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• **Perspectives** •

Strategic Global Deployment of Photovoltaic Technology: Balancing Economic Capacity and Decarbonization Potential※

Ian Marius PETERS*

Helmholtz-Institut Erlangen-Nürnberg for Renewable Energies, *Forschungszentrum Jülich*, *Immerwahrstraße 2*, *Erlangen* 91058, *Germany*

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ABSTRACT

This study investigates the disparities in the deployment of photovoltaic (PV) technology for carbon emissions reduction across different nations, highlighting the mismatch between countries with high economic capacity and those where PV installation would maximize global decarbonization benefits. This mismatch is discussed based on three key factors influencing decarbonization via PV technology: per capita gross domestic product; carbon intensity of the energy system; and solar resource availability. Current PV deployment is predominantly concentrated in economically advanced countries, and does not coincide with regions where the environmental and economic impact of such installations would be most significant. Through a series of thought experiments, it is demonstrated how alternative prioritization strategies could significantly reduce global carbon emissions. Argument is put forward for a globally coordinated approach to PV deployment, particularly targeting high-impact sunbelt regions, to enhance the efficacy of decarbonization efforts and promote equitable energy access. The study underscores the need for international policies that support sustainable energy transitions in economically less developed regions through workforce development and assistance with the activation of capital.

Key words: photovoltaic deployment, decarbonization strategies, solar resource availability, global energy equity, carbon emission reductions

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1. Introduction

Photovoltaic (PV) technology has emerged as the most promising solution in the transition to a low-carbon economy, given its potential to significantly mitigate greenhouse gas emissions (IPCC, 2022). However, the global deployment of PV systems exhibits a marked disparity, with a concentration of PV capacity in economically advanced nations (IRENA, 2024). This uneven distribution prompts a critical examination of how PV adoption strategies impact global decarbonization efforts.

This study aims to elucidate the disparities in agency among countries concerning the adoption of PV technology for carbon emissions reduction. Notably, the capacity of nations to implement such technologies does not always align with where these interventions would yield the greatest benefits for global decarbonization. Typically, decarbonization strategies are developed at the national level (Wallach, 2021), prioritizing individual national decarbonization over a coordinated global strategy. While such approaches will contribute to global carbon reduction goals, they do not harness the full potential of PV technology to achieve these objectives with optimal speed and efficiency.

This paper focuses on three primary variables: the gross domestic product (GDP) per capita, reflecting a country's economic capability to invest in significant projects; the carbon intensity of each nation's energy system, indicating the environmental impact of their current energy sources; and the availability of solar resources, which affects the efficiency of PV installations. These factors often do not align, leading to a mismatch between where PV technology is deployed and where it could achieve the greatest decarbonization benefits.

To address this disparity, this study explores how a globally coordinated approach to PV deployment, prioritizing regions with high carbon intensity and abundant solar resources, could accelerate and enhance decarbonization efforts. This approach not only aims to reduce global carbon emissions more effectively but also promotes equitable

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* Corresponding author: Ian Marius PETERS
Email: im.peters@fz-juelich.de

access to clean energy in less economically developed regions.

2. Global inequity—the core issue

This study investigates the disparity in agency among countries regarding the adoption of PV technology for carbon emissions reduction. Nations that possess the economic capacity to implement PV technology do not always coincide with those where such action would yield the greatest global benefits for decarbonization. Currently, PV deployment strategies are developed at the national level. While individual national decarbonization will ultimately achieve the global objective, it will not do so with the greatest speed and efficiency.

This disparity can be examined through three key parameters: GDP per capita; the carbon intensity of each country's energy system; and solar resource availability. GDP per capita reflects a country's economic agency, or its ability to allocate resources toward significant projects. This variable, illustrated in Fig. 1a (World Bank, 2022a), displays the broadest range among the parameters studied. Wealthier nations such as the United States, Germany, and Australia exhibit per capita productivity exceeding that of lower-income countries like Niger, Madagascar, and South Sudan several hundred times over. As a result, mobilizing capital for nationwide solar projects is substantially more challenging and time-consuming in these less affluent countries.

One consequence of this investment challenge is that lower-income countries operate older, more polluting power plants, primarily reliant on coal. These plants are significant contributors to carbon emissions, with high carbon intensity [i.e., the amount of carbon dioxide (CO_2) emitted per kilowatt-hour of electricity produced]. The global distribution of carbon intensity by country is depicted in Fig. 1b (Ember, 2022). Countries like Gambia, Botswana, and Mongolia are among those with the highest energy intensity. Many highly industrialized nations, despite their substantial use of fossil fuels, often have newer, more efficient coal power plants and a higher prevalence of gas power plants, and hence a lower carbon intensity. These countries, above all China and the United States, still emit more CO_2 overall due to their much higher energy demand, yet decarbonizing sources with the highest carbon intensity first still has a disproportionally high impact.

