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Snapshot of photovoltaics – February 2024

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Abstract. In 2023 global renewable energy investments increased by 8% to USD 623 billion, with solar investments accounting for 63% or USD 393 billion (+12%). The total installed solar photovoltaic capacity exceeded 1.6 TWp at the end of 2023, with an annual newly installed capacity of more than 420 GWp. The number of countries installing 1 GWp/year or more has increased to 35. After the increases in hardware costs for solar photovoltaic systems and battery storage in 2022, prices in both markets mostly decreased in 2023. Levelised costs of electricity for non-tracking solar photovoltaic systems as well as levelised cost of battery storage decreased. However, the global benchmark of levelised cost for electricity for tracking systems increased mainly due to higher costs for labour, balance of systems and debt in the USA. The market outlook for 2024 is optimistic as electrification of heating, transport and industry creates additional demand for renewable electricity, including solar. However, a more rapid deployment of renewable energy is needed to stay on track for not more than 1.5 °C global temperature increase.

Keywords: Renewable energies / photovoltaic / green hydrogen / energy challenge / policy options / technological development / market development

1 Introduction

The renewable energy pledge to triple the capacity of renewable energies by 2030 compared to 2022 was signed by 123 countries during COP 28 [1]. However, current policies and market conditions will only enable a 2.5 times growth, according to an assessment by the International Energy Agency (IEA) published in January 2024 [2]. The only region which currently is on track to triple its renewable energy capacity is Asia, driven by the strong growth of renewable energy deployment in China and India [3]. Those two countries are responsible for 90% of the total renewable capacity in the region and compensate for the lesser growth in the remaining countries. However, in order to be 1.5 °C compatible and in alignment with the Paris Agreement the global renewable capacity has to increase 3.2–3.4 times compared with 2022. Different scenarios vary between 11 TW_{AC} by the IEA net zero by 2050 scenario (NZE_{2023}), 11.2 TW_{AC} by the International Renewable Energy Agency (IRENA) and 11.5 TW_{AC} by Climate Analytics [3–5].

In the IEA NZE_{2023}, electricity generation will increase from 29,033 TWh in 2022 to 38,207 TWh in 2030 (+31.6%) and 76,838 TWh in 2050 (+165%). Renewable energy generation should increase from 8,599 TWh in 2022 to 22,532 TWh (+162%) in 2030, providing 59% of the total electricity. To realise this, solar photovoltaic generation capacity has to increase more than fivefold to 6.1 TW_{AC} and wind has to triple to 2.7 TW_{AC}. Solar photovoltaics and wind should then provide 40% of the total generated electricity. This is a significant increase in the share of solar and wind compared to the IEA World Energy Outlook (WEO) 2021. This would take place to varying degrees in every country and is an acknowledgement of the fact that neither solar nor wind resources can be monopolized. One of the great advantages of Solar photovoltaics (PV) is that it can be deployed in a modular way almost everywhere on this planet from installations with a few Wp capacity to multi GWp solar plants.

Between 2015 and 2023 investments in clean energy gradually increased from USD 1074 billion to USD 1770 billion or 1.7% of global GDP [6–8]. Investments in renewable power capacity amounted to USD 623 billion, second to electrified transport with USD 634 billion, followed by USD 310 billion for grids and USD 36 billion for storage. According to the IEA, the level of investment

