renewable energy system analysis was published in 1996 by Sørensen [178], and it took more than 15 years for the second study by Jacobson and Delucchi [97] to appear. However, the latter marked a breakthrough for the entire research field, as it is the most cited article in the field right now, with about 1000 citations, and it served as a growth catalyst for the field.

Several advances in methods have substantially improved the models used for 100% renewable energy system analyses over the past 15 years. In 2005, Czisch [48] introduced the first multi-node, hourly resolved 100% **Renewable Energy Systems** (RES) analysis based on



Solar Photovoltaics in 100% Renewable Energy Systems, Fig. 2 Development of peer-reviewed journal articles based on 100% renewable energy system analyses. Only 12 articles are known from pre-2004

historic weather data, applied for about one billion people in Europe, North Africa, Middle East, and Western Eurasia. Around the same time Heide et al. [87] derived for the first time the optimal balance of solar PV and wind energy for a 100% RE system on the case of Europe in hourly and high spatial resolution and concluded that 45% solar PV and 55% wind energy would be an optimal mix. In 2009, Sterner [180] introduced the modern view of sector coupling. This involves linking all energy sectors, enabling seasonal storage without geographic constraints, and describing an energy system fully based on electricity, encompassing both direct and indirect electrification and overcoming the limitations of hydrogen by adding CO_2-to-X synthesis. In 2017–2019, Bogdanov and Breyer et al. [13, 14, 23, 156] added the combination of high geographic resolution of more than 100 global regions with hourly modeling, regions composed of multiple nodes, power-to-X, and sector coupling, thus enabling a model that includes the five major e-fuels/e-chemicals – hydrogen, methane, Fischer-Tropsch fuels, ammonia, methanol – in a full energy system analysis, as is required for realistic energy-industry transition modeling [15].

One of the most important contributions was realized by Teske and the DLR in a series of reports and articles in collaboration with Greenpeace [76, 184, 185], which led to a broad dissemination of 100% RES insights beyond scientific circles to a broad range of experts and stakeholders across disciplines and far more awareness among policy makers. In recent years, more and more co-benefits of 100% renewable energy systems have been investigated, such as less air pollution [102], substantial reduction in energy-induced water stress [126], a strong increase in jobs in the energy system [102, 157], and higher levels of energy security [9].

Several research teams have published global 100% renewable energy system analyses as summarized in Table 1. Models and methods used by research teams differ, but they consistently find that a global 100% renewable energy system can be achieved by mid-century.

The research results listed in Table 1 all comprise the entire energy system for power, heat, and transport sectors, while industrial energy demand is typically included as a component of other sectors. However, a clear deficit and research gap exists for two major segments of the energy system: First, a detailed description of the industry sector is lacking in all research and full defossilization of the non-energetic fuels demand of the industry sector is not modeled. The industry sector is described in detail in Pursiheimo et al. [153], though the authors admit that TIMES, the

Solar Photovoltaics in 100% Renewable Energy Systems, Table 1 Global 100% renewable energy system analyses. A minimum 95% renewables share is required for inclusion in the table, for at least the electricity supply

	Model	Model type	Temporal resolution	Sectors	Pathway	Regions	PV electricity [TWh]	PV share electricity	PV share TPED	RE share	Remark
Teske et al. [186]	Mesap/PlaNet	Simulation	Hourly/ annual	All	Transition	72	19,800	30%	n/a	100%	1
Bogdanov et al. [14]	LUT model	Optimization	Hourly	All	Transition	145	104,300	76%	69%	100%	1
Jacobson et al. [102]	LOADMATCH, GATOR-GCMOM	Optimization	Hourly	APl	Overnight	20	36,070	44%	44%	100%	1
Bogdanov et al. [13]	LUT model	Optimization	Hourly	Power	Transition	145	38,130	69%	99.7%	100%	
Pursiheimo et al. [153]	VTT-TIMES	Optimization	Time slices	All	Transition	13	92,900	77%	44%%	84.1%	2
Teske et al. [185]	Mesap/PlaNet	Simulation	Annual	All	Transition	10	13,610	34%	n/a	100%	3
Jacobson et al. [101]	LOADMATCH, GATOR-GCMOM	Optimization	Hourly	All	Overnight	20	45,710	35%	34%	100%	1
Löffler et al. [125]	GENeSYS-MOD	Optimization	Time slices	All	Transition	10	25,560	n/a	33%	100%	
Jacobson et al. [99]	LOADMATCH, GATOR-GCMOM	Optimization	Hourly	All	Overnight	139	49,270	48%	48%	100%	1
Breyer et al. [23]	LUT model	Optimization	Hourly	Power	Overnight	145	21,670	41%	n/a	100%	
Sgouridis et al. [171]	NETSET	Simulation	Annual	All	Transition	1	76,700	n/a	35%	98.3%	4

(continued)

Solar Photovoltaics in 100% Renewable Energy Systems, Table 1 (continued)

	Model	Model type	Temporal resolution	Sectors	Pathway	Regions	PV electricity [TWh]	PV share electricity	PV share TPED	RE share	Remark
Plessmann et al. [151]	MRESOM	Optimization	Hourly	Power	Overnight	-[5]	9,400	34%	n/a	100%	
Deng et al. [49]	Ecofys	Simulation	Annual	All	Transition	1	10,160	14%	n/a	95%	
Teske et al. [184]	Mesap/PlaNet	Simulation	Annual	All	Transition	10	6,860	16%	n/a	95%	6
Jacobson and Delucchi [97]	GATOR-GCMOM	Simulation	Annually	All	Overnight	1	20,100	20%	20%	100%	
Sørensen [178]	Unspecified	Simulation	Annually	All	Overnight	1	29,610	n/a	28%	100%	7

[1]Industrial feedstock is missing resulting in remaining fossil fuels material demand
[2]Model is unable to defossilize non-energetic industrial demand
[3]Non-energy fossil hydrocarbon use of 9620 TWh_{th}
[4]Remaining nonrenewable energy is nuclear energy
[5]The world is calculated in 0.45 degree regions
[6]RE share in electricity 95%, for all energy use 92% and including non-energy use 82%
[7]Non-energy fossil hydrocarbon use of 21,900 TWh_{th}

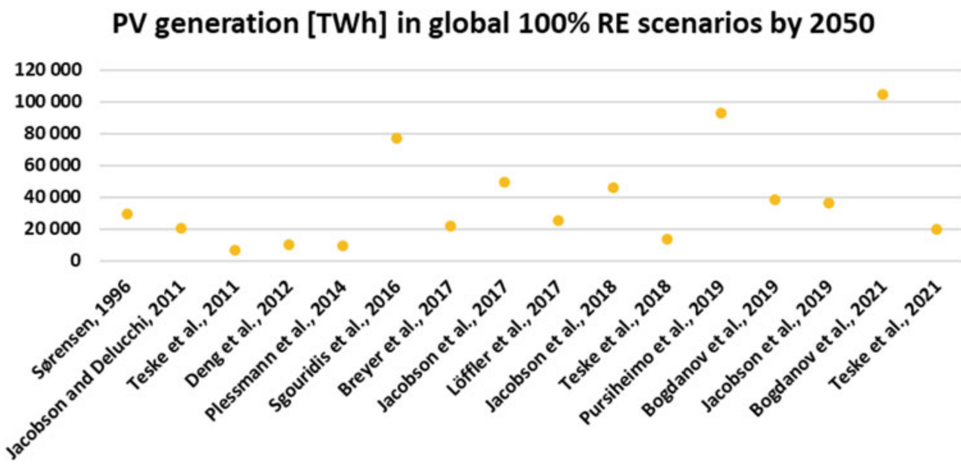
model used, was not capable of applying full power-to-X functionality for the industry sector; thus fossil hydrocarbon inputs to the industry sector were still required by the model. Similarly, Teske et al. [186] mention that the chemical industry is still fully based on fossil fuels. The latest version of the LUT model has the full functionality of a 100% renewable energy-industry system [15], but it has not yet been implemented on a global level.