3. Significance of the solar resource

A critical aspect of PV deployment, beyond per capita GDP and carbon intensity, is the solar resource. The solar resource determines the potential energy production of a solar panel and its capacity to displace carbon emissions. The average solar potential per country (Suri et al., 2020), shown in Fig. 2, highlights the variance in this parameter across regions.

Solar potential is primarily determined by insolation, but other factors influence the energy yield of a solar panel. For instance, temperature impacts solar cell voltage and fill factor, with higher temperatures reducing both (Dupré et al., 2015). This effect is summarized in a solar panel's temperature coefficient, indicating the percentage decrease in power output with each degree of temperature increase. The panel temperature depends on insolation, ambient temperature, wind speed, and humidity (Veldhuis et al., 2015). The solar spectrum's shape also affects energy yield, with aerosols and total precipitable water altering the spectrum's characteristics (Peters et al., 2018a).

While average values are useful for general guidance, PV performance is governed by local atmospheric conditions. Cloud cover (Lave and Kleissl, 2013), air quality (Peters et al., 2018b), and climate variations (Peters and Buonassisi, 2021) all impact the local solar resource, affecting solar energy deployment. Exact predictions of the available solar resource and accurate solar forecasts (Yang et al., 2022) are valuable for planning solar projects. Making these insights available to developing countries is a significant contribution that atmospheric science can make to support decarbonization.

Many countries with low per capita GDP and high carbon intensity have high solar resource levels, while countries with the most installed solar capacities typically have moderate solar potential. Countries and regions like Chile,

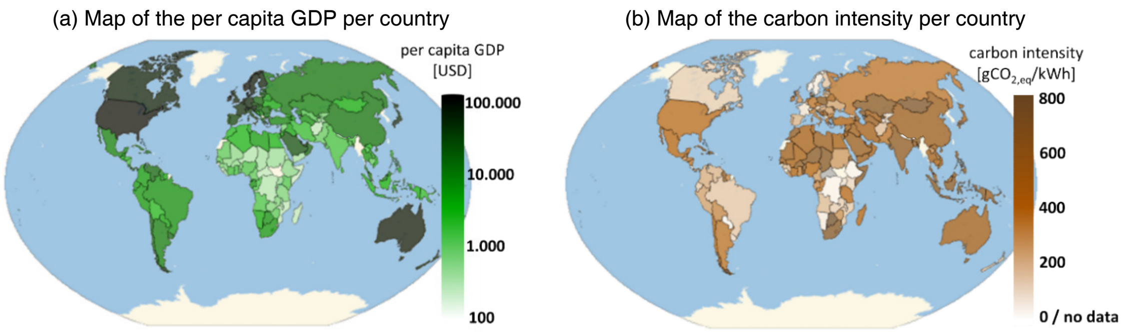

Fig. 1. Two maps that, taken together, illustrate a global dilemma for global PV installations. The first map indicates per capita GDP on a logarithmic scale, and represents a country's agency to carry out large projects. The second illustrates how carbon-intensive each country's electricity system is. Data displayed in this figure were taken from the World Bank (2022a) and Ember (2022).

Bolivia, South Sudan, Namibia, and Egypt have some of the highest solar potentials globally, making them excellent candidates for PV installations to offset carbon emissions. For example, in Namibia, a solar panel can generate twice the power of a similar panel in northern Germany, suggesting that half the panels would be required to replace, for instance, a coal power plant.

However, these high-potential regions face significant challenges in generating capital for solar investments. Many are among the world's poorest, with limited financial resources and infrastructure. This creates a critical dilemma in global decarbonization efforts, as the regions most effective for PV deployment often lack the means to implement large-scale solar projects. Beyond financial constraints, other challenges—such as political instability, limited infrastructure, and technical expertise—further complicate solar deployment in sunbelt countries.

Despite these hurdles, deploying PV systems in sunbelt regions can yield broader socioeconomic benefits. It can create jobs (Ram et al., 2020), stimulate local economies, and improve energy access, particularly in areas with limited electricity infrastructure. Moreover, sunbelt countries typically feature much lower seasonal differences in their solar resources than countries with temperate climates. This more favorable temporal distribution supports a highly stable PV power supply. By prioritizing these regions, the global community can boost decarbonization efforts and promote sustainable development. Addressing these challenges requires tailored, equitable strategies that consider both economic capacity and environmental impact. This highlights the importance of international cooperation and support to facilitate the deployment of solar energy in regions with high solar potential.

