The Global Technical, Economic, and Feasible Potential of Renewable Electricity

de La Beaumelle, Nils Angliviel; Blok, Kornelis; de Chalendar, Jacques A.; Clarke, Leon; Hahmann, Andrea N.; Huster, Jonathan; Nemet, Gregory F.; Suri, Dhruv; Wild, Thomas B.; Azevedo, Inês M.L.

DOI
10.1146/annurev-environ-112321-091140

Publication date
2023

Document Version
Final published version

Published in
Annual Review of Environment and Resources

Citation (APA)
de La Beaumelle, N. A., Blok, K., de Chalendar, J. A., Clarke, L., Hahmann, A. N., Huster, J., Nemet, G. F., Suri, D., Wild, T. B., & Azevedo, I. M. L. (2023). The Global Technical, Economic, and Feasible Potential of Renewable Electricity. *Annual Review of Environment and Resources*, *48*, 419-449. https://doi.org/10.1146/annurev-environ-112321-091140

ANNUAL REVIEWS

Annual Review of Environment and Resources

The Global Technical, Economic, and Feasible Potential of Renewable Electricity

Nils Angliviel de La Beaumelle,[1] Kornelis Blok,[2] Jacques A. de Chalendar,[3] Leon Clarke,[4] Andrea N. Hahmann,[5] Jonathan Huster,[3] Gregory F. Nemet,[6] Dhruv Suri,[3] Thomas B. Wild,[7,8] and Inês M.L. Azevedo[3]

[1] Department of Civil and Environmental Engineering, Stanford University, Stanford, California, USA; email: ndelabea@stanford.edu

[2] Faculty of Technology, Policy and Management, Delft University of Technology, Delft, The Netherlands

[3] Department of Energy Science and Engineering, Stanford University, Stanford, California, USA

[4] Bezos Earth Fund, Washington, DC, USA

[5] Department of Wind and Energy Systems, Technical University of Denmark, Roskilde, Denmark

[6] La Follette School of Public Affairs, University of Wisconsin–Madison, Wisconsin, USA

[7] Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, Maryland, USA

[8] Earth System Science Interdisciplinary Center and Center for Global Sustainability, University of Maryland, College Park, Maryland, USA

Annu. Rev. Environ. Resour. 2023. 48:419–49

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-112321-091140

Keywords

technical potential, economic potential, feasible potential, renewables, solar PV, CSP, wind, hydropower, geothermal, ocean

Abstract

Renewable electricity generation will need to be rapidly scaled to address climate change and other environmental challenges. Doing so effectively will require an understanding of resource availability. We review estimates for renewable electricity of the global technical potential, defined as the amount of electricity that could be produced with current technologies when accounting for geographical and technical limitations as well as conversion efficiencies; economic potential, which also includes cost; and feasible potential, which accounts for societal and environmental constraints. We consider utility-scale and rooftop solar photovoltaics, concentrated solar power, onshore and offshore wind, hydropower, geothermal electricity, and ocean (wave, tidal, ocean thermal energy conversion, and salinity gradient energy) technologies. We find that the reported technical potential for each energy resource ranges over several orders of magnitude across and often within technologies. Therefore, we also discuss the main factors explaining why authors find such different results. According to this review and on the basis of the most robust studies, we find that technical potentials for utility-scale solar photovoltaic, concentrated solar power, onshore wind, and offshore wind are above 100 PWh/year. Hydropower, geothermal electricity, and ocean thermal energy conversion have technical potentials above 10 PWh/year. Rooftop solar photovoltaic, wave, and tidal have technical potentials above 1 PWh/year. Salinity gradient has a technical potential above 0.1 PWh/year. The literature assessing the global economic potential of renewables, which considers the cost of each renewable resource, shows that the economic potential is higher than current and near-future electricity demand. Fewer studies have calculated the global feasible potential, which considers societal and environmental constraints. While these ranges are useful for assessing the magnitude of available energy sources, they may omit challenges for large-scale renewable portfolios.

Contents

1. INTRODUCTION

To address climate change consequences and other environmental impacts, the world will need to reduce emissions of greenhouse gases and other air pollutants by an unprecedented amount and at a rapid pace. In 2021, our global energy system produced 36.6 gigatons of CO_2 equivalent ($GtCO_2e$) per year, of which the electricity sector contributed 13 $GtCO_2e$ (1). Global electricity demand in 2021 was 24.7 petawatt-hours (PWh), with 62% of electricity generation produced by fossil fuels and 29% by renewable energy sources (RES). The International Energy Agency (IEA) (1) suggests that future global electricity demand could grow to between 43.7 and 62.2 PWh/year by 2050, underscoring the importance of increasing low-carbon, sustainable, and reliable electricity generation. Although there is considerable uncertainty regarding projections,

IEA: International Energy Agency

increasing renewable electricity generation will almost certainly play a key role in addressing climate change and helping to meet global energy demand. At the same time, renewable energy comes with limitations, such as the distance between where the best resources are located and where the demand needs to be met, as well as the variable nature of wind and solar.

In this article, we review global technical, economic, and feasible potential for different electricity generating technologies and sources. Specifically, we review studies that estimate the global technical potential for the following energy sources, resources, and technologies: utility-scale and rooftop solar photovoltaics (PV), concentrated solar power (CSP), onshore and offshore wind, hydropower, geothermal electricity, and ocean [wave, tidal, ocean thermal energy conversion (OTEC), and salinity gradient energy]. We aim to summarize the ranges of estimates and discuss the sources of uncertainty that exist across studies for each technology. We highlight the key factors contributing to the wide range of reported potentials, so that future studies can focus on reducing uncertainty. As far as we are aware, such a large review and summary of global renewable potential has not been performed since the Special Report of the International Panel on Climate Change (IPCC) (7), and a renewed analysis can help policy makers, the public, and researchers inform their decision-making process. We consider only studies that estimate the potential for these technologies at a global scale. There is, of course, considerable additional literature that estimates the resource potential for a region or country, and we exclude those studies from this review for the sake of consistency. We also utilize previous reviews focused on understanding the different estimates of technical potential for one or more RES. While there may be competition between different energy technologies, such as for land, we do not consider those issues here.

Authors have been loosely using the following taxonomy when assessing the potential for renewable electricity generation:

- Theoretical potential, the total amount of renewable energy on Earth from a particular resource, such as the total amount of irradiation hitting the surface of the planet, the total energy in winds in the atmosphere, or the total energy stored in waves (2–15).
- Geographical potential, the amount of theoretical potential that is available in suitable areas. The assessment may exclude protected land area or the built environment (3–6, 10, 16).
- Technical potential, the amount of electricity that can be produced in available and suitable areas given current (or soon-to-be-developed) technologies, specifications, and efficiencies. Technical potential includes, for instance, the conversion efficiency of solar panels or wind turbines (2–10, 12, 13, 15–19).
- Economic potential, which represents the fraction of technical potential that can be produced at costs competitive with those of other technologies or electricity market prices (2–6, 8–10, 12, 13, 20).
- Feasible potential, which, while less well defined, may represent a subset of economic potential that accounts for social and environmental factors that may limit technology deployment, such as high up-front costs that may deter investment, policies or market distortions, and user choices and preferences (3, 5, 6, 12, 13, 15).

In this review, we focus on the technical potential, although we cover the economic and feasible potentials to the extent possible. We compare these potentials with the IEA's Stated Policy Scenario (STEPS) and Net Zero Emissions (NZE) scenario (1). These scenarios are designed to predict future energy demand. STEPS "shows the trajectory implied by today's policy settings," and the NZE scenario "maps out a way to achieve a 1.5°C stabilization in the rise in global average temperatures, alongside universal access to modern energy by 2030" (1, p. 20).

The rest of this review is organized as follows. First, we summarize our findings across all energy sources and technologies covered in this review. Next, we discuss and classify the sources

Renewables: sources of energy that do not deplete by use and do not emit greenhouse gases during the energy generation process

Renewable electricity: electricity generated from renewable sources such as solar, wind, geothermal, ocean, or hydropower

Theoretical potential: the total amount of renewable energy on Earth from a particular resource, such as the total amount of irradiation hitting the surface of the planet

Geographical potential: the amount of theoretical potential that is available in suitable areas; the assessment may exclude protected land area or the built environment

Technical potential: the amount of electricity that can be produced in available and suitable areas given current (or soon-to-be-developed) technologies, specifications, and efficiencies

Economic potential: the fraction of technical potential that can be produced at costs competitive with those of other technologies or electricity market prices

Feasible potential: may represent a subset of economic potential that accounts for social and environmental factors that may limit technology deployment, such as high up-front costs that may deter investment

PV: photovoltaic

CSP: concentrated solar power

OTEC: ocean thermal energy conversion

STEPS: Stated Policy Scenario from the International Energy Agency

NZE: Net Zero Emissions scenario from the International Energy Agency

Supplemental Material >

of uncertainty. We then provide a detailed assessment by energy source and technology. Finally, we discuss gaps in the literature and future research that could help guide future decisions on renewable deployment.

2. GLOBAL TECHNICAL POTENTIAL OF RENEWABLE ENERGY SOURCES

We consider studies that estimate the global technical potential for utility-scale and rooftop solar PV, CSP, onshore and offshore wind, hydropower, geothermal electricity, and ocean (wave, tidal, OTEC, and salinity gradient energy) technologies. The review encompasses 17 studies that had estimates for multiple technologies, 3 papers on solar PV, 3 papers on CSP, 12 papers on onshore wind, 12 papers on offshore wind, 4 papers on hydropower, 5 papers on geothermal energy, and 11 papers on ocean electricity production technologies. The **Supplemental Appendix**, in particular **Supplemental Table 1**, lists the studies considered and their key characteristics. We limit our assessment to studies, both peer reviewed and produced by international agencies or national labs, published between the years 1998 and 2021 (except for Reference 11). Given the considerable technological changes and efficiency improvements since then, we also show how estimates of the technical potential for each energy source and technology have changed over time.

The units used to represent the technical potential differ across studies; 21 studies use electricity generation units (e.g., terawatt-hours) (3, 4, 9, 10–13, 15, 16, 18, 19, 21–30), whereas 12 studies use energy units (e.g., exajoules per year). Some of the latter present primary energy estimates (2, 8, 31, 32), whereas others provide final energy estimates (5–7, 17, 20, 32–34). Furthermore, 23 studies use power units (e.g., terawatts), which sometimes represent an annual average power output (35–53). Four studies report nameplate capacity, which we multiply by a reasonable capacity factor (14, 54–56). We find that the technical potential ranges from 0.01 to 13,600 PWh/year across technologies and energy sources. Cumulative estimates of the total technical potential for all technologies range from 1.64×10^2 to 2.72×10^4 PWh/year if we consider the minimum and maximum for each resource type and study and assume that these estimates are additive. One of the goals of this review is to determine the most important reasons for the large differences in results. For each technology, factors are discussed in our perceived order of relevance.

Figure 1 shows the estimates for each reviewed study, technology, and energy source, and **Table 1** shows the high and low estimates reported in the literature for each technology. Notably, within the same RES and technology, estimates span several orders of magnitude. However, we find that only a few studies drive these wide ranges. Jacobson et al. (54) provide estimates for solar technologies that are more than double the estimates of the study with the second highest estimates. These authors describe road maps for countries to use only renewable energy, but they build on the methodology described in an earlier paper (see the supplementary information of Reference 57) to calculate the technical potentials of renewables with updated data. That is why we decided to include the technical potential results from Reference 54 (see the data sheets associated with the paper). Aghahosseini & Breyer (14) obtain results that are almost four times larger than the second highest estimate for geothermal. Pelc & Fujita (45) present high estimates for ocean technologies, especially wave energy, where their estimate is more than three times that of the study with the second-highest results. Eight studies represent the high end of the estimates for the energy technologies, and 10 studies represent the low end.

3. SOLAR ENERGY

In this section, we review solar PV (often categorized as utility-scale, commercial, or residential rooftop PV, depending on the scale and sector where the system is installed) and CSP.