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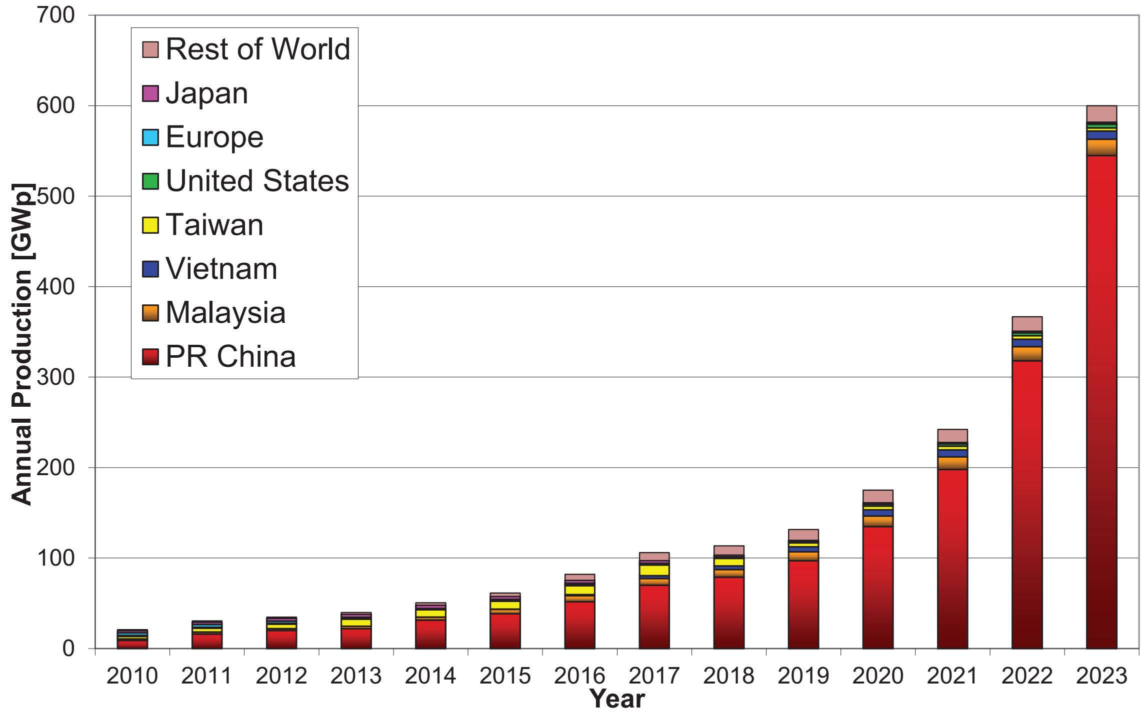

Fig. 1. World PV Cell/Thin Film Module Production from 2010 to 2023.

has to more than double to about USD 4 trillion per year in order to realise the NZE [9]. This looks like a lot of money, but it is dwarfed by the current annual direct and indirect government subsidies for fossil fuels, which amounted to USD 7 trillion or 7.1 percent of worldwide Gross Domestic Product (GDP) in 2022 [10]. Environmental and health costs, which account for roughly 60% of the USD 7 trillion, as well as foregone consumption taxes are included in this calculation according the International Monetary Fund (IMF).

Annual renewable power investments increased from USD 372 billion in 2020 to USD 623 billion in 2023 (+67% or + USD 251 billion) [7]. However, the annual investments in the global fossil fuel supply increased from USD 742 billion to USD 1098 billion (+48% or USD 356 billion), which is over a USD 100 billion more than for renewables. Investments in solar energy was USD 392.7 billion, whereas photovoltaics accounted for USD 385.5 billion and concentrating solar power contributing about USD 7 billion.

But how ambitious is the NZE_{2023}? Various research groups have modelled scenarios which predict much higher needs for PV to stay on a 1.5 °C trajectory [11–14]. Assuming a balance between climate costs and the United Nations (UN) development goals, these scenarios have a range between 50 and 80 TWp by 2050. If the electricity demand for the electrification of heat generation, transport and industry is considered, the needed capacity increases even further [15].

Uncertainty in reported capacity numbers

Not all countries report standard nominal power capacity for solar PV systems (DC or Wp under standard test conditions), but instead cite the inverter or electrical connection capacity, which is in AC. Over the last decade the so called "overpowering", i.e. when the DC capacity is larger than the AC capacity [16] has gradually increased and DC/AC ratios of up to 2 can be observed. This means that the nominal capacity can be significantly higher than the reported AC capacity. Overpowering of PV systems leads to a fuller utilization of the grid connection capacity and can be cheaper than the installation of electricity stabilisers to maintain steady supply at the required power.

Looking at energy system scenarios, modelers are only interested in AC capacity, since the electricity network is AC. Therefore, significant differences can exist between the actual needed nominal power of PV systems, which in turn determines the number of modules needed, and the modeled network PV capacity.

The capacity numbers of PV installations in this paper are given in nominal DC power or Wp. Production volumes are reported here in Wp as well. Where national statistics report capacities in AC, a conversion factor based on industry information and project descriptions is used to give a DC value.

2 PV solar cell production

Estimates for global cell production[1] in 2023 are in the range of 580 to 630 GWp. For 2024 a further increase is expected. The decreasing number of public companies with published accounts, different publication requirements in various countries and the fact that shipment figures, sales numbers and solar products are reported inconsistently, all add to uncertainty in this data.

Data were collected from stock market reports of listed companies, press announcements and market reports and were then cross checked. For 2023 this led to an estimate of 600 GWp, over 50% more than in 2022 (Fig. 1). The share of thin film solar modules is estimated to be between 2% and 3%. Numbers from previous years were updated where necessary. According to Bloomberg New Energy Finance, China alone exported 40GWp of solar cells and 215 GWp of solar modules.