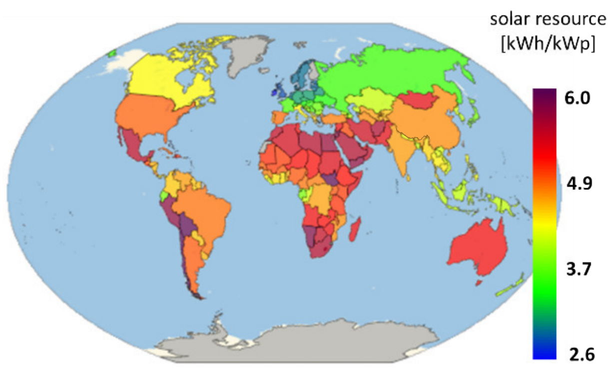

Fig. 2. Solar resource per country, according to Suri et al. (2020).

4. Decarbonization sequences

To assess the impact of different prioritization strategies in global decarbonization efforts, a thought experiment was conducted using two scenarios where electricity generation is decarbonized country by country. In both scenarios, renewable capacities generating 1000 terawatt-hours (TWh) of electricity are added annually. After 26 years, the entire global electricity system becomes decarbonized, replacing the existing energy infrastructure. This timeline is consistent with current decarbonization goals and deployment scenarios to limit global warming (IRENA, 2024; Haegel, 2023). Throughout this process, global CO_2 emissions are tracked.

In the first scenario, shown in Fig. 3a, the sequence of decarbonization is determined by a country's per capita GDP, with wealthier countries completing their decarbonization processes before poorer ones begin. This scenario reflects the current decarbonization trajectory and results in a total emission of 137 billion metric tons of CO_2. In contrast, the second scenario, shown in Fig. 3b, prioritizes countries based on the carbon intensity of their energy systems, targeting the highest emitters first. This approach results in a total CO_2 emission of 103 billion metric tons, demonstrating a reduction of one third compared to the first scenario.

It is important to note that this thought experiment, while simplistic, is designed to illustrate how different decarbonization priorities can significantly affect overall carbon emissions. The numbers used align with global objectives, yet they represent hypothetical extremes, and the total emissions figures are illustrative rather than absolute. The key takeaway is the one third relative difference in emissions between the two scenarios. This value should not be overinterpreted, but it highlights that strategic prioritization can have

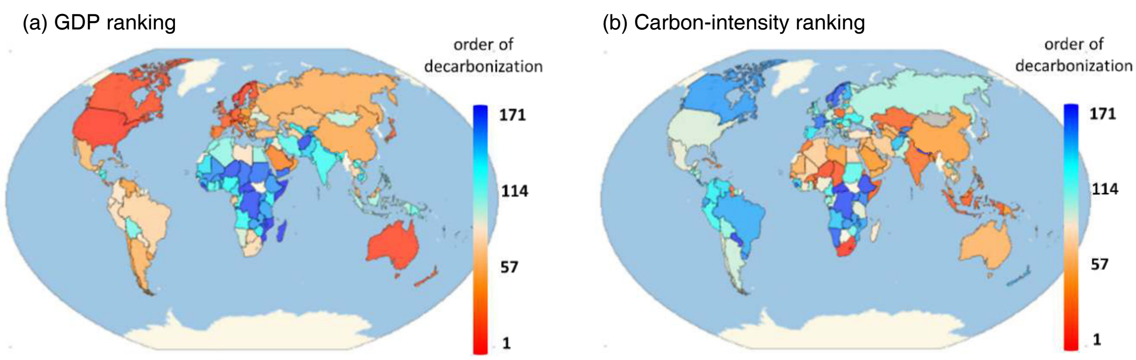

Fig. 3. The color code in this map illustrates the ranking of different countries in terms of (a) per capita GDP and (b) carbon intensity. The ranking has been used in the described thought experiment to define the sequence in which countries or regions are decarbonized.

a substantial impact, particularly since we are currently on a path to failing to achieve even moderately ambitious carbon reduction goals (DWD, 2023).

A few critical points need further clarification in this thought experiment:

Electricity as a proxy for primary energy: The scenarios use electricity production as a surrogate for primary energy consumption, though it only constitutes about one-fifth of the primary energy (Ember, 2022). Countries with carbon-intensive electricity are likely to have less stringent regulations across other energy uses, such as heating and transportation. Thus, prioritizing these countries in decarbonization efforts will disproportionately enhance global benefits.