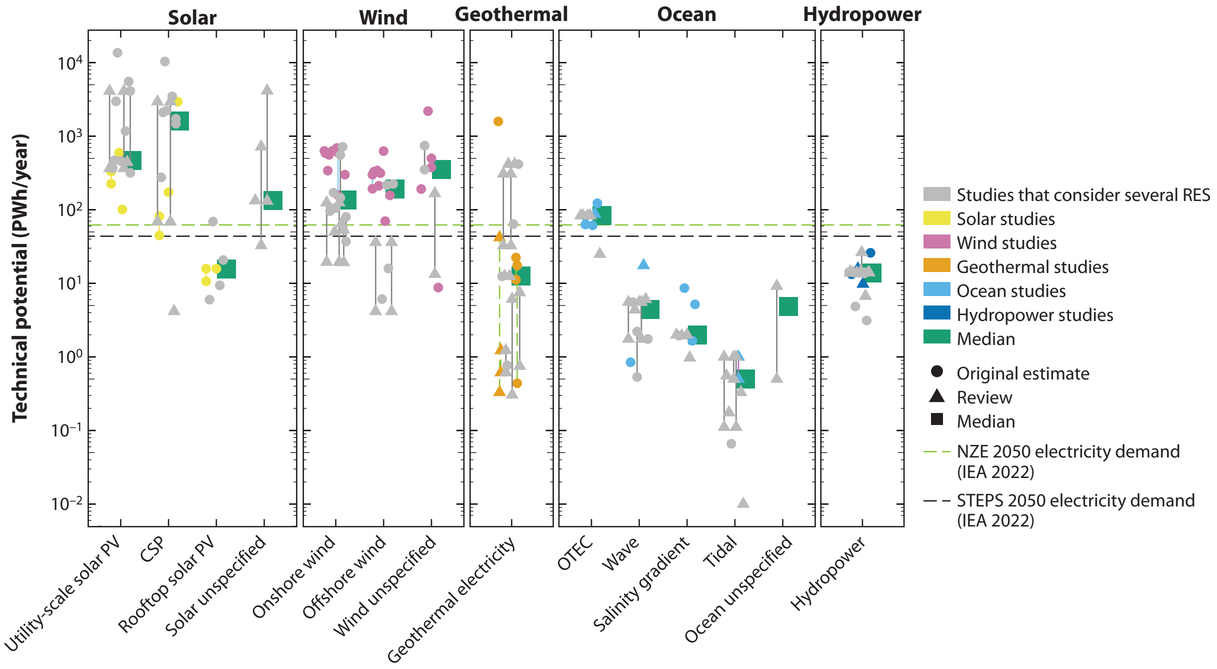


Figure 1

Global technical potential estimates for electricity in petawatt-hours (PWh) per year, in a logarithmic scale, for solar, wind, geothermal, ocean, and hydropower. Each marker and color combination represents a study. When studies report a range, maximum and minimum values are connected by vertical lines. The shape of the markers represents either an original estimate (*circle*) or a review study (*triangle*). Squares represent the median potential for an energy source/technology listed on the x-axis. The black and green dashed lines represent the electricity demand in 2050 in the STEPS and NZE scenarios from the International Energy Agency *World Energy Outlook 2022* (1), respectively. Abbreviations: CSP, concentrated solar power; NZE, net zero emissions; OTEC, ocean thermal energy conversion; PV, photovoltaic; RES, renewable energy sources; STEPS, stated policies scenario.

3.1. Solar Photovoltaics

In PV panels, photons from incident solar radiation excite electrons, inducing the flow of electricity. Electricity is generated in the form of direct current (DC), thus requiring inverters for DC-to-AC (alternate current) conversion. PV technology, first developed in the late nineteenth century (58), now exists in multiple forms that vary in efficiency, materials, and cost, although almost all commercial PV panels are made from silicon. The three main PV categories today are monocrystalline, polycrystalline, and thin film (58). Although these types of panels function differently, most authors do not specify which technology they assume, but rather consider a constant efficiency in their models.

In 2020, the global solar PV installed capacity was 710.7 GW, producing 0.83 PWh (59). Asia (409.3 GW), Europe (160.4 GW), and North America (82.3 GW) are the regions with the greatest utility-scale installed capacity (59). The IEA's STEPS estimates that in 2050 the solar PV capacity (utility-scale and rooftop together) will be 7,464 GW, which will generate 12.12 PWh/year (1).

3.1.1. Utility-scale photovoltaics. The technical potential of utility-scale solar PV is often estimated by multiplying the local irradiance in suitable areas (measured and/or from reanalysis data sets) by the system efficiency. Suitable areas are based on land cover type (different land cover types are assigned to a suitability factor), with exclusions for areas such as water bodies (though

Table 1 Ranges of estimates for each renewable technology

Technology	Low (PWh/year)	High (PWh/year)	Difference (orders of magnitude)
Solar PV: utility	1.01×10^{2} (10)	1.36×10^{4} (54)	2
Solar PV: rooftop	6.00×10^{0} (3)	6.90×10^{1} (54)	1
CSP	4.17×10^{0} (32)	1.04×10^{4} (54)	4
Onshore wind	1.93×10^{1} (2)	7.17×10^{2} (9)	1
Offshore wind	4.17×10^{0} (lower bound of References 7 and 17)	6.26×10^{2} (42)	2
Hydropower	3.13×10^{0} (9)	2.64×10^{1} (upper bound of Reference 20)	1
Geothermal	3.06×10^{-1} (lower bound of Reference 20)	1.59×10^{3} (14)	4
Wave	5.34×10^{-1} (lower bound of Reference 54)	1.75×10^{1} (45)	2
Tidal	1.00×10^{-2} (32)	1.00×10^{0} (upper bound of References 6, 7, 17, and 45)	2
OTEC	2.49×10^{1} (8)	1.23×10^{2} (52)	1
Salinity gradient	9.72×10^{-1} (8)	8.61×10^{0} (48)	1
Total if considered additive	1.64×10^{2}	2.72×10^{4}	2

Abbreviations: CSP, concentrated solar power; OTEC, ocean thermal energy conversion; PV, photovoltaics.

technologies are being developed on water; 60), protected areas, urban areas, and forests (3–6, 8–10, 16, 33, 36, 54). Technological specifications, described below, include conversion efficiency, angle, spacing factor, shading, performance ratio (which includes the efficiency of turning DC into AC), capacity factor, and single versus dual tracking. Some studies also include transmission losses (2, 9), scenarios of development (4, 54), and scarcity of resources (e.g., minerals) (33). Analyses often do not specify a target year but simply use technological characteristics representative of technology already in operation or planned at the time of the study. A few studies (4–6, 9, 10, 54) explicitly assume technological improvements and a specific year for the analysis.

The global technical potential across studies spans two orders of magnitude (**Figure 2**), from 1.01×10^{2} PWh/year (10) to 1.36×10^{4} PWh/year (54). The median of all studies is 4.65×10^{2} PWh/year, and the average is 2.20×10^{3} PWh/year. Reference 54 appears to be an outlier in the order of magnitude reported for solar.

The estimates differ because of the following factors, presented in descending order of importance based on our assessment. The first is land suitability factor or available area approaches, meaning the area of a certain land type that can be used for solar farm deployment. Suitability factors represent the percentage of a certain type of terrain (e.g., grassland, desert) that could be used for installments of a specific technology. For utility-scale PV, all land suitability factor–based studies (3–6, 8–10, 16, 33, 36, 54) exclude urban areas, bioreserves, water bodies, and most forests but make different assumptions regarding exclusions of other types of land. Hoogwijk & Graus (5) and Krewitt et al. (6) rely on the suitability factors from Reference 3. Other authors compute the available area instead of land suitability factors. For example, Jacobson & Delucchi (36) consider all of the world's land, excluding Antarctica, and assume that one-third of it would need to be used for solar panels and other solar farm components and to allow enough area between panels. They then take 20% of that area to account for low-insolation and exclusion areas. Jacobson et al. (54) consider the maximum area to be between (*a*) 5% of the total area of a country's and (*b*) the

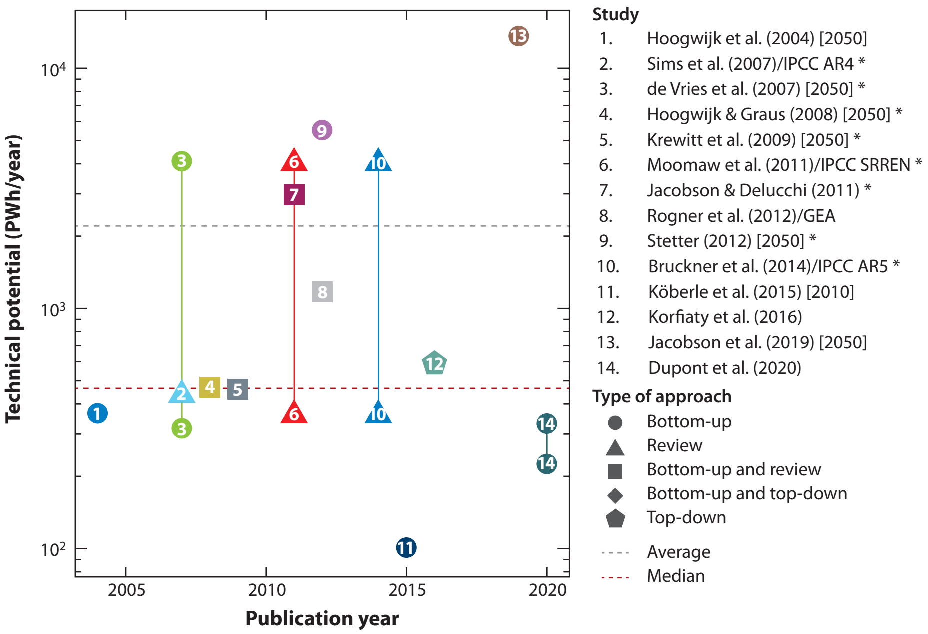


Figure 2

Global utility-scale PV technical potential estimates, in petawatt-hours (PWh) per year, based on year of publication, in a logarithmic scale. Each data point and its color represent a study. When studies report a range, maximum and minimum values are connected with vertical lines. Shapes represent the type of method and approach. The gray and dark red lines represent the average and median across studies, respectively. For papers estimating technical potential for a specific year, the time horizon is in brackets in the legend. Asterisks in the legend mean that utility-scale and rooftop PV were not differentiated, and these papers present a total solar PV estimate. Abbreviations: AR, Assessment Report; GEA, Global Energy Assessment; IPCC, Intergovernmental Panel on Climate Change; PV, photovoltaic; SRREN, Special Report on Renewable Energy Sources and Climate Change Mitigation.

sum of 60% of areas exposed to irradiation greater than 4 $(\mathrm{kWh}\cdot\mathrm{m}^2)$/day and 40% of the areas exposed to more than 5 $(\mathrm{kWh}\cdot\mathrm{m}^2)$/day according to National Renewable Energy Laboratory data. Overall, both strategies (suitability factor and available area approaches) rely heavily on modelers' judgments. The emergence of satellite imagery and data processing will allow for much more detailed assessments in the future.

Second, spacing between panels is necessary to reduce shading and allow for maintenance. Several authors (5, 10, 33, 54) account for spacing and reduce the area by a factor of one-third to one-half, but others (61) note that the suitable area could expand, since another activity (e.g., agriculture) could occur on the same land.

The third factor is panel angle. Depending on the latitude and local characteristics (terrain, surrounding structures, etc.), panels must be placed at a certain angle to maximize electricity generation. Most authors (3–6, 8, 10, 16) assume horizontal panels, whereas others (9, 54) assume optimal angles based on latitude. The latter two studies (9, 54) have high potentials (5.53×10^3 and 1.36×10^4 PWh/year, respectively).

The fourth factor is temporal and geographical resolution of irradiation data. Early studies (e.g., 3, 5, 6) used data from the Climate Research Unit, which has irradiance monthly averages from 4,040 stations around the world. More recent studies (9, 10, 16, 33) use newer data sets that have average daily profiles or hourly resolution (such as NASA's SSE data set or the Global Solar

Atlas). Spatial resolution is not as important as temporal, because weather conditions are similar at distances of the same order as data set resolution.

Fifth, conversion efficiency represents how much irradiation can be converted into DC electricity. Early studies (4–6) estimated that conversion efficiencies would reach 25% in 2050, whereas others (9, 36) use conversion efficiencies between 15% and 18%. Recent studies use a range of values, from point estimates of 13% (10) or 20% (16, 54) to values between 17% and 24% (33). Efficiency is directly proportional to the potential, thus affecting the estimates.

Finally, other factors, which likely explain differences smaller than those mentioned above, include performance ratio (which represents inverter, mismatch, and cable losses), temperature (9, 16), panel degradation (33), land competition between renewables (33), maximum slope where a solar PV system can be installed (9, 16, 33), maximum altitude (6), dust or snow accumulation, and the need for a minimum amount of solar irradiation (16, 54).