Despite a strong market growth in solar photovoltaic generation capacity, even more manufacturing capacity is being added along the solar value chain. According to Bloomberg New Energy Finance, Tier 1 module manufacturers alone had a manufacturing capacity of 839 GWp at the end of 2023 [17]. Despite the exit of a number of smaller polysilicon companies, total production capacity is expected to increase to over 2.4 million metric tonnes, sufficient to produce about 1.1 TWp of silicon solar cells with the assumption of 2.2 g/Wp silicon usage rate. However, even optimistic market forecasts do not expect more than 650 GWp to be installed in 2024, which will not be enough to ease the downwards price pressure.

It is worthwhile noting that the needed production capacity of 820 GWp by 2030 in the NZE_{2021} scenario, was already reached in 2023. This shows that annual manufacturing capacity increase of the industry could even slow to 15% until 2030, and still reach 2.5 TWp by 2030, consistent with that needed for a 100% renewable energy scenario by 2050 [14,15,18]. However, if the current rate of development continues, the target will be reached much earlier.

Could the availability of critical raw materials be a roadblock fur the global growth of photovoltaics?

As numerous studies have shown, due to the availability of alternative routes in solar cell and module design, availability of material should not be a showstopper for the global multi TW growth of photovoltaics [19]. Silicon, the raw material for more than 95% of all solar cells, is one of the most abundant materials on Earth. However, even if the absolute availability is not a problem, the economic availability of high purity quartz (SiO_2 with 99.99%+ purity) used to manufacture crucibles for CZ single crystal silicon ingot growth and silica sand for polysilicon production has to be secured [20].

Silica sand is also used in the glass industry, which also produces solar glass for PV modules. To reduce the amount of contact materials per Wp, e.g. silver, indium and bismuth, the industry with its research partners are exploring alternative contact materials and more efficient manufacturing methods [21]. Research and technology progress continues to increase solar cell efficiencies as well as developing a better understanding of alternative contact materials and solar cell concepts. For some thin film technologies, production volumes could be limited [22,23]. Overall, modern module designs using circular manufacturing concepts and material reduction for the balance of system is of equal importance to achieve the required growth of the PV industry.

3 Solar PV electricity generation and markets

After the increase of the global benchmark LCOE[2] (Levelised Cost Of Electricity) for electricity produced by PV systems at the end of 2021 and in 2022, it continued to decrease for non-tracking systems to a record low of USD_{2022} 41 per MWh at the end of 2023 [24,25]. The main reason for this was the lower module prices due to the oversupply along the value chain. The full range of LCOE for non-tracking PV systems varied between USD 34 and 174 per MWh.

On the other hand, the global cost benchmark for tracking PV systems increased by about 9% in 2023 to USD_{2022} 48 per MWh. This was due mainly to higher costs for labour, balance of systems and financing in the USA.

After freight costs peaked in Q3 2021 (six fold increase compared to H1 2020), they were in the same range as 2020 for most of 2023 with a tendency to fall towards the end. In the beginning of 2024, the shipping disruptions in the Red Sea have already increased freight costs by 20% for solar modules shipped from Asia to Europe [25]. How this situation will develop during the year still has to be seen.

Similar to the manufacturing capacity increase along the solar PV value chain, battery manufacturing expansion is outpacing demand [26]. This will lead to overcapacity and a mounting price pressure, which could force smaller manufacturers to leave the market, form strategic alliances or hope for a merger. There are also other supply chain issues: since the price spike of lithium carbonate at the end of 2022 (more than ten times the price of 2020) the price has dropped during 2023 to about 2.4 times the 2020 level. Increased production capacities and a slower demand growth are likely the main drivers of this development. As a result, the global benchmark LCOE for a four hour battery storage project has decreased to USD_{2022} 135/kWh [27].

Investments in electricity storage increased by USD_{2023} 15.8 billion to USD_{2023} 36.3 billion in 2023. Leading markets include Australia, China, Germany, Italy, Japan, South Korea and the USA. The main motivation for an investment into a residential storage

[1] Solar cell production capacities mean:
– in the case of wafer silicon based solar cells, only the cells
– in the case of thin-films, the complete integrated module
– only those companies which actually produce the active circuit (solar cell) are counted
– companies which purchase these circuits and make cells are not counted.

[2] The global benchmark is calculated by BNEF with capacity-weighted averages using their latest country estimates.