Oversimplification of energy transition: The method employed overlooks the proportion of electricity already produced from renewable sources in each country, overestimating the time required to fully decarbonize their energy systems. A more nuanced approach would displace sources one by one, starting with the most carbon intensive coal power plant. Additionally, real greenhouse gas reduction is influenced by temporal trends of PV power generation and by the specific power plants in the country's energy mix. While beyond the scope of this study, an in-depth analysis of all power plants in the world together with the local generation potential for solar and wind should provide an efficient decarbonization strategy.

Constant deployment assumption: The assumption of constant deployment of renewable technologies across time and locations does not account for the increasing production and installation capacities for solar and wind technologies. Replacing constant deployment with an exponentially growing one showed only a minor impact on the relative difference between scenarios. The constant deployment assumption also ignores that the installation of a single solar panel will result in very different amounts of power generated, depending on location. This aspect further emphasizes the benefits of installing solar panels in sunbelt regions. In the next section, this aspect is further explored.

5. Impact of a single panel

In a second thought experiment, the comparative effectiveness of installing a single 365-W solar panel and the impact of investing a single dollar in carbon reduction across various countries was explored. This analysis consisted of two distinct scenarios.

5.1. *First scenario: Carbon displacement by country*

For the first scenario, the carbon displacement values for each country were calculated, denoted as $\delta CO_2(c)$, using the formula

$$\delta CO_2(c) = E_i(c)\,PV_{out}(c) \times \frac{365}{1000}\,, \qquad (1)$$

in which $E_i(c)$ represents the carbon intensity of each country's electricity system in grams of CO_2 equivalent per kilowatt-hour, as reported in Ember (2022); and $PV_{out}(c)$ is the 75th percentile of each country's specific PV power output in kilowatt-hours per kilowatt-peak, as sourced from Suri et al. (2020). The assumption underpinning this formula is that the solar panel offsets an equivalent amount of electricity generated from the country's grid. The results of this calculation are presented in Fig. 4a. According to our analysis, the top five countries for installing a solar panel to maximize carbon reduction impact are Botswana, South Africa, Mongolia, Somalia, and Niger. In South Africa, the carbon displacement potential of a single solar panel is over twice that of one in the United States and more than three times that of one in Germany. Note that this analysis does not consider the embodied carbon in solar panel manufacturing (Haegel et al., 2023).

5.2. *Second scenario: Cost-effectiveness of carbon displacement investments*

In the second scenario, the cost values for carbon displacement in each country were calculated, denoted as $P_{CO2}(c)$, using the formula

$$P_{CO2}(c) = \frac{P_i(c)}{\delta CO_2(c)} \times 1000\,, \qquad (2)$$

where $P_i(c)$ is the installation cost of PV systems per country, according to Rodríguez-Gallegos et al. (2018). Results for this calculation are shown in Fig. 4b, which reveal that the most cost-effective countries for investing a dollar into

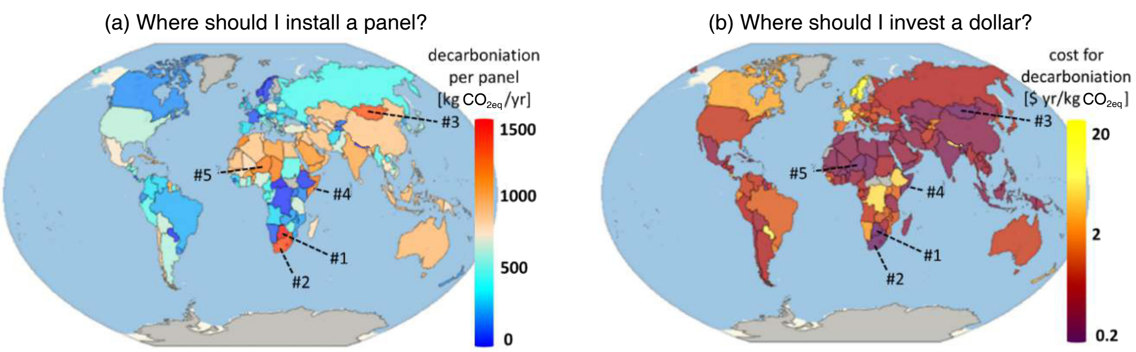

Fig. 4. Effectiveness of displacing carbon by (a) installing one solar panel and (b) investing one dollar into PV installations.

solar electricity for maximizing carbon reduction are the same as those identified in the first scenario. Specifically, investing one dollar in PV installations in South Africa yields nearly five times the carbon reduction compared to the same investment in the United States and nine times more than in Germany.

6. Benefits beyond carbon reduction

The four thought experiments demonstrate that investments in PV installations in sunbelt countries are highly advantageous for effectively mitigating climate change. The advantages of deploying solar panels in these regions extend beyond mere carbon emission reductions, though.