Second, carbon dioxide removal (CDR) technologies are not yet consistently considered in the 100% renewable energy system community. Teske et al. [186] integrated natural climate solutions comprehensively, but their model lacked other CDR options such as direct air captured carbon and storage (DACCS) or bioenergy carbon capture and storage (BECCS) [47]. The LUT model has so far only presented insights on DACCS [26, 27]. The other research teams focus on zero CO_2 emission solutions as a consequence of 100% renewable energy system scenarios, but they do not yet encompass technologies and pathways that could enable net-negative CO_2 emission. Remarkably, not a single scenario created with a model belonging to the Integrated Assessment Models (IAMs) has been found that fulfills the minimum criterion of a 95% renewable energy share by the year 2050 and covering the entire energy system. This research gap within the climate energy research community has been mentioned by Hansen et al. [85] and Victoria et al. [194] and is discussed further in a later section.

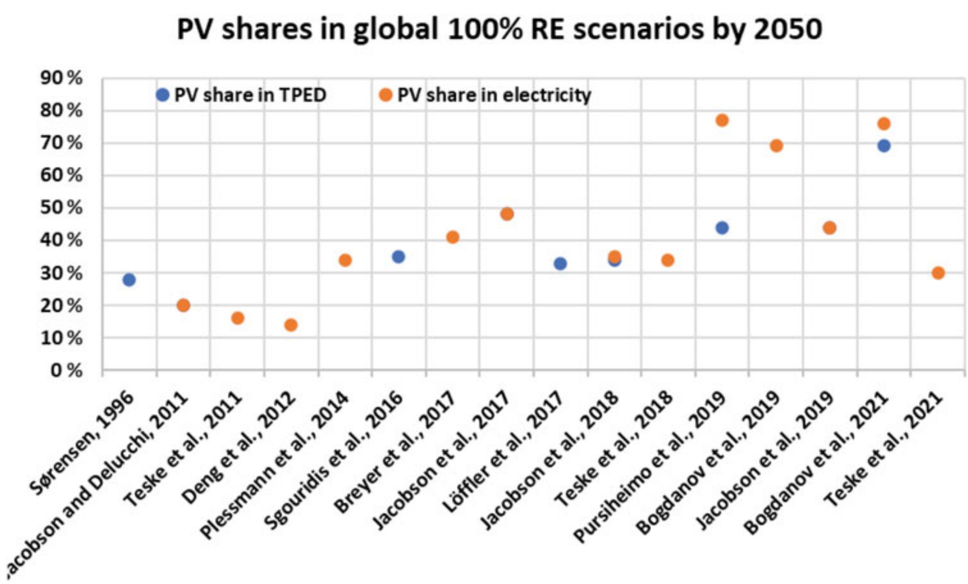
The next major development step in 100% renewable energy research may be highly resolved energy system models capable of describing transition scenarios that trace all fossil fuels-based industrial feedstock flows. This should include non-energetic fossil fuels material use, such as fossil hydrocarbon demand in today's chemical industry, and should consider the full range of energy-industry-CDR options. It is becoming increasingly important to describe 1.5 °C climate target scenarios, that fulfill the latest insights of climate system science, which indicates that the formerly assumed remaining carbon budgets [90] have to be corrected to lower values due to negative climate feedback loops not yet considered correctly [161]. Recent climate science research indicates that climate tipping points [123] may already have been activated at present temperature levels, including dynamics in several Earth systems that are likely irreversible at temperatures from ca. 1.0 °C to 1.5 °C above the preindustrial global average surface air temperature level; these include progressive thawing of permafrost soils [189], melting of Greenland ice [116], Western Antarctic Ice Shield instability [124], and coral reef dieback [90]. This would mean that for a higher level of climate security, substantially more ambitious climate targets must be aimed for. Such climate security temperature target levels may be around 1.0 °C, or even below, and in a range of 280–350 ppm atmospheric CO_2 concentration [8, 84], compared to 420 ppm CO_2 concentration reached in the year 2021. Thus, the most sophisticated energy system models must be upgraded so that they advance the scope of analysis beyond zero emission energy systems. Generating scenarios for a world with lower atmospheric CO_2 levels than today's will mean modeling net-negative emission energy-industry-CDR systems, based on 100% renewable energy supply.

Role of Solar PV in Global 100% Renewable Energy Scenarios

All known global 100% renewable energy system scenarios published in peer-reviewed articles that provided PV electricity generation data were assessed according to the solar PV share they project as a percentage of total electricity supply (Table 1). In total, 16 studies were identified; only the very first, by Sørensen [178], is from the 1990s, while all others were published after the year 2010. The most cited study in the 100% RES research field was the global study by Jacobson and Delucchi [97]. The results for absolute PV electricity generation are presented in Fig. 3 and for the relative PV share in electricity generation and total primary energy demand (TPED) in Fig. 4. Most studies describe an energy transition from the present until 2050 and for all energy demand. Hourly modeling is becoming



Solar Photovoltaics in 100% Renewable Energy Systems, Fig. 3 Solar PV electricity generation in global 100% renewable energy scenarios in the year 2050. References are provided in Table 1



Solar Photovoltaics in 100% Renewable Energy Systems, Fig. 4 Share of solar PV in global electricity generation and in total primary energy demand in the year 2050. References are provided in Table 1

increasingly standard among sophisticated models, and is part of the methods in Jacobson et al., Teske et al., and Breyer/Plessmann/Bogdanov et al.; all other model analyses suffer from lack of hourly resolution.

Further improvement is required, as not a single global 100% RES scenario fulfills the highest required standard: hourly resolution, full sector coupling, cost optimization, separation into major industries, inclusion of the five fundamental e-fuels/e-chemicals, and a pathway description from the present to mid-century. The LUT model encompasses all of these functionalities [15], but has not yet been implemented for a global scenario with all these features. The next step beyond these features should be to include a full portfolio of CDR technologies to enable modeling of global net-negative emission pathways, and thus comprehensive energy-industry-CDR modeling.

Major structural differences can be found in PV electricity contribution. A third of all studies do not find more than 20,000 TWh of PV electricity, and only three studies find more than 50,000 TWh. The two studies with the highest shares of PV have similar results: Pursiheimo et al. [153] arrive at about 93,000 TWh and Bogdanov et al. [14] at 104,000 TWh by 2050. The latter two studies use the lowest solar PV capital expenditures (capex) in 2050, with 246 €/kWp for fixed tilted utility-scale power plants and related capex for rooftop PV, and in Bogdanov et al. also related capex for single-axis tracking PV, as introduced by Afanasyeva et al. [4]. Bogdanov et al. is the only study that considers tracking, which is a major trend in present utility-scale PV power plants [95]. However, even in Bogdanov et al. [14], the applied PV capex number do not reflect the latest cost trends, which indicate about 30% lower capex in 2050 for utility-scale PV, i.e., 164 €/kWp as projected by Vartiainen et al. [191]. This will most likely lead to even higher PV electricity supply in total TWh, higher PV supply shares, and further reductions in projected energy system cost in updated scenarios.