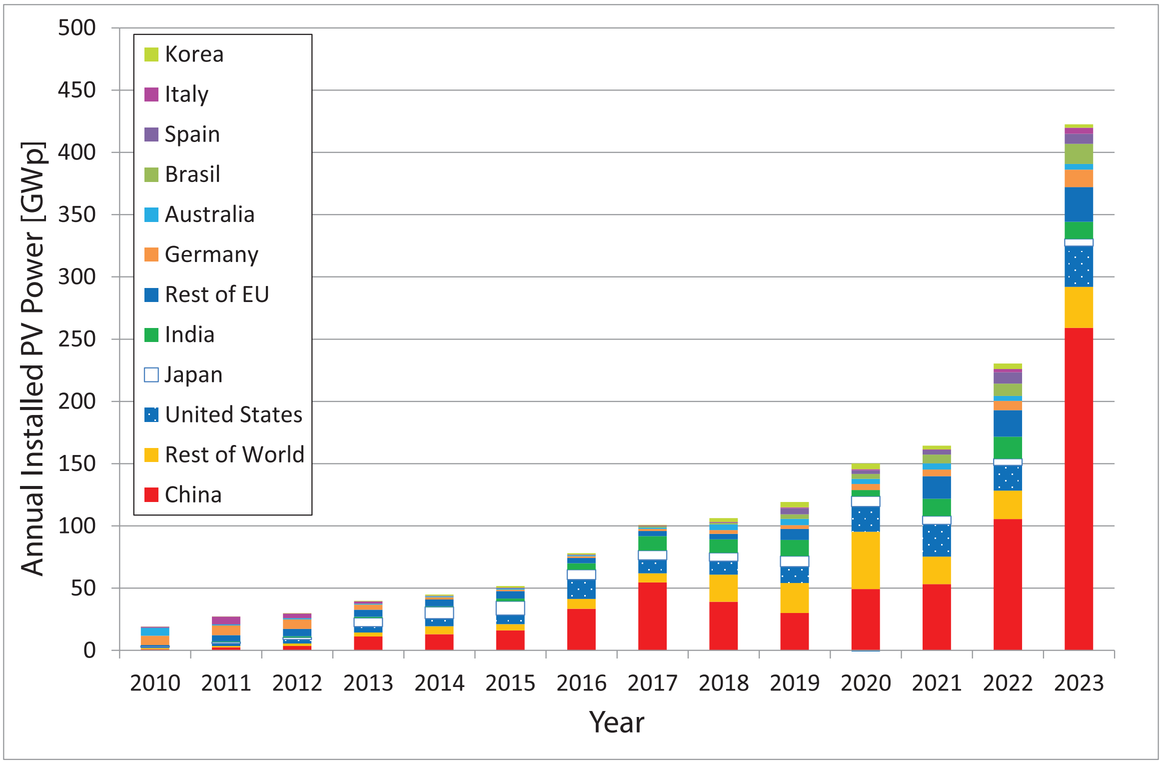

Fig. 2. Annual photovoltaic installations from 2010 to 2023 (data source: [31,32] and own analysis).

system, despite a significant CAPEX increase, were concerns about resilience to grid power disruptions, high grid electricity prices and a growing interest in the self-use of solar power.

The investment in storage systems for large scale PV plants is driven by factors such as the increase of usage hours of the AC connection, access to time dependent offtake contracts or auctions, i.e. participation to new market segments at times without solar radiation and grid services such as guarantee of power quality during ramp times. In 2023, 42 GW (99 GWh) of stationary storage were added, which is more than two and a halftimes the capacity compared to 2021 [26]. Half of this capacity was added in China.

LCOE benchmark costs only show the general trend. Due to local factors like financing and labour costs, regulatory requirements, import duties and taxes, the actual local generation costs can vary significantly. Geographical factors like solar radiation and the choice of technology tracking or no-tracking PV system design, string or central inverter configuration, fixed operation and maintenance (O&M) as well as connection costs add to this. Total financing cost or weighted cost of capital plays an important role on the final generation costs, regardless of the size of the PV system [28]. Another determining factor, which influences the willingness to invest and the financing costs for new renewable power generation systems is the competition in the respective electricity market and the ability to freely participate in it [29]. To summarise: stable and reliable political and regulatory conditions are important factors to attract investors.