Figure 5a illustrates the percentage of the population without access to electricity in various countries, referencing data from the World Bank (2022b). The nations with the lowest electricity access rates include Chad, Burundi, Malawi, the Central African Republic, and Burkina Faso. Establishing renewable energy infrastructure in these countries is not only beneficial for reducing carbon emissions but also crucial for enhancing the quality of life. The minimal presence of existing electrical grids presents a unique opportunity to develop a decarbonized energy system from the ground up, unencumbered by the transition complexities associated with fossil-fuel powered generators (Tiruye et al., 2021), (Denholm et al., 2021).

Additionally, Fig. 5b presents the absolute number of individuals per country who lack access to electricity (World Bank, 2022c), underscoring the potential for PV installations to deliver significant benefits. The countries with the highest numbers of citizens without electricity access are Nigeria, the Democratic Republic of the Congo, Ethiopia, Pakistan, and Tanzania. Each of these countries, situated in the sunbelt, could see transformative gains from targeted solar energy investments, suggesting that these regions should be prioritized in global efforts to expand renewable energy access and combat climate change.

Utilizing the criteria outlined, we have developed a multi-objective framework to evaluate the benefits of PV installations. This framework considers the following factors: (i) the carbon intensity of the national power grid; (ii) the potential for carbon reduction per dollar invested; (iii) the percentage of the population without access to electricity; (iv) the absolute number of citizens without access to electricity; and (v) the potential for carbon reduction per panel installed. Spiderweb plots illustrating these criteria for eight countries are displayed in Fig. 6, arranged clockwise. The values for each criterion per country were established by ranking the countries in a sorted list and normalizing these rankings from 0 to 1.

The selection of countries for this analysis was purposeful, designed to illuminate the varying benefits across different national contexts. Highly industrialized nations with significant areas with temperate climates such as Germany, the United States, and Japan exhibit almost universal access to electricity, relatively clean power grids, high deployment costs, and limited solar resources. Australia shows a higher carbon intensity owing to its reliance on coal power but benefits from a more abundant solar resource compared to the aforementioned countries. Compared to China, Australia faces higher installation costs. Similar to China, India is characterized by a carbon-intensive grid and significant solar potential, coupled with relatively low installation costs. Despite a large portion of the Indian population having access to electricity, the sheer size of its population results in a high absolute number of individuals without electricity. Lastly, Niger features a high carbon intensity grid, ample solar resources, and low installation costs, alongside a significant proportion of the population lacking access to electricity both in relative and absolute terms.

7. Summary and discussion

The thought experiments presented in this study underscore the importance of adopting a global perspective in the deployment of PV technologies, particularly in emerging economies within the sunbelt. Focusing PV installations in these regions maximizes the impact on decarbonization and improves access to electricity for under-resourced communities.

Current PV deployment efforts are concentrated in the world's largest economies, with China, the United States, Japan, India, and Germany accounting for two-thirds of

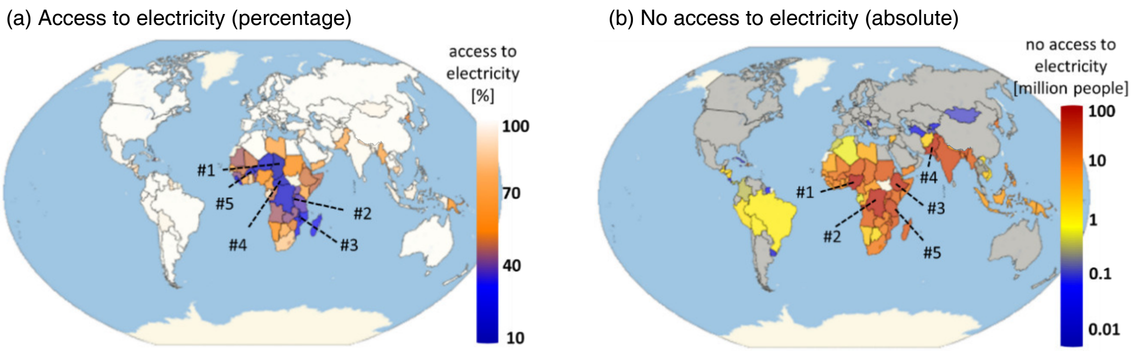

Fig. 5. Illustrations of access to electricity: (a) fraction of a country's population with access to electricity; (b) number of people lacking access to electricity.