3.1.2. Rooftop solar photovoltaics. Most studies use the same approach as described in the utility-scale PV section but consider urban/settlement areas to be suitable areas. Studies estimate the roof and façade percentage of urban areas that is suitable for installing solar panels and do not appear to distinguish between residential, commercial, and industrial rooftop PV. Generally, studies do not specify a time horizon when estimating the technical potential for rooftop PV, and they use technological characteristics representative of technology that is already in operation or planned at the time of the study; only a few studies are explicit about the time horizon and assumed technology improvements (6, 9, 54). Rooftop PV technical potential estimates span an order of magnitude, from 6×10^0 PWh/year (3) to 6.9×10^1 PWh/year (54). The median value is 1.58×10^1 PWh/year, and the average is 2.11×10^1 PWh/year (**Figure 3**).

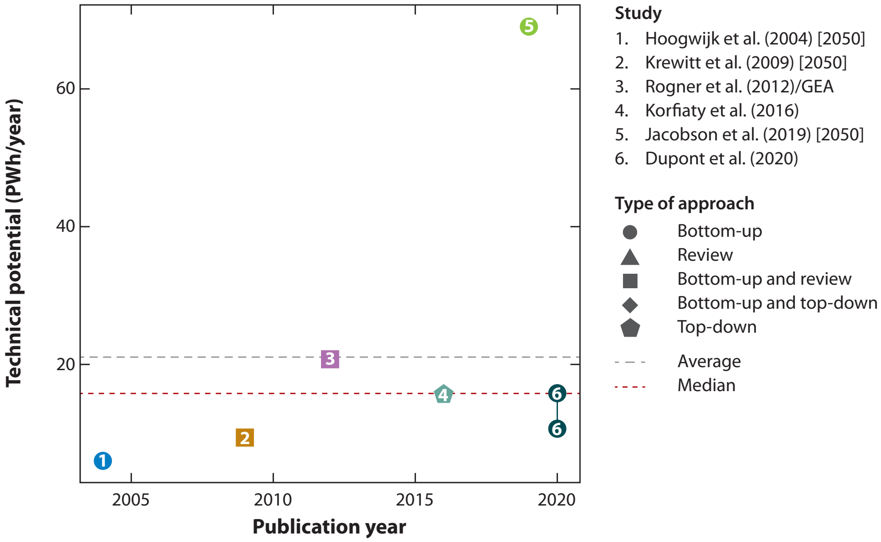


Figure 3

Global rooftop photovoltaic technical potential estimates in petawatt-hours (PWh) per year, based on year of publication, in a linear scale. Each data point and its color represent a study. When studies report a range, maximum and minimum values are connected by vertical lines. Shapes represent the type of method and approach. The gray and dark red lines represent the average and median across studies, respectively. For papers estimating technical potential for a specific year, the time horizon is in brackets in the legend. Abbreviation: GEA, Global Energy Assessment.

Estimates differ for several reasons, which we present in descending order of importance based on our assessment. The first is the method used. Some studies (6, 8, 9, 16) rely on the approach developed in Reference 3, which is based on GDP per capita and population density and which, in turn, relies on data from two earlier studies (62, 63). Jacobson et al. (54), using a method from an earlier paper (57), take a different approach that considers floor space and several other factors (GDP, population density, urban population, construction activity, parking roofs, roof slopes, overhangs, shading, stories per building). Recently, Dupont et al. (33) provided an updated estimate from Reference 64 that includes roof slopes, orientation, maximum shading (number of hours without sunlight), and minimum roof size. Their review and meta-analysis find that 65% of commercial building rooftops and 25% of residential ones can be used for solar panels. Methods using GDP and population density (3, 6, 8, 9, 16) are simpler than methods that use factors such as urban population, floor area, construction activity, parking area, and roof slope. The two studies using those factors (33, 54) present results higher than 10^1 PWh/year and likely provide more robust estimates, where such data exist.

The second factor comprises technological specifications. As for utility-scale PV, conversion efficiencies and performance ratios of solar panels play a role in explaining the range of estimates. The third factor is the angle assumed. Again, as with utility-scale PV, the angle of panels, compared with a flat surface and depending on the latitude, influences energy production. Hoogwijk (3) assumes a horizontal position, and all studies using that method do so as well (6, 8, 9, 16). Jacobson et al. (54) assume an optimal angle based on latitude.

The fourth and fifth factors are spatial and temporal data resolution, namely for irradiance values, and spacing, namely the distance between arrays of panels to reduce shading (3, 6, 9, 33, 54).

3.2. Concentrated Solar Power

CSP plants use arrays of mirrors to concentrate direct solar radiation onto a target, where a fluid heats up and then produces electricity in a steam cycle. CSP was first used in 1866 in parabolic troughs to heat water (65). There are now several CSP technologies; the three main ones are linear concentrator systems (parabolic troughs and linear Fresnel reflector systems), power tower systems, and dish/engine systems (66). The capacities of CSP projects may exceed 500 MW. In 2020, the CSP global capacity was 6.5 GW, producing 0.01 PWh/year, with the largest capacity in Europe (2.3 GW), North America (1.8 GW), and Africa (1.1 GW) (59). The IEA's STEPS has a CSP global capacity of 90 GW (0.33 PWh/year) in 2050 (1).

Global estimates of CSP's technical potential use the total direct irradiation power that reaches Earth and include geographical constraints (i.e., suitable areas based on land cover type, excluding areas such as water bodies, protected areas, and urban areas as well as regions with low direct solar radiation) and technological specifications. Some studies include transmission losses (2, 9), scenarios of development (4, 54), and scarcity of resources (e.g., minerals) (33).

Most CSP global technical potential studies rely on solar irradiation data (measured and/or from reanalysis data sets), generally parsed out by grid cells at the surface where mirrors would be installed. The authors of these studies then determine the suitable areas in each grid cell by applying exclusion layers to the globe and suitability factors to different land types, as described above. They then multiply the local irradiance by technological efficiencies, or sometimes multiply the suitable area with a power density (in megawatts per square kilometer) to determine how many mirrors can be placed over the suitable area. They use either hourly data or assumptions on capacity factors to go from capacity to energy production.

We find that CSP estimates span four orders of magnitude, from 4.17×10^0 PWh/year (32) to 1.04×10^4 PWh/year (54), showing important disagreement (**Figure 4**). The median of all studies is 1.60×10^3 PWh/year, and the average is 1.93×10^3 PWh/year.

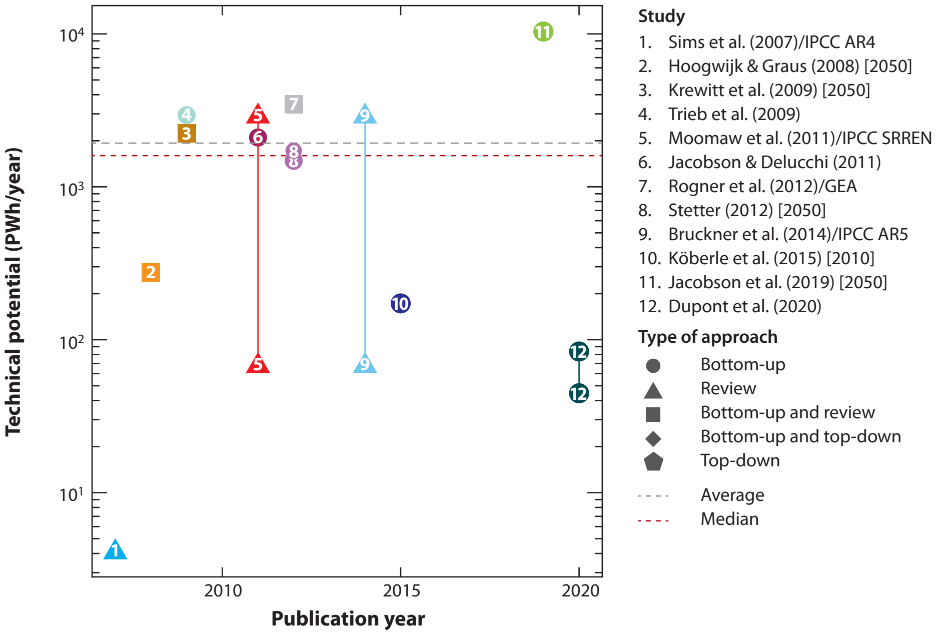


Figure 4

Global CSP technical potential estimates, in petawatt-hours (PWh) per year, based on year of publication, in a logarithmic scale. Each data point and its color represent a study. When studies report a range, maximum and minimum values are connected by vertical lines. Shapes represent the type of method and approach. The gray and dark red lines represent the average and median across studies, respectively. For papers estimating technical potential for a specific year, the time horizon is in brackets in the legend. Abbreviations: AR, Assessment Report; CSP, concentrated solar power; GEA, Global Energy Assessment; IPCC, Intergovernmental Panel on Climate Change; SRREN, Special Report on Renewable Energy Sources and Climate Change Mitigation.

These estimates differ in several aspects, again listed in our perceived descending order of importance. The first is storage. CSP can be coupled with a storage system, usually one that uses molten salt, which can retain thermal energy for hours and therefore produce electricity even when the sun is not shining. Some studies consider systems of CSP with storage (6, 8–10, 21, 33, 54) and consider the area and investment required for storage, as well as losses related to the storage efficiency. Estimates that have included storage result in technical potentials greater than 1,000 PWh/year (exceptions are References 10 and 33). CSP storage has different categories, called solar multiples (SM), which represent how much of the plant's nominal capacity can be produced and stored under nominal irradiation conditions. For instance, SM1 means that there is one solar field capable of producing nominal capacity under nominal irradiation conditions; SM2 has two times the solar field, one to run the plant at nominal capacity and one to produce enough storage for nighttime (21). Studies have used widely different assumptions for SM, ranging from SM2 (10) to SM2.5 (6), SM4 (21), SM1.5/2.5/3.5 (9), and SM3.62 (54) and optimizing SM as part of their model (33). It is unclear whether storage is included in Reference 8.

Suitability factors are the second aspect. All studies presenting a technical potential for CSP, except one (21), also analyze utility-scale PV and use the same suitability factors and exclusion layers.

The third factor is conversion efficiency, which ranges from 12% to 37% across studies. Most studies assume efficiencies between 12% and 15%, although two use higher values: 35% (6) and 37% (9).

The fourth factor is the ratio of covered area to ground area, spacing factor, or land use factor, which accounts for shading and considers land requirements for other characteristics of the CSP farm, such as area required for roads and buildings.

The fifth factor is power density versus irradiation. Some authors multiply the suitable area by a power density factor. For example, Jacobson & Delucchi (36) estimate the power density based on peak power and account for spacing required between mirrors and land requirements for a CSP farm; the result is a power density ranging from 41.2 to 52.6 MW/km^2. Rogner et al. (8) use a density of 50 MWe/km^2.

Minimum irradiation is the sixth aspect. CSP captures direct sunlight, so authors almost always set a minimum resource limit in their models. These limits range from 1,475–1,500 (kWh·m^2)/year (5, 6, 8) to 1,095 (kWh·m^2)/year (9) to 1,800–2,000 (kWh·m^2)/year (9, 21, 54).

The seventh aspect is temporal and spatial resolution for irradiation data, as explained above for other solar technologies. The eighth and ninth are maximum slope and altitude, for which the assumptions vary across studies, and capacity factors, which depend on storage assumptions.

Studies report very large technical potentials of CSP, likely larger than global electricity demand in 2050 (1). Estimates have not increased over time, and despite its high technical potential, the CSP installed capacity (6.5 GW) is very low compared with that of solar PV (710.7 GW) (59).

4. WIND

Wind electricity generation uses the wind's kinetic energy to turn the blades mounted on an elevated nacelle, which then rotates gears that convert mechanical energy into electricity in a generator. Older technologies, such as windmills that convert kinetic energy into mechanical energy, have been used for centuries to grind grain, pump water, and so forth (67). The first wind turbines were used in the late nineteenth century (68). In this review, we consider only horizontal-axis turbines because they are currently the most widely used for power generation. Newly installed turbines are "in the 3–4 MW range onshore and 8–12 MW offshore" (68). The potential wind power flux (in watts per square meter) in a given location is estimated as

$$F = \frac{1}{2}\rho_{\mathrm{air}}\upsilon_{\mathrm{wind}}^{3},$$

where F is the power density of the wind (i.e., kinetic energy), ρ_{air} is the density of air (in kilograms per cubic meter), and υ_{wind} is the wind speed distribution (in meters per second). The maximum power (in watts) that can be extracted from the wind is defined by Betz's law,

$$P = \frac{1}{2}C_{\mathrm{p}}\rho_{\mathrm{air}}A\upsilon_{\mathrm{wind}}^{3},$$

where P is the maximum power output; C_{p} equals 0.593, which is the maximum theoretical efficiency; and A is the area swept by the turbine blades (in square meters).