Total renewable energy investments increased by 8% to reach USD_{2023} 623 billion in 2023 [7]. The largest share (62%) of these investments went into photovoltaic electricity generation systems with USD 385.5_{2023} billion. Despite the moderate increase of 13% in PV investments compared to 2022, the new installed capacity increased by more than two thirds to 422 GWp (Fig. 2) and exceeded 1.6 TWp according to preliminary data (Fig. 3). The main growth came from utility scale plants. This is almost towards the upper side between the conservative (360 GWp) and optimistic forecasts (448 GWp) [30,31]. Market forecasts for 2024 vary from a shrinking market to a significant increase to over 550 GWp, which would bring the total cumulative installed PV capacity to over 2 TWp.

China has a cumulative installed capacity of about 671 GWp, representing almost 42% of the total global installed PV capacity of 1608 GWp. The European Union follows with about 17% or 268 GWp and the USA with over 175 GW (11%) (Fig. 3).

The data in Figures 2 and 3 only takes into account the absolute capacity peer country or region, without considering the actual population or the available land area. The number of countries, which have installed more than 500 Wp/capita has increased from 12 in 2022 to 21 in 2023 (Fig. 4). However, the world average only modestly increased from 148 to 201 Wp per capita, and to reach the IRA NZE_{2023} targets the value would need to increase to 652 Wp per capita in 2030 and 1 755 Wp in 2050. For an energy supply fully based on renewable energy sources 8 kWp per capita would be needed.

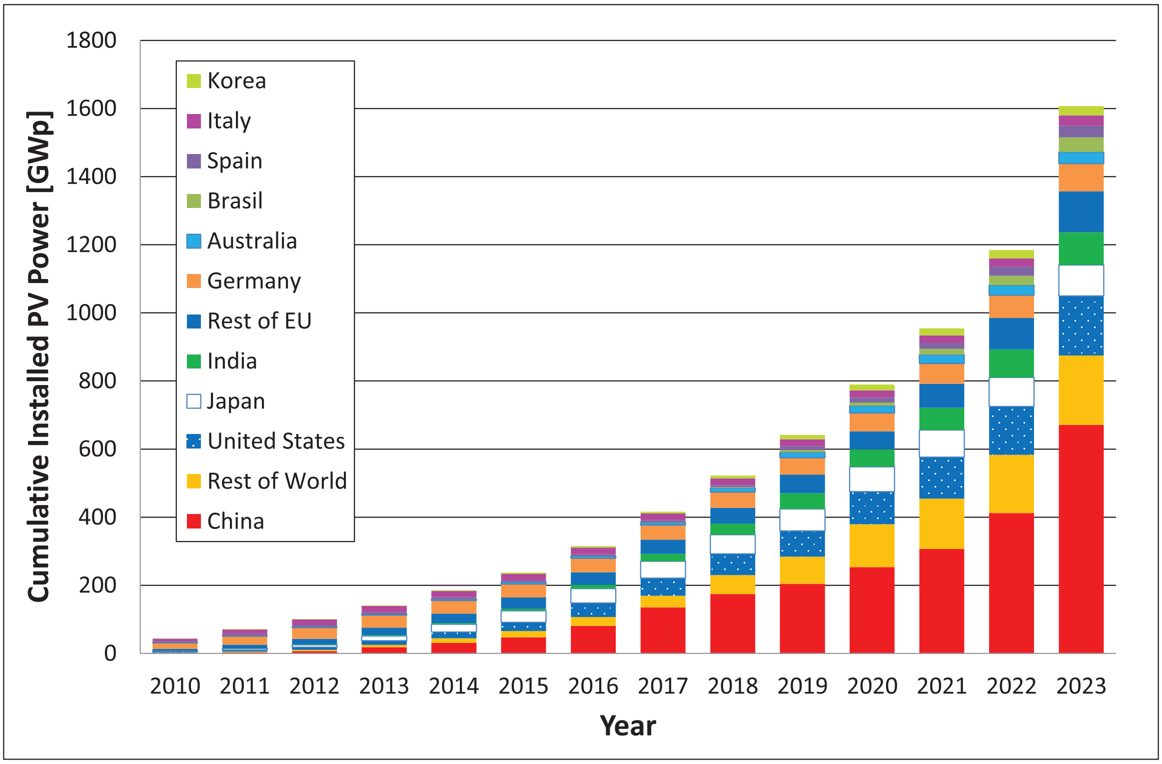

Fig. 3. Cumulative photovoltaic installations from 2010 to 2023 (data source: [31,32] and own analysis).