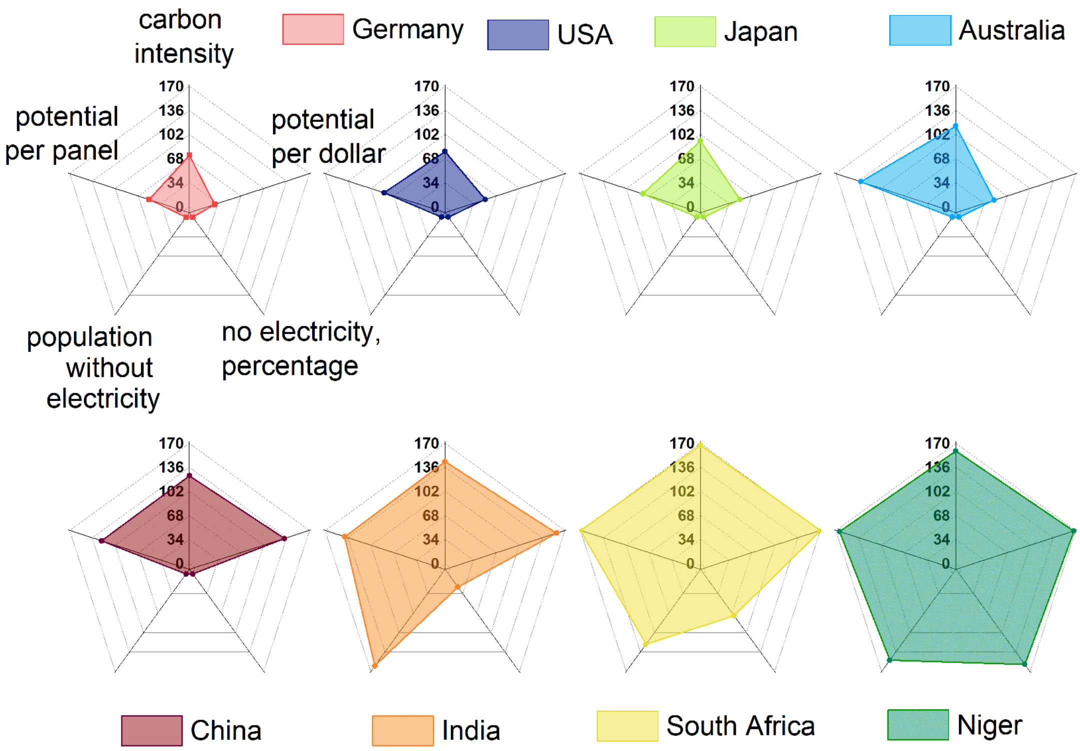

Fig. 6. Spiderweb plot over five criteria related to the urgency of installing solar panels for eight countries. The axes refer to countries ranked on the corresponding criteria from lowest (1) to highest potential (172) for improvement through installation of a PV panel.

global installations in 2022 (IRENA, 2024). While these countries aim to reach carbon neutrality within the next 50 years, it is evident that nationally driven efforts alone are insufficient to meet ambitious global carbon reduction targets necessary to limit warming to below 1.5°C or 2°C (Anderson et al., 2020; UN Environment Program, 2023).

Eliminating carbon emissions requires producing and deploying several terawatts of PV capacity every year (Verlinden, 2020). Global wafer and module manufacturing capacities today stand at 875 GW and 1240 GW, respectively (IEA, 2023), and achieving the required capacities seems within reach. Deployment lags behind, though, with Bloomberg NEF estimating global installations of 574 GW in 2024 and up to 880 GW in 2030 (Chase, 2024). Accelerating deployment requires resolving logistical challenges such as site designation, workforce expansion, and capital mobilization. Developed countries like Germany are somewhat successful in meeting these challenges, being on track to meet their deployment targets despite difficulties in securing installation sites and workforce mobilization (Fraunhofer ISE, 2024). It should also be noted that, within a country, a strategic approach about which sources and sectors to decarbonize first can have a notable impact on cumulative greenhouse gas emissions (Kar et al., 2024).

For less economically potent countries, capital mobilization and developing a well-educated workforce are central challenges. Investments in these regions yield higher returns in terms of carbon reduction per dollar spent compared to more affluent economies. Strategically deploying PV technology in less-industrialized sunbelt regions, especially in Africa, not only facilitates significant carbon reduction but also promotes equitable global development. These regions, often most affected by climate change, benefit greatly from enhanced energy equity and mitigation efforts.

Supporting PV deployment in less developed regions is a global responsibility. Developed countries, with their financial and technological resources, should view this support as integral to a comprehensive strategy to combat climate change and promote sustainable development. Several barriers impede the adoption of this global strategy. Competing national interests, economic constraints, and political instability in less developed regions pose significant challenges. Additionally, the lack of infrastructure and technical expertise further complicates large-scale PV deployment.