Because the electricity generated is related to wind speed by a cubic exponent, and because wind speed increases with height, over time the industry has moved toward wind turbines with higher hub heights (and larger rotor diameters). Recently installed wind projects have hub heights above 100 m and rotor diameters greater than 120 m (69).

The technical potential of wind technologies is defined as the total wind power that is accessible in a suitable area given technological specifications. For onshore wind, a suitable area is determined on the basis of land cover type (different land cover types are assigned suitability factors), excluding areas such as water bodies, protected areas, and urban areas. For offshore wind, suitable area is based on distance from shore and seafloor depth; protected areas are excluded. For both onshore and offshore wind, technological specifications include turbine characteristics (hub height, blade size, rated power, operational limits, etc.), losses (efficiency losses, power density and array losses, etc.), and load factor (capacity factor or minimum wind resource). Some studies include transmission losses (2, 9), development scenarios (4, 54), or material resource scarcity (34).

4.1. Onshore Wind

In 2020, global onshore wind installed capacity was 697.3 GW, producing 1.49 PWh/year, mostly in Asia (322.9 GW), Europe (182.9 GW), and North America (138.8 GW) (59). The IEA's STEPS assumes that 3,564 GW of installed capacity and 10.69 PWh/year will be generated from onshore wind in the year 2050 (1).

Most studies rely on wind speed data (measured or from reanalysis data sets), generally parsed out by grid cells and for different hub heights. Studies determine the suitable areas in each grid cell by applying exclusion layers to the globe and suitability factors to different land types, multiply the suitable area by a power density (in megawatts per square kilometer) to determine capacity (how many turbines can be placed over the suitable area), and use either hourly data or assumptions about capacity factors to estimate electricity generation (i.e., the bottom-up approach). Another approach is to assess the theoretical limit of the kinetic energy of the wind or the total momentum in the atmosphere and/or boundary layer, and then estimate how much could be used by onshore wind turbines without disturbing the atmospheric circulation (i.e., the top-down approach); results are reported in annual average power output (38–41, 43).

Estimates for onshore wind span an order of magnitude, from 1.93×10^1 PWh/year (2) to 7.17×10^2 PWh/year (9). The median of all studies is 1.52×10^2 PWh/year, and the average is 2.72×10^2 PWh/year. The estimates agree reasonably well across studies (**Figure 5**).

The differences among these estimates are due to the following factors, again listed in order of decreasing importance, according to our assessment. The first is spatial resolution. Several bottom-up estimates rely on data sets with low spatial resolution, such as CRUCL v.1.0 (3–6), the GEOS-5 Data Assimilation System (22), and MERRA (9). The availability of the Global Wind Atlas (GWA), published in 2015 and improved in 2017 and 2019 (see **https://globalwindatlas.info/en/about/ReleaseNotes**), and other, higher-resolution data sets have enabled more accurate estimates; several sets of authors (3, 18, 24, 39, 40, 55) underscore that using wind speed at higher spatial resolution improves the estimates of power produced. This is because poor spatial resolution does not capture small, high-wind locations and instead averages over a grid cell. Bosch et al. (18) combine high-resolution temporal data from the MERRA-2 reanalysis data set and high spatial resolution from the GWA to show that, over an area of 50 × 50 km around Marseille, France, the potential from the GWA with a resolution of 2.5 × 0.5 km increases by 50% compared with the potential from the MERRA-2 data set with resolution 50 × 50 km. However, no global study has used the same method or performed a systematic comparison across data sets.

The second factor is temporal resolution. Early studies use average monthly wind data (3–6), with a few exceptions (8, 9, 22, 24). Recent studies use hourly data (some observed, others simulated) (18, 19).

Third is measurement height. Early studies use wind speed data at 10 m aboveground, followed by logarithmic/power laws and Weibull distributions to calculate wind speed at a specific hub height (3–6, 24). Wind speed measurements around the globe at hub height would improve estimates (70). Recent studies include wind speed measurements (or estimates) at multiple heights (22, 35, 39, 40), some of which are close to the assumed hub height (8, 9, 18, 19, 34, 54).

Fourth is hub height. Wind speed increases with height, and since the theoretical power produced is a function of wind speed to the third power, assumptions about hub height are crucial for technical potential estimates. Studies before 2008 tend to assume hub heights of ∼80 m or less, while estimates from 2008 to 2019 assume turbines with hub heights of 100 m or more.

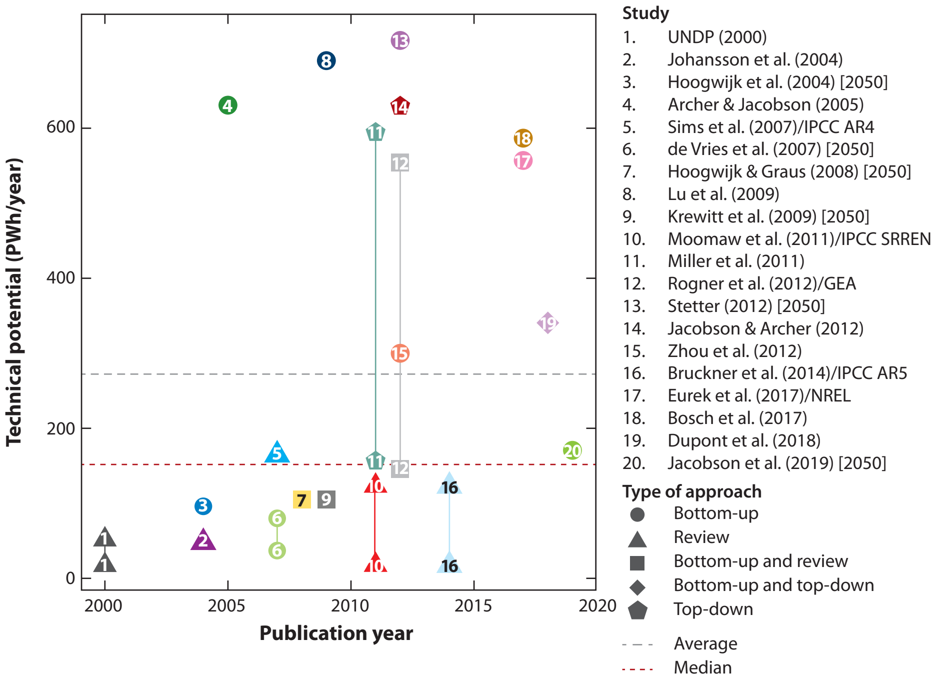


Figure 5

Global onshore wind technical potential estimates, in petawatt-hours (PWh) per year, based on year of publication, in a linear scale. Each data point and its color represent a study. When studies report a range, maximum and minimum values are connected by vertical lines. Shapes represent the type of method and approach. The gray and dark red lines represent the average and median across studies, respectively. For papers estimating technical potential for a specific year, the time horizon is in brackets in the legend. Abbreviations: AR, Assessment Report; GEA, Global Energy Assessment; IPCC, Intergovernmental Panel on Climate Change; NREL, National Renewable Energy Laboratory; SRREN, Special Report on Renewable Energy Sources and Climate Change Mitigation.

Fifth, power density represents how many turbines can be installed per unit area, depending on the size of the turbines. A high power density means that more turbines can be placed per unit area, thus producing more power. However, wind farm losses can become important with increasing power density, especially over large wind farms (71). Optimizing the power density means placing the maximum number of turbines on a given area while minimizing array losses. Studies assume a power density ranging from 0.6 MW/km^2 (34) to 11.3 MW/km^2 (40), showing wide disagreement. In their model, Dupont et al. (34) optimize the power density for each grid cell, leading to a range of 0.6–9.26 MW/km^2.

Sixth is capacity factor. Some studies (3, 5, 6) estimate the energy produced from each location on the basis of (estimated) wind speed data and use the relationship between average annual wind speed and full-load hours (i.e., how many hours per year a wind turbine functions at rated capacity). de Vries et al. (4) also assume a linear relationship between annual average wind speed and full-load hours and use a fixed capacity factor, depending on the scenarios. Studies using data with hourly resolution do not need to apply a capacity factor because the energy production in each hour is determined by the wind speed value (9, 18, 19, 24). In addition, some values reported in terawatts actually represent average annual power outputs (not nameplate capacity) and can therefore be converted into electricity generation (i.e., by multiplying by 8,760 h/year) (38–41, 43).

Suitability factors and minimum amount of resource are the seventh factor. Suitability factors do not have the same impact on wind estimates as they do for solar technologies. Most studies assume large suitability factors based on land types (3, 5, 6, 9, 19, 22, 24, 36). Some also consider areas with a minimum amount of resource, either using capacity factor thresholds (18, 22, 54) or estimating the technical potential per capacity factor category (19). Others consider areas with winds above a certain value (e.g., class 3 winds or >8 m/s at hub height) (3, 4, 6, 35).

The eighth factor is method. While most studies use a bottom-up approach, a few (34, 38–41, 43) perform a top-down analysis to determine the maximum power extractable from the atmosphere. These studies explain that adding more and more wind turbines slows down winds and decreases the energy in the boundary layer. Thus, authors try to determine the tipping point at which one additional turbine would increase total losses in the atmosphere by more than the marginal increase in power produced. Dupont et al. (34) compare each grid cell's bottom-up wind production with the top-down estimate, using the top-down estimate as a cutoff. Except for those in Reference 38, all estimates are above 10^2 PWh/year.

Turbine size is the ninth factor. Turbines had a rated power between 1 and 1.5 MW before 2008 and between 2.5 and 5 MW between 2008 and 2019, with a few exceptions (8, 24, 41, 43). The year for the analysis is often not specified. Still, some studies include a time horizon, with technological improvements changing with time (4–6, 9, 54).

Finally, other aspects that differ across studies but may have less impact on differences are the availability factor (accounting for maintenance and breakdowns), array efficiency losses, transmission losses, maximum altitude, and maximum terrain slope.

4.2. Offshore Wind

Offshore wind has the same principles as onshore wind except that the turbines are placed over large water bodies. The first offshore wind turbines started operating in 1991 in Denmark and had a total installed capacity of 5 MW (72). The two main strategies for siting offshore wind are fixed-bottom and floating. Fixed-bottom turbines are attached to underwater pillars fixed on the seafloor. This strategy represents most of the current installed capacity but is limited to seafloor depths under ∼50 m (73). Floating offshore wind turbine prototypes have recently been developed and installed to tap wind resources offshore for locations with greater seafloor depths (up to ∼1,000 m) (25). Other differences between fixed-bottom and floating offshore turbines include capacity, hub height, and rotor diameter. At present, the largest fixed-bottom offshore wind farm, Hornsea 2, which is located in the North Sea off the coast of Yorkshire, United Kingdom, has a total capacity of 1.3 GW (74). Its 8 MW turbines have hub heights around ∼120 m and rotor diameters around ∼167 m (73, 75). One of the few floating offshore wind farms, and the largest, is located in Kincardine, Scotland. It has a capacity of 50 MW and includes five 9.5 MW turbines, with hub heights around ∼110 m and rotor diameters around ∼164 m (76, 77).

Offshore wind turbines are getting larger, and planned projects worldwide will use 13–15 MW turbines (78). In 2020, offshore global wind capacity was 34.4 GW, producing 0.10 PWh/year, with most of the capacity in Europe (24.9 GW) and Asia (9.4 GW) (59). In 2021, global capacity was 54.3 GW (27.8 GW in Asia and 26.4 GW in Europe), highlighting the rapid growth of offshore wind (59).