Interestingly, Sørensen in 1996 had already found a TPED share of 28% for solar PV, while only two studies found shares higher than 40%: Pursiheimo et al. in 2019 with 44% and Bogdanov et al. [14] with 69%. The main difference between these two studies is the stronger sector coupling in Bogdanov et al. and the fossil hydrocarbons energy supply for industrial demand in Pursiheimo et al., while the lower temporal resolution of TIMES used in Pursiheimo et al. may have some impact on power-to-X applications and sector coupling.

There are several reasons for low PV supply shares in other scenarios.

First, too high cost assumptions for solar PV automatically block higher PV supply shares. This is a major issue in practically all scenarios, except Pursiheimo et al. and Bogdanov et al., in particular for the scenarios created during the first half of the 2010s, when solar PV capex projection had been very high in most cases: there was a failure to anticipate the steep PV cost decline of the mid- to late 2010s.

Second, some scenarios assume relatively high bioenergy shares, such as in Deng et al. or Teske et al., which may be in serious conflict with sustainability criteria, given the global arable land is shrinking [65], ecosystems are under massive pressure [201], world population is growing [190], and more food supply is required, while ongoing climate change impacts menace even current food production [37, 55, 179]. Creutzig et al. [45] conclude that no more than 100 EJ (about 27,800 TWh) of bioenergy can be supplied sustainably. Thus, too high and unsustainable bioenergy supply assumptions in some models block indirect electrification opportunities that, absent bioenergy, will otherwise be covered by solar PV. However, scenarios without any bioenergy supply, as assumed in Jacobson et al. do not lead to least cost solutions as recently shown in a comparison of model scenarios with and without bioenergy [132].

Third, some scenarios lack cost optimization. This is a regular challenge in simulation type scenarios in which modelers define the shares of each of the technologies included in the model; after the model scenario is run, results are then checked for stable energy supply within applied constraints. This seems to be an issue not only in various Teske et al. scenarios, but also in Jacobson et al. scenarios, as they assume a surprisingly high share of concentrating solar thermal power (CSP) plants. CSP is a technically feasible solution, but for higher system cost than solar PV. Lack of full-year hourly resolution or of appropriate inclusion of battery storage may also be a limiting factor, the latter resulting from a pessimistic battery capex cost trajectory assumption.

Fourth, distorted renewable energy resources assumptions can also lead to lower PV supply shares, as in Löffler et al., which is quite interesting, since their PV capex are identical to Pursiheimo et al. and Bogdanov et al., but the role of PV seems to be strongly underestimated due to an artificially limited solar PV potential. This strongly constrains the PV capacity increase from 2035 onward and thus leads to high additional wind capacity installations. In almost all other scenarios for the years beyond 2035, solar PV increasingly grabs market share from wind energy, because the rate of solar PV cost degression is greater, so that solar PV electricity eventually becomes cheaper than wind electricity.

Fifth, many scenarios suffer from not yet fully established power-to-X routes and lack of comprehensive sector coupling, as well as too high costs assumed for key flexibility providing technologies: batteries and electrolyzers. These are the two most important PV supporting technologies, which strongly increase the PV supply share in scenarios by overcoming the day-night limitation, supporting strong electrification of practically all road transportation segments, squeezing out biofuels for road vehicles, and enabling highly cost attractive power-to-hydrogen-to-X routes for almost all remaining energy segments that cannot be directly electrified, including long-distance transportation, high temperature industrial energy demand, and hydrogen-based molecules demand in industry. Thus, low-cost batteries, low-cost electrolyzers and established power-to-X routes strongly increase the solar PV share in covering the total primate energy demand, because low-cost electricity is most efficiently matched with relatively inflexible energy demand categories through the intermediary of batteries and electrolyzer-based power-to-X routes.

More research on global 100% RES scenarios is required for further investigating the limitations on solar PV and determining whether it could indeed achieve a range of 70–80% in supply share for electricity generation and TPED, as projected in Pursiheimo et al. [153] and Bogdanov et al. [14]. A major step ahead for the 100% RES community may be achievable by means of model intercomparisons, such as was carried out for EnergyPLAN and the LUT model [127]. Model intercomparisons could reveal undetected limitations and thus further improve standards, as well as investigate the challenges already identified here. In addition, cost comparisons of different transition pathways generated by using different input assumptions and constraints or technology cost degression assumptions within the same model will allow researchers to further clarify the cost impacts of given scenario constraints and options.

As documented in Bogdanov et al. [13, 14], the solar PV share in electricity supply is found to be comparable to the PV supply share for TPED in a sustainable energy system. This is not only a consequence of comprehensive direct and indirect electrification and utilization of power-to-X technologies for efficient sector coupling, but also due to application of strict sustainability criteria for bioenergy. In Table 2 a brief overview is provided for selected countries and regions for which the PV share in 2050 reaches at least a 50% contribution in electricity supply for the power sector, or the entire energy system, or TPED. Studies are only considered that provide pathway descriptions from the present to the 100% RES state, because stakeholders and policy makers nowadays are less interested in fundamental considerations of greenfield or overnight studies, and more interested how to achieve the aim of 100% RES in several steps over time, starting from the currently existing reality.

A database of 502 articles on 100% RES (as of early April 2021) was analyzed; 377 of these report on overnight studies and thus were excluded. Of the remaining 125 articles, 27 are excluded because they discuss the global energy transition and a further 12 articles are excluded because they discuss subnational regions; thus 86 articles remain. In a final step, the PV electricity supply share in each of these 86 articles was checked, and 34 articles were finally identified that fulfilled all the required criteria. Interestingly,

Solar Photovoltaics in 100% Renewable Energy Systems, Table 2 Countries and regions with detailed 100% RES analyses for a PV share higher than 50%. Studies are only considered for pathway descriptions from the present to a 100% RES no later than the year 2050. Values provided are all for the target year 2050

Country/Region	Reference	PV share	Energy system
120 in 145 global regions	Bogdanov et al. [14]	>50%	All
Europe	SPE [175]	61%	All
Europe south	Victoria et al. [193]	58–100%[a]	All
Europe south	Child et al. [42, 43]	56–85%[b]	Power
Turkey	Kilickaplan et al. [115]	63%	Power, gas, desalination
Kazakhstan	Bogdanov et al. [15]	81%	All
Turkmenistan	Satymov et al. [167]	79%	All
Saudi Arabia	Caldera et al. [32, 33, 35]	76%	Power, desalination
Iran	Ghorbani et al. [69, 70]	85%	Power, gas, desalination
Jordan	Azzuni et al. [9]	82%	All
Israel	Solomon et al. [176]	99%	Power, desalination
Morocco	Breyer et al. [27]	78%	Power
Algeria	Breyer et al. [27]	76%	Power
Nigeria	Oyewo et al. [140]	89%	Power
Ethiopia	Oyewo et al. [143]	66%	All
West Africa	Oyewo et al. [142]	81%	Power
South Africa	Oyewo et al. [141]	71%	Power
Ghana	Mensah et al. [132]	77%	Power
Pakistan	Sadiqa et al. [164]	94%	Power, gas, desalination
India	Gulagi et al. [78, 79]	89%	Power, desalination
India	Lawrenz et al. [121]	70%	All
Bangladesh	Gulagi et al. [80]	95%	Power
Nepal, Bhutan	Gulagi et al. [81]	67%	All
Northeast Asia	Bogdanov et al. [12]	71%	Power
Philippines	Gulagi et al. [81]	97%	All
Singapore, Malaysia	Quek et al. [155]	95%	Power
Australia	Aboumahboub et al. [2, 3]	72%	All
Mexico	Sarmiento et al. [166]	75%	All
Mexico	Buira et al. [30]	54%	All
Bolivia	Lopez et al. [128]	93%	All