Overcoming the barriers requires global collaborations at an unprecedented level. International policies and funding mechanisms should be restructured to facilitate and accelerate PV installations through projects and workforce development in high-impact, high-need areas, ensuring that global decarbonization efforts are both effective and equitable.

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APPENDIX

Calculating Remaining Emissions

The description follows the calculation as it was carried out using the notebook 2206bWPP.nb. The examples given below give the routine in its simplest form; some extensions are provided in the notebook. In a first step, a list of ECLs is created containing the information used in the calculation—namely: {name of country, energy consumption, GDP, energy intensity, population, PV-potential*energy intensity}. This list is then sorted in descending order for a selected criterion. Several options were available for the value of PV potential. Assuming that PV installations will preferably be set up in regions with higher photovoltaic capacity, the 75th percentile value was chosen. The choice did, however, have little impact on the overall results.

In a second step, a certain rate (DEIyt) is defined at which existing capacities are replaced. This rate is arbitrary and has little impact on the result. This rate was chosen to be a certain fraction of the overall capacity (say 1% of total energy capacity), but it can also be set to be a fixed value (say, 1000 TWh per year) or to replace all sources in a certain amount of time.

Then, a list is created with the sorted total energy consumption of each country. In each step, an amount equal to DEIyt is replaced, either for one single country or for several at once. The calculation ends when the remaining unreplaced capacity falls below a threshold.

In each step, the remaining emission is calculated by multiplying the unreplaced capacity by the carbon intensity in each country and summing the result. The code to carry out these steps is:

ECls = Sort[ECl, #1[[3]] > #2[[3]] &];	Sort ECLs according to, in this case, entry number 3 (GDP) in descending order.
DEIyt = 1000;	The rate in GWh at which sources are replaced. This rate can be chosen in various ways.
c1 = 1;	Set counter c1 to 1
cab = 0;	Set value cab to zero
tupl = ECls[[All,2]];	Create list tupl, containing the sorted values of the total electricity consumption of each country
cac = N[ECls[[All,4]]];	Create list cac, containing the energy intensity of each country
While[Last[tupl]>0.1,{	While loop during which electricity sources are replaced by zero-carbon emission sources. The calculation continues while the last value is greater than 0.1 (any small positive number will work).
db = tupl[[c1]]-DEIyt;	The value db is defined, which is the remaining capacity after replacement
While[db<=0,{	If this remaining capacity is smaller than zero, continue to replace…
tupl = ReplacePart[tupl, c1->0];	…the remaining capacity with 0
dex = -db;	…calculate how much can still be replaced in this step
c1+=1;	..increase counter by one
db = tupl[[c1]]-dex;}];	…and move on to the next country. The While loop ensures that this continues while there is replacement capacity left.
tupl = ReplacePart[tupl,c1->db];	If the value is not smaller than zero, replace the value in tupl with whatever is left.
cab+=Sum[(cac*tupl)[[i]],{i,1,Length[tupl]}]; }];	Add the carbon emission after replacement in each step up.

REFERENCES

Anderson, K., J. F. Broderick, and I. Stoddard, 2020: A factor of two: How the mitigation plans of 'climate progressive' nations fall far short of Paris-compliant pathways. *Climate Policy*, **20**, 1290–1304, https://doi.org/10.1080/14693062.2020.1728209.

Chase, J., 2024: 1Q 2024 Global PV Market Outlook. Bloomberg New Energy Finance. Available from https://about.bnef.com/blog/1q-2024-global-pv-market-outlook/.

Denholm, P., and Coauthors, 2021: The challenges of achieving a 100% renewable electricity system in the United States. *Joule*, **5**, 1331–1352, https://doi.org/10.1016/j.joule.2021.03.028.

Dupré, O., R. Vaillon, and M. A. Green, 2015: Physics of the temperature coefficients of solar cells. *Solar Energy Materials and Solar Cells*, **140**, 92–100, https://doi.org/10.1016/j.solmat.2015.03.025.

Ember, 2022: Yearly Electricity Data. Our World in Data. Available from https://ourworldindata.org.

Fraunhofer ISE, 2024: Public Electricity Generation 2023: Renewable Energies Cover the Majority of German Electricity Consumption for the First Time. [Available online from https://www.ise.fraunhofer.de/en/press-media/press-releases/2024/public-electricity-generation-2023-renewable-energies-cover-the-majority-of-german-electricity-consumption-for-the-first-time.html]

German Weather Service (DWD), 2023: Der 13. ExtremWetterKongress in Hamburg. [Available online from https://dwd.de].

Haegel, M. and Coauthors, 2023, Photovoltaics at multi-terawatt scale: Waiting is not an option. Science 380, 39-42. https://doi.org:10.1126/science.adf6957International Energy Agency (IEA), 2023: Renewable Energy Market Update - June 2023. IEA, Paris. [Available online from https://www.iea.org/reports/renewable-energy-market-update-june-2023].