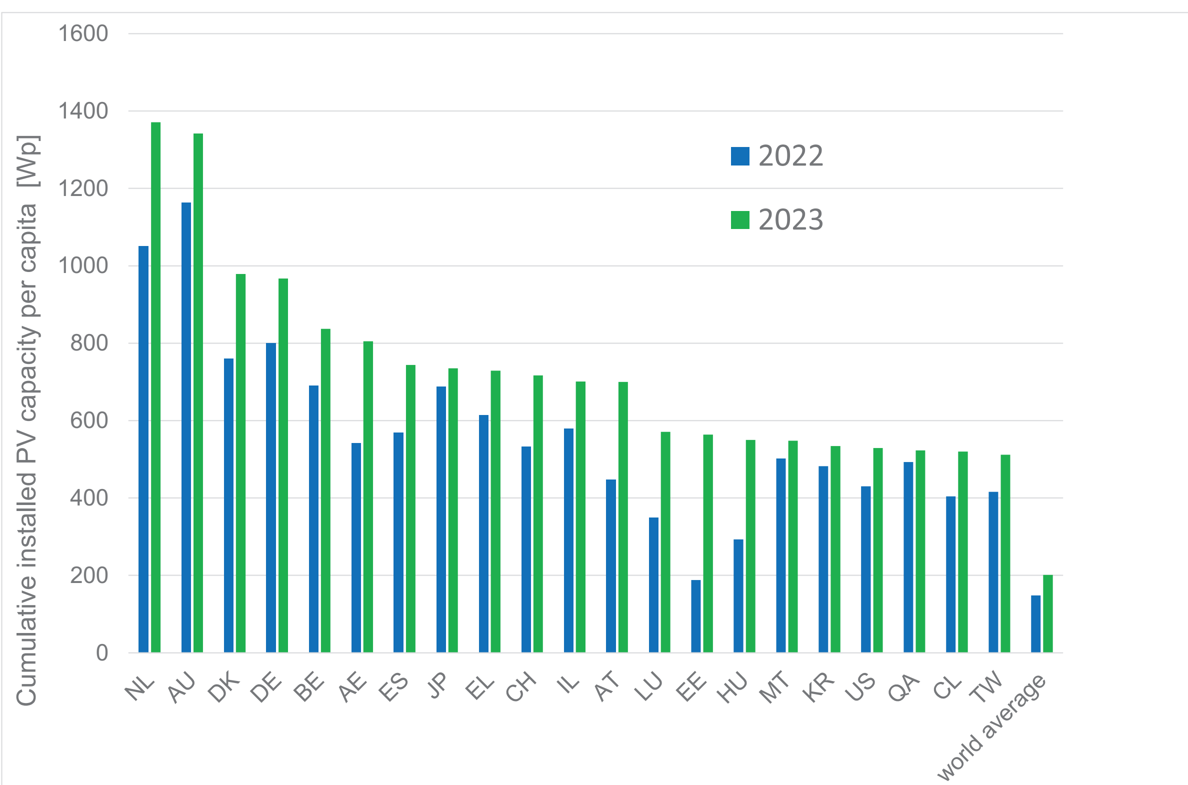

Fig. 4. Countries with a cumulative photovoltaic capacity of at least 500 Wp per capita in 2023 and the world average values are given as well (data source: [31,32] and own analysis).

Table 1. World-wide scenarios of cumulative solar photovoltaic electrical capacities until 2040. With the exception of the LUT scenarios the future projections are AC capacity.

Year	2023 [GWp]	2025 [GW]	2030 [GW]	2040 [GW]
Actual Installations	1 608			
Greenpeace (advanced [r]evolution scenario)		2 000	3 725	6 678
LUT 100% RES Power 2017		3 513	6 980	13 805
LUT 100% Energy 2019		3 528	12 951	30 531
BNEF NEO 2020		1 534	2 382	5 009
IRENA 2023*		2 002	5 643	9 005
IEA Stated Policy Scenario 2023**		1 945	4 699	9 500
IEA NZE Scenario** 2021		1 916	4 956	10 980
IEA NZE Scenario** 2023		2 150	6 101	14 303

* 2025 and 2040 values are interpolated, as only 2020, 2030 and 2050 values are given.
** 2025 value is interpolated, as only 2022, 2030 and 2040 values are given.

Please note that in the 2023 version of this report there was an error in the data for Malta (MT) and in the x-axis legend instead of the United Arab Emirates (AE) it was written Austria (AT) [33].