[a]Europe modeled in multi-node and interconnected, with several countries above 50% PV, while entire Europe remains below 50%; countries above 50% are Portugal, Spain, Italy, Belgium, Luxemburg, Switzerland, Austria, Czech Republic, Slovakia, Hungary, Slovenia, Croatia, Bosnia-Herzegovina, Serbia, Bulgaria, and Greece
[b]Europe modeled in multi-node and interconnected, with several countries and regions above 50% PV, while entire Europe remains below 50%, countries and regions above 50% are Iberia (Portugal, Spain), Italy, Switzerland, Balkan West (Slovenia, Croatia, Bosnia-Herzegovina, Serbia, Albania), Balkan East (Romania, Bulgaria, Greece), and Turkey

only 17% of all 100% RES articles published to date meet the criteria of pathway description and country focus, but of these 17%, 38% demonstrate a PV electricity supply share of at least 50%.

For several regions, very high PV shares of more than 90% have been found, including for Israel, Pakistan, Bangladesh, the Philippines, and Bolivia, and also for several European countries in an interconnected European energy system. All the countries reaching a 90% level without external support belonging to the Sun Belt, where solar resources are very good and typically also quite stable over the year, so that hybrid PV-battery systems are highly effective. In addition, the rather dry climates of the countries listed limit hydropower, and also limit sustainable bioenergy, especially in highly populated countries. Furthermore, wind resources are rather limited in most parts of these countries, or are located longer distance from load centers. These common characteristics lead to an overwhelming solar PV dominance in energy supply in Sun Belt countries.

About 80% of studies listed were carried out by the team of Breyer et al. applying the LUT model. This has several reasons:

- First, only a very limited number of 100% RES analyses are carried out for Sun Belt countries and the Global South, a clear research gap identified in Hansen et al. [85].
- Second, bioenergy use is limited by strict sustainability criteria applied by the team of Breyer et al.
- Third, the latest international cost insights for solar PV, batteries, and electrolyzers are applied in these studies, which reveal the outstandingly high role of solar PV across the countries of the Sun Belt and the Global South. In addition, seawater desalination based on renewable electricity emerges as a major topic for Sun Belt countries [34]. The necessity for desalinated water supplies correlates with dry climates and excellent solar resources, which leads to a 78% PV-based energy supply for desalination plants, similar to the findings for the entire energy system in global average.
- Fourth, many researchers do not yet study transition pathways, but still investigate greenfield and overnight cases. Stakeholders and policy makers are typically interested in what the next steps and the no-regret moves should be, and in avoiding stranded assets, which requires pathway analyses.

Only four models are involved in studies of at least 50% solar PV supply shares: LUT model (82%), OSeMOSYS derivatives (12%), PyPSA (3%), and EnergyPATHWAYS-RIO (3%). These models are all able to describe the full energy system, but in some cases the full energy system is not investigated. All these studies have in common the use of realistic solar PV cost degression projections, and most use highly developed sector coupling features, with batteries and electrolyzers.

The first country study exhibiting a solar PV electricity share of at least 50% was published in 2017. In that year, four country studies fulfilled the criteria of at least 50% PV and transition pathways, all from the team of Breyer et al. [25], nine articles matching the criteria were found, including the first article from another team [121] on the case of India. In 2019, seven country studies with at least 50% PV supply share were published, two articles of them from other teams [155, 166] one on the case Singapore and Malaysia, the other on the case of Mexico. In 2020, eight articles for these criteria were published, including three articles by other teams [2, 3, 193]. In 2021, already five articles have been found (until early April), including one article [30] by a team other than Breyer et al.

Remarkably, first results show that even in the northern hemisphere, sustainable energy systems tend to arrive at PV shares of higher than 50%, as documented for Europe [175, 193] and Northeast Asia [12]. This is a first indication of the enormous economic attractiveness of PV prosumer and hybrid PV-battery-electrolyzer solutions, since wind energy is typically attractive in these regions and power lines are in principle able to widely distribute wind electricity. Despite this, the cost reduction over time is much higher for solar PV, batteries, and electrolyzers, than for wind energy and power lines, so that over time solutions based on solar PV, battery, and electrolyzers gain relative competitiveness. This fundamental observation has been found repeatedly [59, 61].

Critique on Underestimation of Solar PV in Energy Scenarios

Two organizations have attracted repeated criticism (e.g., by [20, 23, 46, 147]) for their too conservative implementation of solar PV in their scenarios and reports: International Energy Agency (IEA) and Intergovernmental Panel on Climate Change (IPCC). In early 2021 three studies [105, 194, 202] investigated, using different methods, data and comparisons, the claims articulated earlier on massive solar PV underestimation in IPCC reports. All three studies strongly emphasized the substantial underestimation of future solar PV deployment in practically all scenarios, in particular in IAMs used for IPCC reports. They found that only a few scenarios were built on plausible future solar PV cost degression projections; most scenarios assumed far too high future PV costs.

Over the last 20 years, the flagship publication of the IEA, the World Energy Outlook, demonstrated a strikingly obvious failure to realistically project solar PV capacity development, which was visualized by Hoekstra as shown in Breyer and Jefferson [20], and comparably in Metayer et al. [133]. Sustained criticism from various stakeholders had no discernable impact before 2019: the IEA continued to publish gross underestimates of the role of renewable energy in its scenarios. However, a massive critique endorsed by dozens of stakeholders in early 2019 [1], including global financial giants such as the insurance global player Allianz, seemed to finally have an impact. In the World Energy Outlook 2020 [92], published in late 2020, the IEA reacted to the years-long criticism and adjusted its wording to acknowledge the now undeniable reality: that solar PV has emerged as the world's least-cost source of electricity. Longtime IEA director Birol nailed home the message by saying "solar is the new king of energy markets." The World Energy Outlook 2020 may mark a turning point for the IEA, as for the very first time it is clearly documented in the WEO report that at present and for the foreseeable future, solar PV is and will remain the least-cost source of electricity in all major regions of the world. Even so, the solar PV shares in most of the IEA scenarios are relatively low, although a new scenario, the net-zero emissions 2050 (NZE2050) scenario, may emerge as the first realistic scenario in two decades for IEA for solar PV. NZE2050 reflects the political reality that low-carbon and climate-neutrality targets have been set for 2050 by most of the major economic powers around the world, including the European Union, the US, Japan, and South Korea. A commitment is also expected soon from India. China may revise its existing carbon-neutrality target for 2060 to 2050. Why the IEA failed for so many years so massively to make realistic solar PV projections remains unclear. It may have resulted from a mix of using outdated data, outdated modeling, distorted overall cost assumptions for fossil CCS, overly optimistic cost estimates for nuclear energy, and overly pessimistic cost estimates for solar PV. It seems plausible that political pressure from major OECD countries may have played a role. Interestingly, in early 2021, the IEA published a report, ordered by the French government, on 100% RES supply for France in 2050 [93], the very first such report for the IEA and the French government.