International Renewable Energy Agency (IRENA), 2024: Renewable capacity statistics 2024. International Renewable Energy Agency, Abu Dhabi.

IPCC, 2022: Summary for policymakers. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, P. R. Shukla et al., Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 3–48, https://doi.org/10.1017/9781009157926.001.

Kar, S., and Coauthors, 2024: A deep decarbonization framework for the United States economy – a sector, sub-sector, and end-use based approach. *Sustainable Energy & Fuels*, **8**, 1024–1039, https://doi.org/10.1039/D3SE00807J.

Lave, M., and J. Kleissl, 2013: Cloud speed impact on solar variability scaling – Application to the wavelet variability model. *Solar Energy*, **91**, 11–21, https://doi.org/10.1016/j.solener.2013.01.023.

Peters, I. M., and T. Buonassisi, 2021: How changes in worldwide operating conditions affect solar cell performance. *Solar Energy*, **220**, 671–679, https://doi.org/10.1016/j.solener.2021.01.017.

Peters, I. M., H. H. Liu, T. Reindl, and T. Buonassisi, 2018a: Global prediction of photovoltaic field performance differences using open-source satellite data. *Joule*, **2**, 307–322, https://doi.org/10.1016/j.joule.2017.11.012.

Peters, I. M., S. Karthik, H. Liu, T. Buonassisi, and A. Nobre, 2018b: Urban haze and photovoltaics. *Energy & Environmental Science*, **11**, 3043–3054, https://doi.org/10.1039/c8ee01100a.

Ram, M., A. Aghahosseini, and C. Breyer, 2020: Job creation during the global energy transition towards 100% renewable power system by 2050. *Technological Forecasting and Social Change*, **151**, 119682, https://doi.org/10.1016/j.techfore.2019.06.008.

Rodríguez-Gallegos, C. D., M. Bieri, O. Gandhi, J. P. Singh, T. Reindl, and S. K. Panda, 2018: Monofacial vs bifacial Si-based PV modules: Which one is more cost-effective?. *Solar Energy*, **176**, 412–438, https://doi.org/10.1016/j.solener.2018.10.012.

Suri, M., J. Betak, K. Rosina, D. Chrkavy, N. Suriova, T. Cebecauer, M. Caltik, and B. Erdelyi, 2020: Global Photovoltaic Power Potential by Country. Energy Sector Management Assistance Program (ESMAP), Washington, D. C.: World Bank Group.

Tiruye, G. A., A. T. Besha, Y. S. Mekonnen, N. E. Benti, G. A. Gebreslase, and R. A. Tufa, 2021: Opportunities and Challenges of Renewable Energy Production in Ethiopia. *Sustainability*, **13**, 10381, https://doi.org/10.3390/su131810381.

UN Environment Program, 2023: Nations must go further than current Paris pledges or face global warming of 2.5-2.9°C. [Available online from https://www.unep.org/news-and-stories/press-release/nations-must-go-further-current-paris-pledges-or-face-global-warming].

Veldhuis, A. J., A. M. Nobre, I. M. Peters, T. Reindl, R. Rüther, and A. H. M. E. Reinders, 2015: An empirical model for rack-mounted PV module temperatures for Southeast Asian locations evaluated for minute time scales. *IEEE Journal of Photovoltaics*, **5**, 774–782, https://doi.org/10.1109/JPHOTOV.2015.2405762.

Verlinden, P. J., 2020: Future challenges for photovoltaic manufacturing at the terawatt level. *Journal of Renewable and Sustainable Energy*, **12**, 053505, https://doi.org/10.1063/5.0020380.

Wallach, O., 2021: Race to Net Zero: Carbon Neutral Goals by Country. Visual Capitalist. [Available online from https://www.visualcapitalist.com/sp/race-to-net-zero-carbon-neutral-goals-by-country/].

World Bank, 2022a: GDP per capita (current US$). World Development Indicators, The World Bank Group. [Available online from https://data.worldbank.org].

World Bank, 2022b: Access to electricity (% of population). World Development Indicators, The World Bank Group. [Available online from https://data.worldbank.org].

World Bank, 2022c: Population, total. World Development Indicators, The World Bank Group. [Available online from https://data.worldbank.org].

Yang, D. Z., and Coauthors, 2022: A review of solar forecasting, its dependence on atmospheric sciences and implications for grid integration: Towards carbon neutrality. *Renewable and Sustainable Energy Reviews*, **161**, 112348, https://doi.org/10.1016/j.rser.2022.112348.