Most global offshore wind technical potential studies use a bottom-up approach, as explained in the onshore wind section. The only difference is that suitability factors depend on the distance from shore and seafloor depth instead of land type. Some studies use a top-down approach, as explained in the onshore wind section (34, 38, 40, 41, 43); here, the only difference is that the energy considered is located close to shore rather than over landmasses. Most studies use technological characteristics representative of technology already in operation or planned at the time

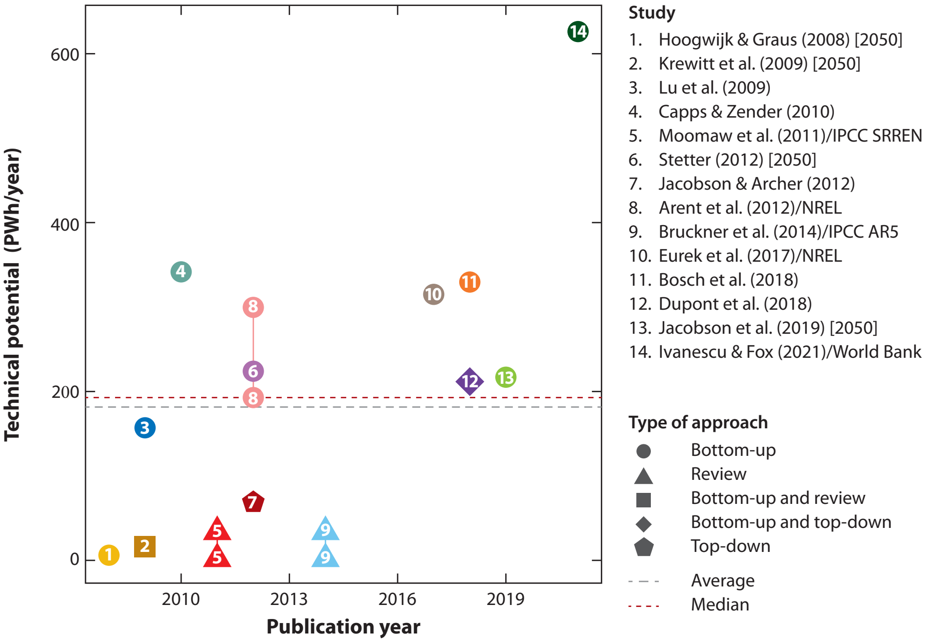


Figure 6

Global offshore wind technical potential estimates, in petawatt-hours (PWh) per year, based on year of publication, in a linear scale. Each data point and its color represent a study. When studies report a range, maximum and minimum values are connected by vertical lines. Shapes represent the type of method and approach. The gray and dark red lines represent the average and median across studies, respectively. For papers estimating technical potential for a specific year, the time horizon is in brackets in the legend. Abbreviations: AR, Assessment Report; IPCC, Intergovernmental Panel on Climate Change; NREL, National Renewable Energy Laboratory; SRREN, Special Report on Renewable Energy Sources and Climate Change Mitigation.

of the study. A few studies (5, 6, 9, 54) include a time horizon, with technological improvements changing over time.

Estimates for offshore wind span two orders of magnitude, from 4.17×10^0 PWh/year (lower bound of References 7 and 17) to 6.26×10^2 PWh/year (42). The median of all studies is 1.93×10^2 PWh/year, and the average is 1.82×10^2 PWh/year. Compared with other technologies and energy sources, for offshore wind there is more agreement between studies (**Figure 6**).

The estimates differ because of the following factors. The first is fixed-bottom versus floating technologies. Early estimates assumed only fixed-bottom technologies (i.e., they were applicable only for depths <50 m) (5–7, 9, 17), whereas more recent estimates consider depths up to 200 m (22, 23, 37, 40) or even 1,000 m (19, 23, 25, 34, 42). This increases the potential area for offshore wind deployment considerably and is a key reason for the resulting differences across estimates.

The second factor is distance from shore. Early studies consider distances shorter than 50 km (5–7, 17, 37), while recent studies consider longer distances (<370 km) (9, 19, 22, 23, 25, 42, 54). Seafloor depth constraints have a larger influence on the estimates for offshore wind potential than does distance from shore.

The third factor, power density, is described above in the onshore wind section. For offshore wind, it ranges from 3.14 MW/km^2 (25) to 16 MW/km^2 (6), with most studies using 7–10 MW/km^2.

Fourth is capacity factor. Some studies estimate the energy produced from each location on the basis of wind speed data (or estimates) and use a relationship between average annual wind speed and full-load hours (5, 6). Other studies use hourly data (9, 19, 23, 25) and, thus, do not rely on capacity factors.

Minimum resource is the fifth factor. Some studies consider only locations with a capacity factor greater than 15–20% (22, 23, 25), provide estimates per capacity factor category (19), or consider only winds above a certain class (9, 23, 37, 42, 54).

For the sixth factor, method, the same description in the onshore wind section applies here.

Seventh is turbine size, which tends to be smaller for earlier studies (5, 6, 19, 22, 23) at approximately 1.5–3.5 MW, compared with 5 MW for more recent studies (9, 25, 34, 37, 40, 42, 54).

Data sets are the eighth factor: offshore wind is more uniform temporally and spatially than onshore. Thus, the use of measured and/or reanalysis data or satellite data does not appear to lead to very different estimates.

For measurement height, the ninth factor, the same issues as those described in the onshore wind section apply. However, because of the relatively smooth surface of water bodies, the use of a logarithmic extrapolation from 10 m to hub height using a constant of 1/7 will overestimate the hub height wind speed (70).

The last factors are hub height and losses. Hub height is almost always assumed to be ∼100 m. For losses, availability factors vary from 0.925 to 0.97 and array efficiencies range from 0.8855 to 0.9; earlier studies do not account for these factors.

5. HYDROPOWER

Hydropower uses the potential energy of water moving from high to low elevation, coupled with a turbine that produces electricity by rotating a generator. The potential energy in a unit volume of water is the product of its specific weight due to gravity and its elevation. Used for centuries to process grains and cloth, hydropower has been employed for electricity production since the nineteenth century (79) and is a mature technology. Impoundment hydropower consists of a dam on a river and water stored in a reservoir, and diversion hydropower uses only a portion of a river's flow (80).

Hydropower represents approximately one-fifth of the world's electricity generation and more than half of global renewable electricity generation (1). In 2020, hydropower global capacity was 1,335.5 GW, producing 4.48 PWh/year; the largest hydropower capacities were in Asia (569.8 GW), Europe (222.8 GW), and North America (200.6 GW) (59). Under the IEA's STEPS, by the year 2050, hydropower global capacity could be 2,027 GW and could generate 6.81 PWh/year (1).

Studies that focus on the technical potential of hydropower generally define it as the total amount of power that could be created by runoff and stream flow on the basis of elevation. Most studies use a grid cell and bottom-up approach. They use stream flow and runoff data to determine the amount of water flowing in each grid cell and look at the elevation difference, or head, in each grid cell. The most detailed temporal resolution uses the monthly average of the water flow in each grid cell. The technical capacity potential is

$$P = Q\Delta h \rho_{\mathrm{water}} g \eta,$$

where P is power extracted (in watts), Q is flow (in cubic meters per second), Δh is head elevation (in meters), ρ_{water} is the density of water (in kilograms per cubic meter), g is gravitational acceleration (in meters per second squared), and η is efficiency (in percent).

Hydropower estimates span an order of magnitude, from 3.13×10^0 PWh/year (9) to 2.64×10^1 PWh/year (upper bound of Reference 20). The median of all studies is 1.39×10^1 PWh/year,

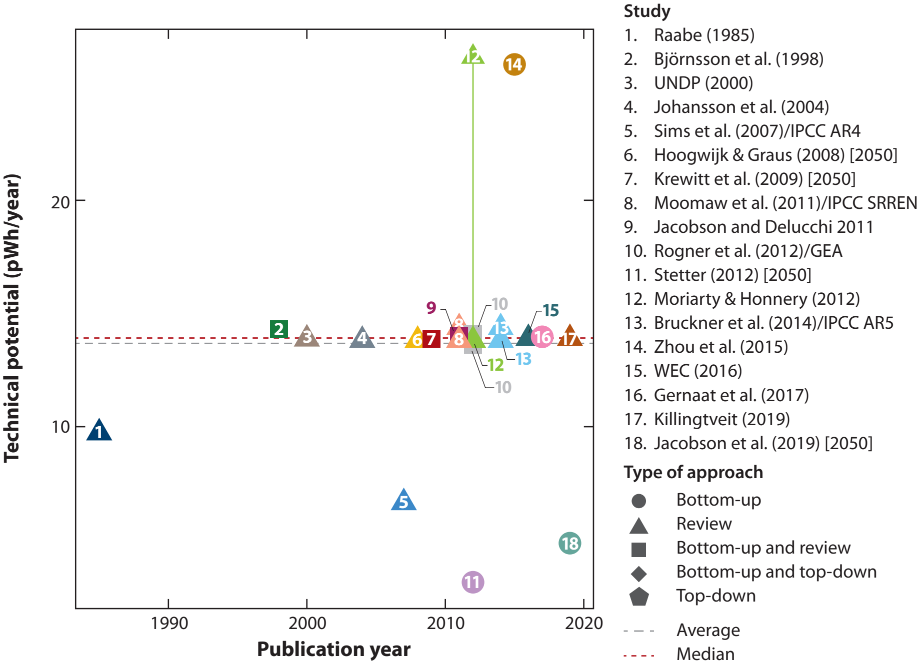


Figure 7

Global hydropower technical potential estimates, in petawatt-hours (PWh) per year, based on year of publication, in a linear scale. Each data point and its color represent a study. When studies report a range, maximum and minimum values are connected by vertical lines. Shapes represent the type of method and approach. The gray and dark red lines represent the average and median across studies, respectively. For papers estimating technical potential for a specific year, the time horizon is in brackets in the legend. Abbreviations: AR, Assessment Report; GEA, Global Energy Assessment; IPCC, Intergovernmental Panel on Climate Change; SRREN, Special Report on Renewable Energy Sources and Climate Change Mitigation.

and the average is 1.37×10^1 PWh/year. Therefore, there is strong agreement across studies for this energy source (**Figure 7**).

Since hydropower is a very well established technology and many of the best, largest, and inexpensive sites are already producing electricity, results across studies are in strong agreement. Therefore, factors explaining the differences are not discussed in descending order of importance as for other technologies. Instead, methods are described separately, with an emphasis on a few of the more robust papers.

In 2020, global electricity generation via hydropower was 4.48×10^0 PWh, which is approximately one-third of the median and mean of hydropower technical potential estimates (59). Hydropower development opportunities still exist in Asia, South America, and Africa (26). The two most robust studies (12, 26), which focus only on hydropower, present methods similar to those used for solar PV or wind estimates. These climate-driven analyses use variables like temperature and precipitation along with runoff and stream flow data sets. Gernaat et al. (26) also optimize the balance between impoundment and diversion canal power plants at each location. Most other studies (2, 5–8, 13, 17, 27, 32, 36, 81) use data from the International Hydropower Association (IHA) and the International Hydropower and Dams World Atlas from the *International Journal on Hydropower and Dams* (IJHD). IJHD data are "based on a disparate range of national government surveys rather than a consistent global methodology" (26, p. 821). Some authors simply use IJHD or IHA numbers, while others add aspects such as a realistic use factor (8).

Throughout the last two decades, the technical potential estimated by the IJHD has remained relatively constant at around 15 to 16 PWh/year. Stetter (9) and Jacobson et al. (54) use different methods. Specifically, Jacobson et al. assume that the currently installed hydropower capacity remains constant but has increased capacity factors in the future, and Stetter uses a top-down method with a river runoff data set that includes both water resources and water uses for industry, irrigation, households, and livestock.

Studies also differ in their data set resolution. Data sets used include WaterGAP 2.1g (9), the Global Water Availability Model (12), GATOR-GCMOM (54), and HydroSHEDS17 (26).

Another factor that differs across studies is efficiency, or the inclusion of an improvement or modernizing factor for existing plants. In fact, older studies often use existing plants as a proxy for the local potential, while climate-driven analyses look at the potential of a water flow without considering already constructed plants. In addition, considering small hydropower, which is what almost all papers do, or considering the effects of dams on the flow regime (the flow exceedance quantile above which hydropower can no longer be exploited) also partly explains the differences between estimates.

6. GEOTHERMAL ELECTRICITY

Geothermal energy uses the heat in Earth's crust, from the deep interior of the planet, to produce electricity or heat (56). We do not review geothermal heat potential here—we limit our assessment to electricity. The use of geothermal energy for electricity production started with the first electric geothermal power plant, built in 1913 in Italy (56). Heat is recovered at greater and greater depths, and different steam cycles (e.g., flash steam, dry steam, or binary cycle in newer plants) are used to produce electricity. Two types of geothermal energy systems exist: conventional geothermal systems (hydrothermal) and enhanced (engineered) geothermal systems (EGS) (14). Conventional systems use heat in specific locations where it can be reached in reservoirs with high fluid and rock permeability, relatively close to the surface (0–3 km deep). EGS are a more recent technological development that use heat stored at much greater depths (down to 10 km) by fracturing reservoirs to increase permeability.