The challenge posed by the fact that IPCC reports are mainly based on Integrated Assessment Models (IAMs) is more severe, given that the IPCC has emerged as the central advisory institution for managing the climate emergency. The IAMs used for scenario analyses show multiple deficits and failures, leading to severely distorted scenario outcomes. A major issue is the extremely outdated cost assumptions in virtually all scenarios based on IAMs. The comparison of the solar PV capex used in IAMs, documented in Krey et al. [120], leads to 4–5 times higher cost in 2050 in comparison of projections of Vartiainen et al. [191]. Strikingly, the 2050 cost assumptions are consistently higher than the real empirical cost that had been already achieved in the year 2020. Strongly distorted scenario results are the consequence, for instance, presented in Eom et al. [54], confirmed by Victoria et al. [194], Xiao et al. [202], and indicated in Jaxa-Rozen and Trutnevyte [105]. Xiao et al. concluded: "In the worst case, transformation efforts toward clean energy are delayed, in the false belief that they are too expensive that may lead to misadjusted incentive systems." Jaxa-Rozen and Trutnevyte [105] wrote: "We . . . recommend increasing the diversity of models and scenario methods included in IPCC assessments to represent the multiple perspectives present in the PV scenario literature." Victoria et al. [194] found that "the contribution of solar electricity to primary energy in 2050 averages to 3.1%/6.8% in the IPCC 5thAR/SR1.5." In other words, the first global 100% RES publication in 1996 [178] indicated four times the TPED contribution of solar PV than the average of IAMs used for the most recent

IPCC report published over 20 years later. Victoria et al. also reported some progress in some publications using IAMs, though a major turn in correct PV cost data usage has not yet been observed. In addition, Victoria et al. also point out that sector coupling and comprehensive electrification for all energy demand is still missing from almost all IAMs and their respective scenarios.

The IPCC reports are meant to summarize existing scientific insights on climate change and the mitigation options. Historically, the first IPCC report that has mentioned the existence of 100% RES scenarios was the IPCC report on "Global Warming of 1.5 °C" in 2018 [90]. In this report, 100% RES scenarios were not discussed broadly; rather, their existence was briefly mentioned. This was 43 years after the first 100% RES article and 22 years after the first global 100% RES article. Further, by end of 2017, at least 280 research articles discussing 100% RES were available. As Jaxa-Rozen and Trutnevyte [105] have correctly pointed out, more diversity is required, not only in scenarios, but obviously also in the authors writing IPCC reports, so that existing scientific knowledge can be assessed and made available to stakeholders and decision makers more rapidly and comprehensively.

Reports from a broad range of stakeholders have been assessed by various authors [18, 23, 24, 41, 42, 105, 202] for their suitability for describing a sustainable future and their views on solar PV. Nearly all reports assessed were skeptical about highly renewable energy systems. However, two exceptions were found: the German Advisory Council on Global Change [196] published a report in 2003 that found a 67% primary energy supply share for solar energy by 2100, and the Shell Sky scenario [173] finds a 32% solar energy primary energy supply share for the year 2070, and 59% renewables in total, which is still not sufficient for ambitious 1.5 °C targets, but is the most progressive energy scenario so far published by a major oil and gas corporation.

Summing up, major international institutions have failed during the 2000s and 2010s to correctly project solar PV development, even though more accurate projections were not impossible as documented by several researchers [16, 17, 46, 184, 185]. The latest and realistic solar PV capex cost degression trajectory estimates must be applied in energy scenarios so that realistic results can be obtained [202]. Further, sector coupling and power-to-X functionalities must be implemented for describing sustainable energy systems with proper accuracy [194].

Implications of Fully Sustainable Energy Systems on Solar PV

This section first summarizes the key requirements for a sound representation of solar PV in sustainable energy system scenarios, so that researchers, modelers and stakeholders can better check whether scenarios avoid artificial limitations. Following this summary, additional implications are briefly discussed regarding what a majority solar PV supply share for the TPED may mean for required PV industry scaling, PV prosumer and building-related PV, required area demand for utility-scale PV, continued discourse with critics, energy return on invested (EROI), and materials availability.

The most relevant **requirements for a well-balanced representation of solar PV** in sustainable energy system scenarios are as follows:

- Realistic solar PV capex must be applied for the full scenario period.
- Cost shall matter in scenarios, i.e., cost optimization has to be considered. Higher cost solutions may well be justified, but assumptions must be made transparent.
- Hourly temporal resolution for the whole year (all 8760 h) is required for a proper representation of variable renewables.
- Multi-region models with interconnected infrastructure for transmission power lines must become standard, preferably including transmission pipeline infrastructure and regional and global trade of energy-related products, for more realistic systemwide cost optimization.

- Realistic battery capex must be applied for realistic PV-battery solutions as well as realistic phase-in of battery-electric vehicles.
- Electricity-based sector coupling is a central feature in sustainable energy systems, and must be implemented in detail, including all relevant power-to-X routes.
- Realistic electrolyzer capex must be applied for realistic electricity-based hydrogen production cost.
- Climate targets and carbon trajectories should reflect international policy commitments and, in some scenarios, higher-safety variations in required policies should be explored in accordance with the latest insights from climate science, driven by the twin goals of avoiding a collapse of civilization and biodiversity.
- Realistic bioenergy potential assumptions must be reflected for a world facing decreasing arable land, increasing water stress, growing population, and higher standards of living.
- Models used for energy scenarios must be documented in a transparent way and published in peer-reviewed scientific journal publications to ensure they meet minimum scientific standards.
- Transparency in input data is a must, especially for all cost assumptions, all key technical assumptions, and major constraints.
- Simplified greenfield overnight scenarios should be avoided and substituted by pathway descriptions, so that stakeholders can use the scenarios to inform societal discourse on how to transition from the present to a sustainable energy system.

The required **PV industry scaling** may be a major challenge, as the cumulative installed PV capacity of 756 GW at the end of 2020 must be scaled to roughly 70 TW within three decades in order to contribute solar energy's share of the global goal to achieve net-zero emissions by 2050, according to Haegel et al. [83], Bogdanov et al. [14], and Verlinden [192]. Such an enormous scaling would require growth rates of the PV industry of about 30% annually for the entire 2020s, so that the annual PV industry output would reach about 3 TW/a in the early 2030s [192], a level and pace unprecedented in history. However, a comparable compound annual growth rate was achieved by PV industry in terms of relative CAGR for most recent decades, and is expected to be reached again for the year 2021 [154]. Fundamental cost trends in the PV industry [39] indicate a continued cost decline, and generated cash flows enable a steady annual growth of industrial output of about 20% [83]. Higher profits or external cash inflow may be required to lift the CAGR to the required level of 30%. It seems that the transition from past subsidy and regulation-driven PV deployment growth to the present market price-driven growth pattern has slowed the average CAGR to about 20% in recent years. However, the first signals for the year 2021 suggest that growth rates can be again lifted to 30%, which would be required to fulfill these extremely ambitious targets.