Africa: Between 2010 and 2023, the total installed solar PV capacity increased from 110 MWp to over 23 GWp. However, on a per capita basis this is still far below the world average (201 Wp per capita) with only 18 Wp per capita. Five African nations, namely Egypt, Kenya, Morocco, Nigeria and South Africa have more than 1 GWp and together they account for about 56% of the total capacity. Four countries have more than 500 MWp and another 14 are now home to more than 100 MWp of PV capacity. Hydropower is still the largest source of renewable electricity generation and supplies about 17% of the demand, showing that the continent's vast solar resources are still not harvested [34]. However, changing patterns in rainfall and temperatures caused by climate change could not only hamper future hydropower expansion, but reduce the power generation of existing plants as well. Combining existing hydropower plants with floating PV on their reservoirs could help to better utilise the existing hydro resources and enhance the economic performance of the plants. If just 1% of the reservoirs' area would be covered with floating PV, it would increase the electricity power output of these plants by 50% [35].

The World Bank's Scaling Solar programme is one of the successful tools to finance large scale solar PV projects in Africa [36]. Seven African nations, Côte d'Ivoire, Ethiopia, Madagascar, Niger, Senegal, Togo and Zambia have signed financing agreements and plants in Madagascar, Senegal and Zambia have already been realised.

In 2018, the "Desert to Power" initiative was launched by the Africa Development Bank (AfDB). The programme aims to deploy 10 GW solar power for the 250 million people across the Sahel zone by 2030. Five investment projects in Burkina Faso, Chad and Sudan with a combined capacity of 102 MW_{AC} were included in the Desert to Power portfolio in 2022 [37], with an investment close to USD 415 million. In December 2022, the African Development Bank approved two more Desert to Power investment projects, and the Sahel G5 Desert to Power Financing Facility with an investment volume of approximately USD 715 million and an additional PV capacity of 548.5 MW_{AC}. These projects should be operational by 2026.

Americas: 2023 saw a strong growth of almost 27% in the Americas. Together, North and South American countries added almost 55 GWp of new solar photovoltaic power capacity, mainly driven by strong market performance in the USA (+32.7 GWp), Brasil (+16.7 GWp) and Chile (+2.2 GWp).The strong performance in the USA was chiefly attributed to Inflation Reduction Act (IRA), which was signed in the fall of 2022 [38]. The total installed PV capacity in the Americas increased to 255.5 GWp or 251 Wp per capita, which is 25% more than the world average. Still 68.8% of the total PV capacity in the Americas are in the USA only a slight reduction from the 70% in 2022. Market expectations for 2024 forecasts a slower growth rate but indicate the possibility of adding more than 60 GWp.

Asia & Pacific Region: After China changed its national reporting system from nominal capacity to AC capacity in 2022, the installation numbers in nominal power, which determine the production volume have to be estimated from the ratio of residential to commercial/utility scale installations. For 2023 the National Energy Administration of China reported 216.8 GW_{AC} of new installed PV capacity [39]. With the assumption that two thirds of this capacity was large scale (DC/AC ~ 1.3) and one third decentralised (DC/AC ~ 1), this translates to approximately 259 GWp.

The Institute for Energy Economics and Financial Analysis (IEEFA) reported that India added 10.01 GW_{AC} of solar PV capacity in 2023 [40]. This 28.2% decline compared to 2022 is attributed to project commissioning delays as a result of procurement issues from the Approved List of Models and Manufacturers (ALMM) policy. As before, most of this capacity were large scale plants and for rooftops, with commercial and industrial applications dominating this segment.

Australia, Pakistan, Saudi Arabia and the United Arab Emirates were markets with significant growth. Overall the Asian-Pacific PV market more than doubled to 296 GWp. Total installed PV capacity at the end of 2023 was a little over 1 TWp or 220 Wp per capita. For 2023, a growth of between 10 and 20% is considered possible, which would lift the annual market to the range of 350 GWp.

European Union: In November 2023 the revised Renewable Energy Directive went into force. It sets an overall renewable energy target of at least 42.5% binding at EU level by 2030–but aiming for 45% [41]. The photovoltaic market grew again by over a third to more than 56 GWp in 2023 and could reach 100 GWp per annum in 2030 if the current market trend continues [42]. With this trend, EU Solar Energy Strategy's target of achieving a nominal capacity of over 720 GWp (600GW_{AC}) by 2030 will be exceeded [43].

The implementation of the EU's Solar Energy Strategy, an essential component of the REPowerEU plan, is supported by the European Solar Industry Alliance, endorsed by the European Commission in October 2022 [44,45]. The Solar Industry Alliance will support the objectives of the EU's Solar Energy Strategy, which set out how to massively scale-up and speed-up the production of renewable energy in Europe to regain its independence from Russian fossil fuels, and make its energy system more resilient. This latter goal is also being addressed by the proposed Net Zero Industry Act, with a series of measures to scale up the manufacturing of clean technologies. However the broadening of the Net Zero Industry Act's final scope (due for implementation later in 2024) bring the risk of diluting the focus from the most competitive and urgently needed industries [46–48].