In 2020, global geothermal electric capacity was 14.4 GW, producing 0.10 PWh/year, mostly in Asia (4.5 GW), North America (3.6 GW), and Eurasia (1.7 GW) (59). STEPS has a geothermal electric capacity of 66 GW, with a projected production of 0.46 PWh/year in 2050 (1).

Electric geothermal technical potential is generally defined as the total heat that can be extracted from the earth and turned into electricity in a power plant through a steam cycle. Earlier studies use proxies such as volcanic activity to determine the global geothermal potential (13, 28, 44), whereas more recent ones use assumptions such as efficiency based on the temperature of the resource or the improvement in capacity factor over time (8, 54). The study by Aghahosseini & Breyer (14) is the only one that uses a bottom-up approach similar to those used for other renewables. These authors use a grid cell approach and global data on heat flow, thermal conductivity of rocks, radiogenic heat production, and surface temperature to derive temperature profiles in the first 10 km of the crust all around the globe. To obtain the technical potential, they remove the potential in protected areas, densely populated areas, large lakes and reservoirs, and areas of high water stress.

Geothermal estimates span four orders of magnitude, from 3.06×10^{-1} PWh/year (lower bound of Reference 20) to 1.59×10^{3} PWh/year (14), showing significant disagreement (**Figure 8**). The median of all studies is 1.25×10^{1} PWh/year, and the average is 1.38×10^{1} PWh/year. The study by Aghahosseini & Breyer (14) seems to be an outlier in the order of magnitude reported for geothermal.

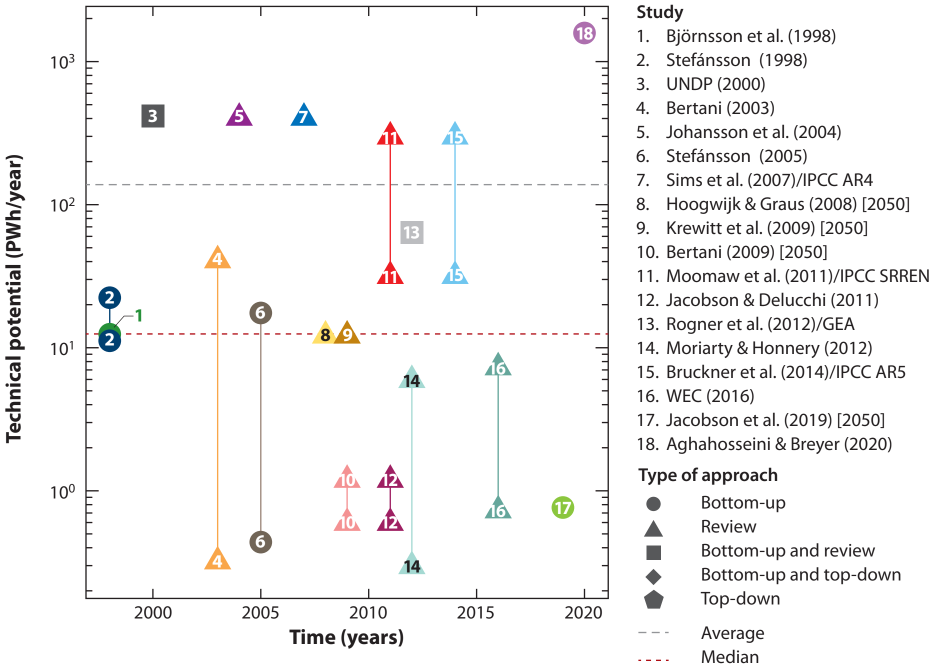


Figure 8

Global electric geothermal technical potential estimates, in petawatt-hours (PWh) per year, based on year of publication, in a logarithmic scale. Each data point and its color represent a study. When studies report a range, maximum and minimum values are connected by vertical lines. Shapes represent the type of method and approach. The gray and dark red lines represent the average and median across studies, respectively. For papers estimating technical potential for a specific year, the time horizon is in brackets in the legend. Abbreviations: AR, Assessment Report; GEA, Global Energy Assessment; IPCC, Intergovernmental Panel on Climate Change; SRREN, Special Report on Renewable Energy Sources and Climate Change Mitigation.

The estimates differ because of the following factors, in our perceived descending order of importance. First, the maximum depth/EGS assumed is the most important factor. If the geothermal resource can be extracted at significant depth, geothermal electricity production could be done virtually anywhere. Older estimates (13, 28, 44) consider only conventional/hydrothermal resources, since at the time EGS were only experimental (56), which explains why their results are lower than those of more recent studies. The UN Development Programme (2; cited in 31, 32) presents a ballpark estimate of geothermal resources that would become economical in 40–50 years, assuming that deeper resources can be reached. Moomaw et al. (7; cited in 17) and Rogner et al. (8) also consider EGS and geothermal heat at significant depths. Aghahosseini & Breyer (14) considers energy at depths up to 10 km. Estimates for resources deeper than 2–3 km are all greater than 10^1 PWh/year.

The second factor is the dynamic component. Stefánsson (44) explains that the “subsurface heat appears in two forms, a) as continuous energy current from the mantle to surface (dynamic) and b) the heat stored in the crust (static).” Since the static component is large, extracting heat at a rate higher than that of the replenishing heat flow would still allow geothermal energy production, but it would need to be treated as a finite resource (44). Björnsson et al. (13) and Stefánsson (28) consider only the static component. Other authors (14) partly account for the dynamic component by applying reservoir temperature drop limits, even though they explicitly apply dynamic component constraints only to their sustainable potential, which is much lower. This is most likely why Aghahosseini & Breyer (14) have much higher results for their technical potential.

The third factor is minimum temperature. Binary turbines enable the production of electricity from rocks at temperatures as low as 100°C. Stefánsson (44) estimates that the total energy stored in rocks at temperatures between 100°C and 150°C is equal to the total energy in rocks at temperatures above 150°C. However, current technologies present very low efficiencies at temperatures around 100–120°C, and this resource is often disregarded. Stefánsson (28, 44) considers temperatures starting at 100°C, while Rogner et al. (8) use temperatures above 120°C and Aghahosseini & Breyer (14) do not consider cases below 150°C.

Fourth, the efficiency of turning heat in the reservoir into electricity also affects results. Older studies assume a constant value (e.g., 44), while more recent ones consider rock temperature–dependent values (8, 14). Finally, other factors, such as the year of the estimate and capacity factors, also explain differences to a small extent.

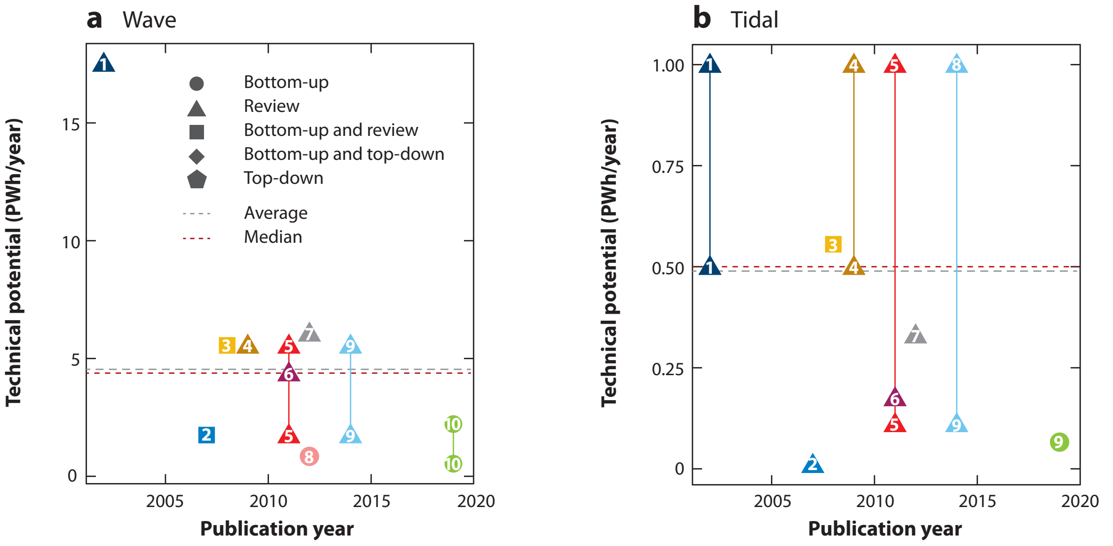
7. ELECTRICITY FROM THE OCEAN

Oceans and seas can offer large amounts of energy in different forms. The four kinds reviewed here are wave, tidal, OTEC, and salinity gradient (osmotic) energy. The first of these uses a wave energy converter to produce electricity from waves' potential and kinetic energies. Tidal energy takes advantage of water tides going back and forth through a turbine to produce electricity. OTEC uses the temperature difference between deep (~1,000 m) oceans and the surface in a heat engine. Salinity gradient uses the difference in salinity where rivers flow into oceans. The first ocean energy technologies were developed in the twentieth century, though waterwheels have been using tidal energy for centuries (82).

In 2020, the combined capacity of all ocean energy technologies amounted to 0.53 GW, producing 0.001 PWh/year, mostly in Asia (0.26 GW) and Europe (0.24 GW) (59). Tidal represented more than 80% of installed capacity, though no new project has been developed for more than 10 years (83). These technologies are at much earlier stages of development than other renewable electricity–producing technologies. STEPS has an ocean energy capacity of 37 GW, forecasting production of 0.10 PWh/year in 2050 (1).

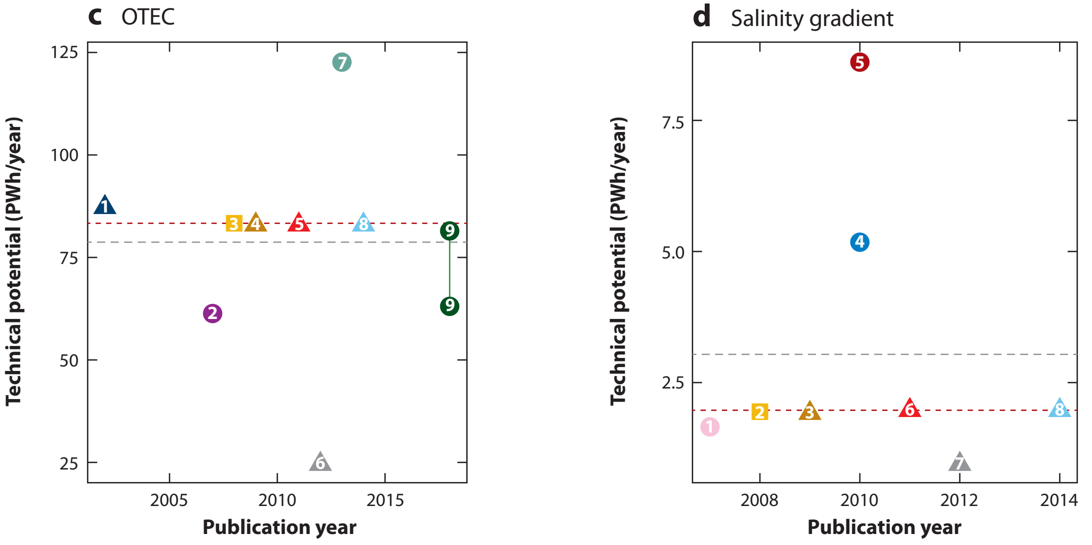
The technical potential for electricity produced with ocean technologies is generally defined as the amount of theoretical energy that could be captured by current or future technologies. Fewer bottom-up approaches using global data have been developed in comparison to those for other renewables. Most of the studies covered in this article refer to previous papers and reviews. Older studies often use theoretical methods to determine theoretical and sometimes technical potentials for different ocean resources (2, 5, 6, 45, 84–86). More recent studies use global data and bottom-up approaches (5, 15, 30, 32, 46–54, 87).