The approximately 70 TW of installed PV capacity in the year 2050 leads to a concomitant ground mounted area demand, as discussed in the next paragraph. Additionally, high penetration of solar PV implies installing as much PV capacity on buildings as possible, which offers economic synergy with **PV prosumers**. Building surfaces can be regarded as zero impact areas, where electricity supply can be very close physically to energy demands including direct electricity, heat supply, and battery-electric vehicles. Building-applied PV and building-integrated PV must become a matter of much higher priority for urban area planning. In most urban areas, PV offers by far the largest local energy resource potential. Bogdanov et al. [14] assume a global building-related PV capacity in 2050 of about 9.7 TW, 15% of total PV capacity. It should be mandatory that virtually all rooftop areas and suited façade areas be used for PV electricity generation. This may entail lower electricity yield per installed capacity than ground mounted solar PV plants in the countryside; however, the benefits would include less land demand and closer proximity of electricity supply and demand. In combination with energy storage, a high degree of self-supply can be achieved, which is particularly beneficial for equatorial regions [145]. Keiner et al.

[109, 110] have investigated the value to solar PV prosumers of behind-the-meter solutions, including direct electricity supply, heat supply, and battery-electric vehicle supply as well as micro sector coupling, for all regions of the world. The results indicate that it will be financially advantageous to be a PV prosumer in the residential segment. Surprisingly, detailed consideration of PV prosumers [148] is not standard in energy system models, despite the high attractiveness of behind-the-meter solutions, as well as the strong interaction of prosumers with the overall energy system, as excess electricity is fed into the grid and supply deficits are covered by grid supply. Child et al. [43] find that PV prosumer inclusion in energy system transition scenarios also reduces high voltage power transmission capacity requirements. More comprehensive research may be required for PV prosumers to reflect the opportunities for peer-to-peer solutions possible for end-users [163].

It is regularly claimed that very high renewable energy or solar PV supply shares would not be possible due to high **area demand** [86, 114, 135]. The highest published PV capacity demand based on a detailed analysis is Bogdanov et al. [14] (see also Table 2 and Figs. 3 and 4). Therefore, the following discussion on the required area demand is based on these results. The total installed PV capacity in the year 2050 is projected to reach 63.4 TW, of which 9.7 TW will be PV prosumer installations linked to buildings, which do not require ground area. The remaining 53.7 TW require ground mounting or agricultural PV systems to be installed. The projected cumulative installed capacities and required additional capacities per period are tabulated in Table 3, in addition to the projected PV module efficiencies according to Vartiainen et al. [191]. This leads to the additional required area in each 5-year period, the total area and the fraction of the total land area, assuming a capacity density of 75 MW/km^2 for 15% efficient PV modules [11].

As shown in Table 3, about 0.3% of the total land area is required, which may be acceptable given that PV would then deliver about 70% of total energy supply in the year 2050, and enable a sustainable energy system. Very high fractions of these capacities can be easily located in remote areas, on barren land, as many semidesert areas have excellent solar PV resources. Past research investigated global power grid solutions as summarized by Breyer et al. [28], and recent insights indicate that grid integration on the level of major world regions is beneficial, but not for even larger grid integrations beyond a major region level toward a global grid integration. However, indirect solar PV electricity trade in the form of e-fuels/e-chemicals production is found to be attractive on a global scale [59–61, 63] and may be part of a global least cost energy system [50]. In addition, floating PV on onshore water areas has a capacity potential of about 5.7 TW if 25% of water reservoirs are used [58]; this is a fast growing PV market segment [122, 149, 200]. Research on offshore floating PV indicates further floating PV

Solar Photovoltaics in 100% Renewable Energy Systems, Table 3 Projected PV ground mounted PV capacity demand and respective area demand

		2015	2020	2025	2030	2035	2040	2045	2050
Ground mounted – Cumulative	GWp	131	634	2569	7590	13,988	24,233	35,720	53,712
Ground mounted – Added	GWp	0	503	1935	5021	6398	10,245	11,487	17,992
Module efficiency	%	0.15	0.18	0.20	0.22	0.24	0.26	0.28	0.30
Area density	MW/km^2	75	90	100	110	120	130	140	150
Area additional	km^2	0	5589	19,350	45,645	53,317	78,808	82,050	119,947
Area total	km^2	1747	7336	26,686	72,331	125,648	204,455	286,505	406,452
Global land for PV	%	0.00%	0.00%	0.02%	0.05%	0.08%	0.14%	0.19%	0.27%

potential [71, 146], which would lead to practically unlimited area availability if it can be made technically robust enough and financially viable. Moreover, agricultural PV allows to continue agricultural production to continue beneath raised solar rooftops, under partial shade, enabling farmers to add solar PV systems to their land for complementary and synergetic yields, which do not significantly compromise either agricultural or PV yields [168]. These solutions accompany the very promising further technological development of bifacial PV [118, 119, 160], which is expected to have a global market share of about 45% by 2024 and 70% by 2030 [95]. If combined with tracking [4, 160] or agricultural PV, the potential efficiency gains of this module type can be even greater, and it could become the next-generation utility-scale PV standard [144]. Importantly for area demand considerations, bifacial tracking PV raises the yield per installed capacity by about 35% compared to fixed-tilted monofacial PV power plants [160], which were the standard in the 2010s. In summary, devoting about 0.3% of total land area (much of it barren land) to solar PV deployment seems like an acceptable price to pay for a sustainable energy system and a stable climate, yet less land may in fact be required, because a substantial fraction of total PV could be realized by making use of building roofs and façades, water surfaces, solar PV fences, etc. Taking a round view, concerns over net land use seem unnecessary.

Critics of 100% RE systems, such as Clack et al. [44], Trainer [187], Jenkins et al. [106], Heard et al. [86], and others claim that such systems would be technically impossible, too expensive if possible, or, if affordable, would lack required resources. These claims are debunked by ongoing research, such as Jacobson et al. [98, 100] and Aghahosseini et al. [5, 6] for the case of Clack et al. [44]. Brown et al. [29] highlighted the technical feasibility of 100% RE systems in great detail and provided the first broad overview of 100% RE research and respective economics in response to Heard et al. [86]. Attractive overall economics are shown by several researchers in various studies, and are shown on the global level by Teske et al. [186], Jacobson et al. [99, 101, 102], and Bogdanov et al. [13, 14] (see also Table 1). Studies on 100% RE published up to the year 2018 were comprehensively summarized by Hansen et al. [85] and updated in Fig. 2, showing a strongly growing research field, which increasingly covers all energy sectors.

It has been regularly claimed that a 100% RES scenario would be impossible due to limitations in fundamental energy economics [64, 135, 188], called **energy return on invested** (EROI). However, these considerations have been repeatedly debunked, including those by Raugei et al. [158], Diesendorf and Wiedmann [51], and White and Kramer [197]. Regular issues in EROI debates are the use of outdated data, neglect of the energy learning rate [72], or fundamental misconceptions (White and Kramer [197]; Diesendorf and Wiedmann [51]). Indications are strong that the energy payback time of solar PV is on track to reach a value of about 1 year [72, 198] for a technical lifetime of at least 30 years, or even 35 years [131]. This implies an EROI of about 30, with the energy learning curve steadily improving the values. Moreover, a fast electrification of the energy system may change the primary energy input to the PV production system, which further reduce these values. More research is required to investigate the impact of a fast energy transition and dominance of variable renewable energy in the energy system on the EROI. Most EROI analyses and debates so far were for the power sector; a comprehensive EROI analysis for the entire energy system transition constitutes a research gap that needs to be closed soon.