In 2023, 14 countries of the European Union have installed more than 1 GWp new PV capacity, namely Germany (13.9 to 14.1 GWp), Spain (8.1 to 8.3 GWp), Poland (5.3 to 5.5 GW), Netherlands (5.4 to 5.5 GWp), Italy (4.7 to 4.9 GWp), France (2.9 to 3.1 GWp), Austria (2.4 to 2.6 GWp), Hungary (1.4 to 1.6 GWp), Belgium (1.4 to 1.5 GWp), Denmark (1.2 to 1.3 GWp), Greece (1.1 to 1.3 GWp), and Czech Republic, Portugal, Sweden (1.1 to 1.2 GWp) each.

In terms of installed capacity per capita, the Netherlands are now the leading country worldwide with 1371 Wp and slightly edged in front of Australia with 1343 Wp. Seven EU countries have more than the European Union average of 601 Wp per capita, namely, the Netherlands (1371 Wp), Denmark (979 Wp), Germany (967 Wp), Belgium (837 Wp), Spain (744 Wp) Greece (729 Wp) and Austria (700 Wp). The number of countries with less than 100 Wp per capita has decreased from five to two.

4 Conclusions

Solar photovoltaic electricity generation is already the lowest cost power source in many countries and regions around the globe. Nevertheless, photovoltaic technology still has a considerable cost reduction potential along the whole value chain. Together with the rising deployment of battery storage, photovoltaic electricity generation provides already now offers dispatchable power and, in a growing number of cases, the most economic solution as well. The electrification trend of our energy use, which includes heating and transport as well as the production of hydrogen from renewable energy sources, together with the overall need to provide CO_2 free energy, are the drivers behind the continuous growth of PV installations. After achieving a cumulative installed PV power capacity of more than 1 TWp in 2022, the 2 TWp mark will be reached before the end of 2024.

Various scientists, financial consultants, non-governmental organisations (NGOs) and supranational organisations, like Greenpeace, the Energy Watch Group, Bloomberg New Energy Finance (BNEF), the International Energy Agency as well as the International Renewable Energy Agency (IRENA), have developed scenarios for the future growth of PV systems as shown in Table 1 [4, 5, 49–53]. References to earlier scenarios can be found in earlier versions of the PV Snapshot.

All scenarios foresee a significant growth of PV power capacity in the future. This is independent of the existing differences in ambitions and deployment pathways. In 2022, total electricity generation was 29,165 TWh and could have been generated with a PV capacity of about 21.6 TWp. To install this capacity would use approximately 0.3% of the world's land area or 30% of the global settlement area [54]. Over the last years studies have identified huge potentials to install PV on rooftops, facades, with dual use of infrastructure, on brownfield sites or novel applications like agri-photovoltaics or floating PV systems [35, 55–61].

Key challenges to achieve any of the before mentioned scenarios remain: massive support of all stakeholders has to be secured, as well as a truly enabling policy framework. Up to now, there is a lot of positive encouragement, but the decisive policy actions are lacking or being implemented too slowly. In order to make the energy transition work, fundamental system changes are needed.

The acceleration of renewable energy use, storage build up and market changes are necessary and this will not happen by themselves. Our societies have to embrace the fact that more effort is needed to realise the energy transition and to stay on a pathway for a maximum of 1.5 °C global temperature increase. This is not an easy task and the window of opportunity to stay on track is narrowing every day.

The technical characteristics of solar photovoltaics, its modularity, a very low CO_2 footprint (based on a full life cycle analysis), make it a perfect solution for dense urban environments and a crucial pillar for realizing a net zero carbon energy supply by 2050 [62].

However, there are still challenges ranging from perception, legal and regulatory conditions as well as technical limitations of the existing transmission and distribution systems to be overcome. So far, neither the necessary adaptation and transformation of the energy networks, nor changes of electricity market business models nor the political will to accelerate the use of renewable energy sources such as PV is in line with the urgency to decarbonise our energy supply by 2050.

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Conflicts of interest

The author declares to have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

Data are available on request.

Author contribution statement

A. J-W. is the sole author.

Disclaimer

The views expressed are based on the current information available to the author and may not in any circumstances be regarded as stating an official or policy position of the European Commission.

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