The technical potentials for ocean technologies are as follows. Wave energy technical potential estimates span two orders of magnitude, from 5.34×10^{-1} PWh/year (lower bound of Reference 54) to 1.75×10^{1} PWh/year (45). The median of the studies is 4.04×10^{0} PWh/year, and the average is 4.48×10^{0} PWh/year. Tidal energy technical potential estimates span two orders of magnitude, from 1.00×10^{-2} PWh/year (32) to 1.00×10^{0} PWh/year (upper bound of References 6, 7, 17, and 45). The median of all studies is 5.00×10^{-1} PWh/year, and the average is 4.89×10^{-1} PWh/year. OTEC technical potential estimates span one order of magnitude, from 2.49×10^{1} PWh/year (8) to 1.23×10^{2} PWh/year (52). The median of all studies is 8.33×10^{1} PWh/year, and the average is 7.87×10^{1} PWh/year. Salinity gradient technical potential estimates also span one order of magnitude, from 9.72×10^{-1} PWh/year (8) to 8.61×10^{0} PWh/year (48). The median of all studies is 1.97×10^{0} PWh/year, and the average is 3.04×10^{0} PWh/year (**Figure 9**).



1. Pelc & Fujita (2002)
2. Sims et al. (2007)/IPCC AR4
3. Hoogwijk & Graus (2008) [2050]
4. Krewitt et al. (2009) [2050]
5. Moomaw et al. (2011)/ IPCC SRREN
6. Jacobson & Delucchi (2011)
7. Rogner et al. (2012)/GEA
8. Gunn & Stock-Williams (2012)
9. Bruckner et al. (2014)/IPCC AR5
10. Jacobson et al. (2019) [2050]

1. Pelc & Fujita (2002)
2. Sims et al. (2007)/IPCC AR4
3. Hoogwijk & Graus (2008) [2050]
4. Krewitt et al. (2009) [2050]
5. Moomaw et al. (2011)/IPCC SRREN
6. Jacobson & Delucchi (2011)
7. Rogner et al. (2012)/GEA
8. Bruckner et al. (2014)/IPCC AR5
9. Jacobson et al. (2019) [2050]



1. Pelc & Fujita (2002)
2. Nihous (2007)
3. Hoogwijk & Graus (2008) [2050]
4. Krewitt et al. (2009) [2050]
5. Moomaw et al. (2011)/IPCC SRREN
6. Rogner et al. (2012)/GEA
7. Rajagopalan & Nihous (2013)
8. Bruckner et al. (2014)/IPCC AR5
9. Jia et al. (2018)

1. Skilhagen et al. (2008)
2. Hoogwijk & Graus (2008) [2050]
3. Krewitt et al. (2009) [2050]
4. Stenzel & Wagner (2010)
5. Kuleszo et al. (2010)
6. Moomaw et al. (2011)/IPCC SRREN
7. Rogner et al. (2012)/GEA
8. Bruckner et al. (2014)/IPCC AR5

(Caption appears on following page)

Figure 9 (*Figure appears on preceding page*)

Global wave (*a*), tidal (*b*), OTEC (*c*), and salinity gradient (*d*) technical potential estimates, in petawatt-hours (PWh) per year, based on year of publication, in a linear scale. Each data point and its color represent a study. When studies report a range, maximum and minimum values are connected by vertical lines. Shapes represent the type of method and approach. The gray and dark red lines represent the average and median across studies, respectively. For papers estimating technical potential for a specific year, the time horizon is in brackets in the legend. Abbreviations: AR, Assessment Report; GEA, Global Energy Assessment; IPCC, Intergovernmental Panel on Climate Change; OTEC, ocean thermal energy conversion; SRREN, Special Report on Renewable Energy Sources and Climate Change Mitigation.

Due to the small number of studies, the order of importance of factors explaining differences cannot be accurately determined. Instead, we discuss papers and methods, and the main factors of differences for each technology in no specific order.

For wave energy, an often-cited value is 2 TW or 1–10 TW, which "come[s] from derivation pioneered by Kinsman [88, pp. 150–54], who comments openly on the lack of rigour in his methods, which are essentially inspired guesswork" (49, p. 296). In addition, most results found in the literature are for theoretical and not technical potentials (2, 45, 84, 87). The only studies that estimate technical potentials for wave energy (32, 49, 54) use wave power data from various sources, exclude icy and protected areas, consider areas above a minimum amount of resource, apply technological efficiencies, and consider the device capture front (comparable to the spacing factor for solar technologies). The lack of original estimates precludes a clear understanding of the sources of differences. The main inputs and factors explaining differences are data sets, the capture front/width considered, methods of calculating coastline length, the minimum amount of resource considered, capacity factors, and efficiencies.

For tidal energy, two early studies by Marchuk & Kagan (85) and Munk & Wunsch (86) determined theoretical potentials. The literature often mentions $0.50–1.00 \times 10^0$ PWh/year as the technical potential of tidal energy, and the source cited (45) is a review. This review cites Hammons (89), who in turn cites Baker (90). These values cannot be found in Baker's paper (90), which focuses on specific sites located mainly in Europe. Hammons (89) might have extrapolated Baker's method to determine the global potential, but it is not explained or described in detail. The study by Jacobson et al. (54) is the only recent study that uses its own methodology, based on an earlier paper by the same authors (57). They use data that "provide[] estimates of the technical potential for tidal power in 28 countries with relatively favorable conditions" (p. 93 of supplemental information from 57). They then estimate the technical potential for other countries on the basis of coastline length and use a nonlinear function with experimentally determined parameters that seem to create "reasonable results" (54). Jacobson et al. find a technical potential of 0.1 PWh/year. The lack of original estimates precludes a clear understanding of the sources of differences. Data sets and methods are the main differences between studies.

For OTEC, older studies (91, 92) either estimate potential with limited description of their methods and assumptions or cite earlier literature. Nihous (46, 47), Rajagopalan & Nihous (50–52), and Jia et al. (53) perform original estimates by considering regions where the temperature difference between the surface and 1,000 m depth was more than 18°C or 20°C and by taking the technology's efficiency into account. Building on an earlier study (46), Nihous (47) assumes a 1D water column from surface to seafloor and ignores horizontal transport into and out of the water column. Nihous (47) also considers temperature disruptions in the vertical water column to make sure that the resource is truly renewable (analogous to the static versus dynamic component of the geothermal resource) and assumes that the deep cold water is the limiting flow in the system (in Reference 46 it was assumed to be the warm surface water). The two studies by Nihous (46, 47) find a technical potential of ~3 TW and ~7 TW, respectively.

Rajagopalan & Nihous (50–52) reviewed this method and used an oceanic general circulation model for the first time to estimate the technical potential of OTEC. They accounted for horizontal transport and realized that it slows down the "local erosion of the water column's thermal stratification as OTEC flow intensity increases" (51). The difference between their three studies is that the third (52) accounts for higher spatial resolution and geographical constraints, such as distance from shore. Their second study (51) does not consider geographical limits, and the first (50) uses a low spatial resolution. These authors find 30 TW (50), 14 TW (51), and 12–14 TW (52). The first two results differ significantly because the maximum potential depends on temperature difference and flow intensity. Higher resolution allows for more accurate temperature feedback (how accurately the temperature difference changes, depending on flow intensity). Temperature difference changes are minimized at lower flow intensity with higher resolution, so even though temperature differences remain more constant in the 1° × 1° model, flow intensity decreases more, leading to a smaller technical potential (51).

Two of the studies by Nihous (47) and Rajagopalan & Nihous (52) built on and were published soon after Reference 46 and References 50 and 51, respectively; therefore, we do not represent the latter three references (46, 50, 51) in the figures. Jia et al. (53) add to the method proposed earlier (52) by adding ocean–atmospheric interactions, such as long-wave radiation and horizontal atmospheric transport. This study obtained values of 7.2–9.3 TW. The small number of original estimates makes it difficult to determine an accurate technical potential. The dynamic component and how it is considered (e.g., 1D model, horizontal transport, ocean–atmospheric exchanges), geographical constraints, and limiting flow primarily explain the differences in results.

Regarding salinity gradient, only a few studies (5, 8, 15, 30, 48) obtain a technical potential. Skilhagen et al. (30) do not explain their method; they simply state that the exploitation potential as 1.66 PWh/year. Both Stenzel & Wagner (15) and Kuleszo et al. (48, summarizing 93) perform an analysis based on global data using a bottom-up approach. They look at seawater and freshwater temperature and salinity, river discharge, and other parameters, and they account for technical specifications such as efficiencies. Both Hoogwijk & Graus (5, p. 32) and Rogner et al. (8, p. 503) use similar, simple methods, stating that "the global discharge of fresh water to seas is about 44.500 km^3 per year," and then use simple assumptions. Hoogwijk & Graus (5, p. 32) assume that "20% of this discharge can be used for osmotic power." Rogner et al. (8) explain that there is a potential energy of 2.35 $MJ/(m^3{\cdot}s)$ in this discharge and, therefore, that 105 EJ/year (∼29.2 PWh/year) could theoretically be extracted. They assume that 10% of this theoretical potential is technically feasible. Again, there are too few original estimates, and it is difficult to determine the sources of the differences. Methods and efficiencies are currently the main assumed sources of differences.

8. ECONOMIC AND FEASIBLE POTENTIAL

Economic potential is defined consistently across the literature (2–5, 8–10, 12–14, 16, 24, 26, 28) as the amount of the technical potential that can be produced below a certain cost. The cost thresholds vary across studies. Costs are typically represented by the levelized cost of electricity (LCOE) of a grid cell, which is calculated by dividing annualized costs by the electricity produced. Annualized costs include the capital costs of installed capacity (i.e., the initial cost of building, installing, and financing) as well as operation and maintenance costs. The capital costs are annualized using an annuity factor or capital recovery factor (CRF),

$$\mathrm{LCOE} = \frac{\mathrm{CRF} \times I + O}{E},$$

where LCOE is in dollars per kilowatt hour, I is the investment cost (in US dollars or euros, depending on the study), O refers to operation and maintenance costs (in dollars or euros per year), and E is the electricity produced (in kilowatt-hours per year). CRF is defined as follows:

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1},$$

where i is the discount rate and n is the number of years for which the technology will be operating.

Other similar metrics, such as dividing the net present value of the costs by the discounted electricity generation, are also used. This approach and the one described in the equation above will lead to slightly different results.

The discount/interest rates used in these studies range between 6% and 12.5%. While the lifetime varies among technologies, studies tend to agree within each respective technology. The dollar values reported pertain to different years, and the capital cost assumptions are highly dependent on the year of analysis. Investment costs of renewables have drastically decreased over the last two decades, especially for solar PV (69), so earlier estimates are quite outdated.

Supplemental Material >

Some differences between economic potentials come from the numbers used for specific investment costs, operation and maintenance costs, discount/interest rates, and technology lifetimes. However, these tend to be relatively similar between studies. Most differences in economic potential arise from the original differences in technical potential, since studies use the technical potential as the energy produced in the cost of energy calculations. Because most of these costs and technical potentials are fairly outdated, we do not include figures showing these results here but rather summarize the findings and figures in **Supplemental Table 10** and **Supplemental Figures 1–3**. The Sixth Assessment Report of the IPCC does provide some estimates of potential for different electricity generation technologies and sources at different price points (see figure TS.23 of Reference 94).

The Sixth Assessment Report chapter on energy systems (69) provides recent estimates of current LCOEs for different technologies: 1.94–16.30 ¢/kWh for utility-scale solar PV, 4.14–23.60 ¢/kWh for rooftop PV, 4.62–15.60 ¢/kWh for CSP, 2.60–7.08 ¢/kWh for onshore wind, 5.04–19.10 ¢/kWh for offshore wind, 2.01–33.1 ¢/kWh for hydropower, and 4.53–38.18 ¢/kWh for geothermal electricity (all amounts are in 2020 US dollars). Another recent study (83) shows that for ocean-based electricity generation the LCOEs are 30–55 ¢/kWh for wave electricity (83) and 20–45 ¢/kWh for tidal (83). The same study also finds that OTEC and salinity gradient energy are not yet mature enough and do not yet have representative LCOEs (83).

While some studies do not calculate the economic potential, they provide results that are a good proxy for this potential. For example, Zhou et al. (24) state that for onshore wind, a capacity factor of 30% represents a cost of 11 ¢/kWh, establishing a relationship between resource quality and cost. Eurek et al. (19), Arent et al. (23), and Jacobson et al. (54) provide capacity factor categories but do not convert them into equivalent economic potentials. In addition, Bosch et al. (18, 25) provide the technical potential for the best 25% of the resource area. In another approach, Dupont et al. (33, 34) analyze the energy return on investment (EROI); these authors look at the energy required to produce, install, and retire solar or wind technologies and compare it with the energy produced by these technologies over their lifetimes. This procedure results in technical potential per EROI threshold; an EROI of 3 means that the technology produces twice as much energy as it requires. A certain EROI could also represent an economic threshold.