Increasing attention is paid to the **material basis** required for a sustainable energy system. Practically all research in this field finds critical limits for material availability. This may be a major concern and should be addressed with more consideration and analyses to truly test the material limits. Highly ambitious energy system transition scenarios toward 100% RES have been used as a basis for investigating material availability limits. Junne et al. [107] used the scenarios of Jacobson et al. [102], Teske et al. [186], and Bogdanov et al. [14] and identified criticalities for the four focused materials: lithium, cobalt, neodymium, and dysprosium. Independent research by Greim et al. [77] concluded that lithium is close to its material limits. However, scenario combinations have been identified that enable transition scenarios without conflicting the lithium resource basis, according to Bogdanov et al. [14] and Khalili et al. [113]. Extremely high collection and recycling rates close to 100% will be mandatory. Cobalt may be manageable with cobalt-free lithium batteries [73, 159]. The challenge of securing enough neodymium and dysprosium requires further investigation. Additional potentially critical materials are silver and tellurium, which are both required for solar PV. The tellurium resource limitation seems to be severe and may limit annual CdTe PV output to about 10–25 GW [31]. However, this criticality may not be dramatic, since CdTe PV represents less than 5% of the annual PV market [96]. If multi-TW annual manufacturing is achieved, silver supply will be not be sufficient for continuing to apply current c-Si PV metallization techniques [74, 192]. The silver supply challenge may not be critical, though, as a substitution with copper has already been investigated [7, 192] and PV cells with the substitute technology are expected to be commercially introduced during the 2020s [95]. The current silver price level does not trigger a copper substitute: a silver price increase of 50–100% may phase-in copper as a metallization substitute. The phase-in of passivated emitter and rear cell (PERC) c-Si technology has shown that a major technology shift in much of the global manufacturing capacity may be doable within about 3 years [95]. Copper may be another material that requires more detailed analyses, as a comprehensive electrification of the energy system will inevitably lead to a surge in copper demand. If copper constraints exist, aluminum, which is typically regarded as a natural and practically unlimited substitute, can be used. So far researchers analyzing copper criticality have not yet identified copper limitation; however, most have considered copper demand growth according to economic development and population growth and collection-recycling rates of about 70% [181, 195]. In contradiction to that, Elshkaki et al. [53] considered additional demand from a more equitable energy supply development and found significant copper supply limitation, while a comprehensive electrification has not yet been considered in full, but indications by Kleijn et al. [117] strongly indicate that the challenges will be increased. More material criticalities may be identified in the years to come and increased attention is required on the materials required for a fast energy transition toward 100% renewable energy systems. Solar PV itself seems to be less affected by materials limitations; however, the sustained growth of PV also requires several supporting technologies, and limits on these must be avoided in order to limit the required scaling of PV.

Dawn of the Solar Age for Rebalancing Civilization Within the Limits of Planet Earth

The latest studies find global energy supply shares of solar PV of up to about 70% [14] of the entire primary energy demand of humankind. The dawning Solar Age is enabled by historically unrivalled low solar PV electricity generation cost leading to a broad electrification of up to 90% of global primary energy supply and to deployment of a set of power-to-X technologies, which convert PV electricity, water, and CO_2 captured from the air to heat, fuels, chemicals, clean water, and refined materials, as well as providing the energy source that will be needed to remove excess CO_2 waste from the atmosphere and oceans.

It is necessary to fully incorporate the planetary boundary framework into global energy scenario modeling [41], so that a rebalancing of humankind within the limits of plant Earth can be achieved [24]. In the following, a first attempt at estimating the solar PV demand for a truly sustainable civilization is presented. Three fundamental achievements are assumed:

- First, by 2100, all people in the world shall reach the standards of living achieved in Europe in 2050 following earlier considerations in [24] but with updated assumptions according to Bogdanov et al. [14].
- Second, the entire energy-industry system shall be switched on a 100% RES basis by 2050.
- Third, a net-negative CO_2 emissions CDR sector shall reduce the atmospheric CO_2 concentration from the present 420 ppm back to 350 ppm solely by means of PV-based DACCS, as it is the only massively scalable CDR technology known to date.

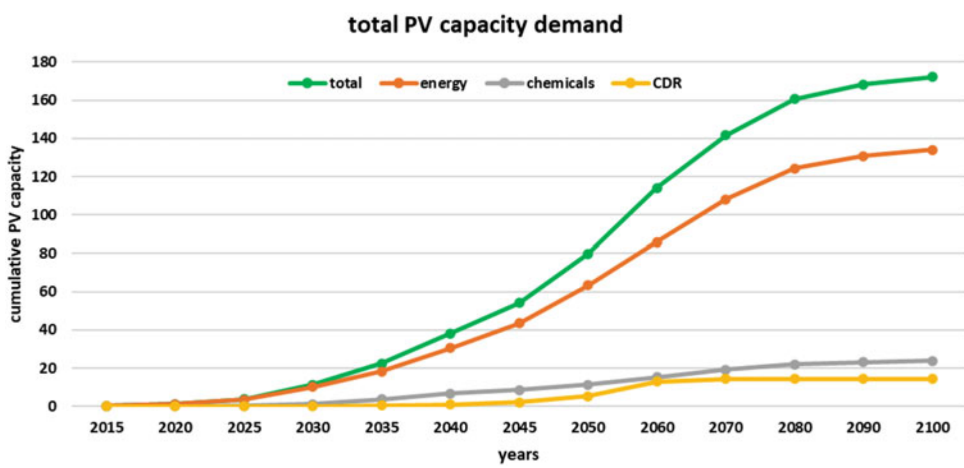
The primary electricity supply per capita in Europe in the year 2050 will reach a level of 26.7 MWh according to Bogdanov et al. [14]. The global average in 2050 will reach 14.2 MWh/capita according to the same source. The world population is projected to reach 9.7 billion in 2050 and 10.9 billion in 2100 [190]. Bogdanov et al. covered the entire energy system and the energy demand of industry, but the fossil material demand of the chemical industry has not been included. The global chemical industry required fossil materials in the energy equivalent of 10,620 TWh in 2020 and is expected to grow to 15,510 TWh in the year 2050 [50], which leads to an electricity demand of 24,390 TWh for the assumptions according to Bogdanov et al. [15]. The scaling of the chemical industry from 2050 to 2100 is assumed to be proportional to the global energy demand increase. The CDR volume is roughly estimated to fully remove all energy-related emissions of the scenario according to Bogdanov et al. [14] as indicated from 2018 onward until reaching zero emissions by 2050, which are 422 $GtCO_2$. The CO_2 emissions related to all fossil CO_2 emissions for the same period are estimated to be 567 $GtCO_2$. The target 350 ppm level was surpassed in the year 1988, and the estimated CO_2 emissions for the years 1988–2017 had been 916 $GtCO_2$ according to Friedlingstein et al. [66]. Thus, the total amount of CO_2 to be removed is roughly estimated to be 1483 $GtCO_2$. This estimate is consistent with an assumed extraction requirement of 695–1630 $GtCO_2$, if the extraction begins in 2020s and includes further emissions in years to come, while aiming for a 350 ppm CO_2 target in 2100 [84]. The CO_2 removal period of 60 years is relatively short, with substantial industrial scaling from 2040 onward, reaching a steady annual removal level of 33 $GtCO_2$ in the year 2060 with continued removal at the same rate until the year 2100. The electricity demand for removing 1 $GtCO_2$ is estimated to be 713 TWh according to Breyer et al. [27]. The DACCS phase-in assumes 1 $GtCO_2$ in 2035 and CAGR of 15% and 20% for the 5-year intervals starting 2040 and 2045, respectively, and a CAGR of 19%, 10%, and 1% for the 10-year periods starting 2050, 2060, and 2070, respectively. Continued operation of 33 $GtCO_2$/a then occurs until the end of the century. For comparison, Chen and Tavoni [38] report a DACCS demand by the end of the century of 37 $GtCO_2$/a, which indicates a similar demand to that derived in this analysis. Beyond the year 2100 carbon removal may have to be continued to balance the further global warming impact of other greenhouse gases. Further, a historic zero-emission return to pre-industrial CO_2 levels should be considered to slow down, as much as possible, tipping points already triggered, such as the Greenland and West Antarctic ice sheet mass loss dynamics. The high uncertainty of these considerations must be reduced and revised in later research. The considerations outlined here reflect some principle requirements of energy-industry-CDR scenarios for $T \ll 1.5$ °C conditions, but they are a first estimate, not a final conclusion on the topic.

The targeted atmospheric CO_2 concentration of 350 ppm was chosen in accordance with Hansen et al. [84] and Azar and Rodhe [8]. The historic-zero emission concentration would be around 277 ppm, which was the value around 1750, before the industrial revolution led to massive fossil fuels use and consequent anthropogenic CO_2 emissions. Increasing the ambition beyond an atmospheric CO_2 level of 350 ppm to 277 ppm would require an additional 737 $GtCO_2$ negative emissions [66]. Such a scenario would either require increasing the steady removal amount from 33 $GtCO_2$/a to 49 $GtCO_2$/a to achieve this revised target by the year 2100, or proceeding with negative emissions at the 30 $GtCO_2$/a level for another 22 years beyond 2100. In the period from 1750 to 1850, cumulative CO_2 emissions from fossil hydrocarbon combustion were 4.4 $GtCO_2$ [66], and therefore are not significant in light of the fact that we now emit about 10x that amount every year. The tipping points of Greenland ice melting and the Western Antarctic Ice Shield instability [116, 123, 124] may require pushing atmospheric CO_2 concentration levels far below 350 ppm. If the tipping point emergency is not urgent, then additional CO_2 removal from the atmosphere below a 350 ppm level can occur due to the natural decay of CO_2 in the atmosphere. This may lead to an additional 50–100 ppm of atmospheric CO_2 emission reduction in the time span of 50 years at the lower and 100 years at the higher range, respectively, after net-zero CO_2 emissions have been achieved [130].

Table 4 and Fig. 5 summarize the key findings regarding the solar PV capacity that may be required for a truly sustainable civilization to be realized by the year 2100. For all installed PV capacity, the global average yield of solar PV systems is estimated to be 1670 kWh/kWp per annum as of 2050, and the PV electricity generation share is estimated to be 76% of total electricity generation, complemented with wind electricity hydropower and geothermal; these numbers are in accordance with Bogdanov et al. [14]. Some additional important factors are not yet reflected in this first estimate, but shall be briefly mentioned: First, the PV share will be most likely higher, as the stark increase in additional energy demand beyond 2050 will lead to sustainability limits for hydropower and land limitations on wind energy, which would be balanced by more PV electricity. Second, there is no further cost reduction considered for energy technologies beyond the level of the year 2050, but, if

Solar Photovoltaics in 100% Renewable Energy Systems, Table 4 Key solar PV demand drivers for a truly sustainable civilization in the year 2100

		2030	2035	2040	2045	2050	2060	2070	2080	2090	2100
Total	TW	11.3	22.4	38.1	54.6	79.8	114.0	141.7	160.5	168.3	172.2
Energy	TW	10.2	18.3	30.5	43.5	63.4	85.8	108.2	124.2	130.7	134.0
Chemicals	TW	1.1	3.7	6.7	8.6	11.3	15.2	19.2	22.1	23.2	23.8
CDR	TW	0.0	0.4	0.9	2.6	5.2	13.0	14.3	14.3	14.3	14.3



Solar Photovoltaics in 100% Renewable Energy Systems, Fig. 5 Key solar PV demand sectors energy, chemicals and CDR for a truly sustainable society in the year 2100 considered, they would most likely increase the PV supply share, assuming further cost decline of PV, batteries, and electrolyzers. Third, the per capita primary energy demand for Europe may decline beyond 2050, due to higher direct electrification shares in the transport sector with more direct electric flights and more kilometers driven by battery-electric vehicles compared to the assumed reference, reducing the total energy and PV demands. Fourth, more CDR options than PV-based DACCS are available and shall be considered, which would lead to less DACCS and thus lower PV demand. Conversely, even more ambition may be required for higher negative annual emissions, which requires detailed consideration for a well-balanced CDR portfolio, as detailed later in this section.

A rough estimate of total solar PV capacity required in the year 2050 for a full energy-industry-CDR system has the following components: energy system demand of 63.4 TW, 11.3 TW for PtX-based chemicals, and 5.2 TW for CDR, totaling 79.8 TW. A truly sustainable civilization in the year 2100 requires about 171 TW of solar PV in total, of which about 134 TW is for the energy system, 24 TW for chemicals, and 13 TW for CDR. The assumed PV share in TPED equals the 69% for energy and chemicals demand as found in Bogdanov et al. [14] but a sole PV electricity supply for CDR is assumed. These estimates reveal two fundamental insights: First, the mid-century global energy demand marks the period in history with the largest annual changes in TPED and requires annual PV capacity installations of 4–5 TW. Second, the rebalancing of CO_2 levels within planetary limits may be comparably affordable from an energetic perspective, since an assumed CO_2 removal of about 1400 $GtCO_2$ by 2100 leads to a cumulative PV capacity share devoted to CDR of about 6.5% in the year 2050 and 11.4% in 2060, and then gradually declining to 7.6% in the year 2100.

Such a scenario would lead to a global installed PV capacity of about 171 TWp around the year 2100. Rebalancing civilization within the geochemical limits of planet Earth appears to be technically feasible and financially viable if the dominating source of energy is solar PV electricity, which is practically unlimited, scalable, and already today the historically least-cost source of energy, with the cost continuing to decrease. Only a fraction of the true solar PV technology potential has been realized to date, as present-day PV module efficiencies reach about 20% and mid-term c-Si tandem modules are projected to attain 30% module efficiencies without using critical materials, with the non-concentrating theoretical limit being around 70%. Low-cost technology roadmaps beyond 30% PV module efficiency remain rather unclear from present understanding of PV technology, but the situation was similar in the 1950s, when laboratory records had just surpassed 6% efficiency.

The fast-growing research field of negative emission technologies (NETs) is motivated by the rising recognition that NETs will be urgently necessary for rebalancing the consequences of human actions on our planet's climate [134]. A comprehensive CDR technology portfolio must be developed, including an investigation of technological and environmental limitations of the various technology options [47, 67, 134, 162]. With low-cost solar PV available globally, electricity-based, highly area- and resource-efficient solutions may light the way ahead.

We have arrived at the threshold of a truly sustainable civilization, a prosperous and enduring Solar Age which leaves no one behind. Humankind may have never been closer to making this dream a reality, despite the existential climate emergency. But the climate emergency demands that we act fast and think big. May the citizens and leaders of the world recognize this unique chance to achieve both prosperity and climate stability, and take action with historically unparalleled ambition. Solar PV is THE key for opening the door to a truly sustainable future.

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