Finally, some studies venture to estimate a feasible potential. Feasible potential is often defined differently across studies, for example, as "realistic or constrained technical," "realizable," "market," "ecological," "practical," "exploitable," "implementation," "remaining economic potential," or "sustainable" potential. The definitions of this potential usually incorporates features such as social and institutional dynamics, policies, ecological constraints, land competition, fuel competition, and a time frame. Other studies use scenarios, and the contribution of each renewable to the results could also be considered a feasible potential. The only two studies that perform this analysis on a global scale for utility-scale PV are those by de Castro et al. (95) and Deng et al. (96); the latter is the only one for rooftop PV, CSP, onshore wind, and offshore wind. Studies by Zhou et al. (12), Björnsson et al. (13), Gernaat et al. (26), and Deng et al. (96) estimate a potential similar to feasible for hydropower. Aghahosseini & Breyer (14) and Deng et al. (96) do the same for geothermal, as do Stenzel & Wagner (15) for salinity gradient (see **Supplemental Figure 4** and **Supplemental Table 11**).

Supplemental Material >

Deng et al. (96) are the only authors to perform this analysis across different technologies. However, they qualify their results as a "realistic or constrained technical potential" that includes "acceptance, cost, competition with other uses or remoteness." Other studies (e.g., 15, 95) do not consider the economic aspect of the resource.

9. CONCLUSION

Table 2 shows the technical potential for each of the energy sources and technologies based on this review. Technical potentials for utility-scale solar PV, CSP, onshore wind, offshore wind, and potentially geothermal and OTEC are larger than the projected electricity demand in 2050 of 43.7 PWh/year according to STEPS or 62.2 PWh/year according to the NZE scenario (1).

The differences between results for each technology are due mostly to the following factors:

- Utility-scale solar PV: land type suitability factors or available area, spacing, panel angles, data set temporal and spatial resolution, and conversion efficiencies.
- Rooftop solar PV: methods, conversion efficiencies, panel angles, data set temporal and spatial resolution, and spacing.
- CSP: storage, suitability factors, conversion efficiencies, ratios of covered area to ground area, power density versus irradiance data, minimum irradiation, and data set temporal and spatial resolution.
- Onshore wind: spatial and temporal resolution of wind speed data, measurement height, hub height, power density, capacity factors, minimum amount of resource, methods, turbine size, and time horizon.

Table 2 Technical potential for each technology based on this review

Technology	Technical potential (PWh/year)
Utility-scale solar PV	>100
Rooftop solar PV	>10
CSP	>100
Onshore wind	>100
Offshore wind	>100
Hydropower	>10
Geothermal	>10 (or more if EGS is considered)
Wave	>1
Tidal	>1
OTEC	>10
Salinity gradient	>0.1

Abbreviations: CSP, concentrated solar power; EGS, enhanced (engineered) geothermal systems; OTEC, ocean thermal energy conversion; PV, photovoltaics.

- Offshore wind: maximum depth (fixed-bottom only versus fixed-bottom and floating), distance from shore, power density, capacity factors, minimum amount of resource, methods, turbine size, data sets, measurement height, hub height, and losses.
- Hydropower: data sets and spatial resolution.
- Geothermal: maximum depth (EGS included or not), dynamic components, minimum temperature, and efficiencies.
- Wave: data sets, capture front/width, coastline length, minimum amount of resource, capacity factors, and efficiencies.
- Tidal: data sets and methods.
- OTEC: dynamic component, energy transport (1D models, horizontal transport, ocean–atmospheric exchanges, etc.), geographical constraints, and limiting flow.
- Salinity gradient: methods and efficiencies.

In the future, estimates of potential for renewable electricity can make use of new and more detailed data on localized and temporally specific resources and exclusion factors, as well as updated technology specifications and costs. In addition to this more traditional approach, researchers should consider novel challenges associated with large-scale integration of renewable resources. These include how to cope with variability and intermittency, investments in long-distance transmission, mineral scarcity, the need for flexible generation or storage that has fast ramping capability, the need for other services such as frequency and inertia, and how electricity-generating technologies will need to operate under specific market designs. Although these parameters are complicated to account for on a global scale, researchers have moved toward such modeling approaches under the net-zero and low-carbon electricity scenarios. Such literature is only now emerging.

SUMMARY POINTS

1. The technical and economic potential of renewable energies is much larger than the predicted 2050 electricity demand (both STEPS and NZE scenarios).
2. The range of estimates for each renewable's technical potential is very large and comes from differences of assumptions and data used from one study to another. Understanding where exactly most of the differences come from is quite challenging.
3. Individually, each of utility-scale solar PV, CSP, onshore wind, and offshore wind have larger technical potentials than the STEPS or NZE 2050 electricity demand.
4. Hydropower is the renewable technology that has proportionally tapped the most of its technical potential (approximately 1/3). More potential exists in certain regions, but its technical potential could not power the whole world in 2050. In addition, this resource is expected to be more impacted by climate change than others due to the rise in temperature and the increase in frequency of extreme events such as droughts or floods.
5. Geothermal technical potential could be larger than the electricity demand in 2050 (both STEPS and NZE scenarios) if EGS became viable. If not, it still has a technical potential on the same order of magnitude as hydropower.
6. Wave, tidal, and salinity gradient have smaller technical potentials, but each could play a role locally. OTEC has a large technical potential but is not mature enough to understand its economic or feasible potential.

7. Economic potential analyses on a global scale are complicated and usually do not capture all aspects of renewable deployment, such as coping with variability and intermittency, transmission constraints, and mineral scarcity.
8. There are few feasible potential studies, and incorporating social and environmental constraints is quite challenging. It seems that such studies have been replaced by modeling under certain scenarios of development.

FUTURE ISSUES

1. Most technical potential estimates are based on outdated data, and future studies could make use of newer, more accurate data sets.
2. Economic potential studies might try to incorporate more aspects of renewable energy use, such as transmission or storage.
3. Feasible potential estimations are extremely hard to perform on a global scale, where societal and environmental specifications vary from one region to another. Performing such analyses on a more granular scale and then aggregating over the whole world could produce more accurate results, though this would be complicated to accomplish.
4. Researchers have moved toward modeling under scenarios of development that might represent a new definition of feasible potential.
5. The amount of resource and technical potential is much larger than what humanity needs. Future research needs to focus on how to access this potential in a just, environmentally friendly, equitable, and economically viable way.

DISCLOSURE STATEMENT

Jonathan Huster is an employee at Ascend Analytics. The other authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

LITERATURE CITED

1. IEA (Int. Energy Agency). 2022. *World Energy Outlook 2022*. Paris: IEA
2. UNDP (UN Dev. Progr.). 2000. *Energy and the Challenge of Sustainability*. New York: UNDP
3. Hoogwijk M, de Vries B, Turkenburg W. 2004. Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. *Energy Econ.* 26(5):889–919
4. de Vries BJM, Hoogwijk MM. 2007. Renewable energy sources: their global potential for the first half of the 21st century at a global level: an integrated approach. *Energy Policy* 35(4):2590–610
5. Hoogwijk M, Graus W. 2008. *Global potential of renewable energy sources: a literature assessment*. Backgr. Rep., Ecofys, Utrecht, Neth.
6. Krewitt W, Nienhaus K, Kleßmann C, Capone C, Stricker E, et al. 2009. *Role and potential of renewable energy and energy efficiency for global energy supply*. Rep. 18/2009, Fed. Environ. Agency, Dessau-Roßlau, Ger.
7. Moomaw W, Yamba F, Kamimoto M, Maurice L, Nyboer J, et al. 2011. Renewable energy and climate change. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, ed. O Edenhofer, R Pichs-Madruga, Y Sokona, K Seyboth, P Matschoss, et al., pp. 161–208. Cambridge, UK/New York: Cambridge Univ. Press

8. Rogner H-H, Aguilera RF, Archer C, Bertani R, Bhattacharya SC, et al. 2012. Energy resources and potentials. In *Global Energy Assessment: Toward a Sustainable Future*, ed. TB Johanssen, A Patwardhan, N Nakicenovic, L Gomez-Echeverri, pp. 423–512. Cambridge, UK/Laxenburg, Austria: Cambridge Univ. Press/Int. Inst. Appl. Syst. Anal.
9. Stetter D. 2012. *Enhancement of the REMix energy system model: global renewable energy potentials, optimized power plant siting and scenario validation*. PhD Thesis, Univ. Stuttgart, Stuttgart, Ger.
10. Köberle AC, Gernaat DEHJ, van Vuuren DP. 2015. Assessing current and future techno-economic potential of concentrated solar power and photovoltaic electricity generation. *Energy* 89:739–56
11. Raabe J. 1985. *Hydro Power*. Düsseldorf, Ger.: VDI
12. Zhou Y, Hejazi M, Smith S, Edmonds J, Li H, et al. 2015. A comprehensive view of global potential for hydro-generated electricity. *Energy Environ. Sci.* 8:2622–33
13. Björnsson J, Fridleifsson B, Helgason T, Jonatansson H, Mariusson J, et al. 1998. The potential role of geothermal energy and hydropower in the world energy scenario in year 2020. In *Proceedings of the 17th Congress of the World Energy Council*, Vol. 5, pp. 69–87. London: World Energy Counc.
14. Aghahosseini A, Breyer C. 2020. From hot rock to useful energy: a global estimate of enhanced geothermal systems potential. *Appl. Energy* 279:115769
15. Stenzel P, Wagner H. 2010. Osmotic power plants: potential analysis and site criteria. In *Proceedings of the 3rd International Conference on Ocean Energy*, pp. 1–5. Lisbon: Ocean Energy Syst.
16. Korfiaty A, Gkonos C, Veronesi F, Gaki A, Grassi S. 2016. Estimation of the global solar energy potential and photovoltaic cost with the use of open data. *Int. J. Sustain. Energy Plan. Manag.* 9:17–30
17. Bruckner T, Bashmakov IA, Mulugetta Y, Chum H, de la Vega Navarro A, et al. 2014. Energy systems. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the 5th Assessment Report of the Intergovernmental Panel on Climate Change*, ed. O Edenhofer, R Pichs-Madruga, Y Sokona, E Farahani, S Kadner, et al., pp. 511–97. Cambridge, UK/New York: Cambridge Univ. Press
18. Bosch J, Staffell I, Hawkes AD. 2017. Temporally-explicit and spatially-resolved global onshore wind energy potentials. *Energy* 131:207–17
19. Eurek K, Sullivan P, Gleason M, Hettinger D, Heimiller D, Lopez A. 2017. An improved global wind resource estimate for integrated assessment models. *Energy Econ.* 64:552–67
20. Moriarty P, Honnery D. 2012. What is the global potential for renewable energy? *Renew. Sustain. Energy Rev.* 16:244–52
21. Trieb F, Schillings C, O'Sullivan M, Pregger T, Hoyer-Klick C. 2009. *Global potential of concentrating solar power*. Paper presented at 15th SolarPACES Conference, Berlin, Sept. 15–18
22. Lu X, McElroy MB, Kiviluoma J. 2009. Global potential for wind-generated electricity. *PNAS* 106(27):10933–38
23. Arent D, Sullivan P, Heimiller D, Lopez A, Eurek K, et al. 2012. *Improved offshore wind resource assessment in global climate stabilization scenarios*. Tech. Rep. NREL/TP-6A20-55049, Natl. Renew. Energy Lab., Washington, DC
24. Zhou Y, Luckow P, Smith SJ, Clarke L. 2012. Evaluation of global onshore wind energy potential and generation costs. *Environ. Sci. Technol.* 46:7857–64
25. Bosch J, Staffell I, Hawkes AD. 2018. Temporally explicit and spatially resolved global offshore wind energy potentials. *Energy* 163:766–81
26. Gernaat DEHJ, Bogaart PW, van Vuuren DP, Biemans H, Niessink R. 2017. High-resolution assessment of global technical and economic hydropower potential. *Nat. Energy* 2:821–28
27. Killingtveit Å. 2019. Hydropower. In *Managing Global Warming: An Interface of Technology and Human Issues*, ed. TM Letcher, pp. 265–315. San Diego, CA: Academic
28. Stefánsson V. 1998. Estimate of the world geothermal potential. In *Proceedings of the 20th Anniversary Workshop of the United Nations University Geothermal Training Programme*, pp. 111–21. Reykjavik: U. N. Univ.
29. Bertani R. 2003. What is geothermal potential? *IGA News* 53:1–3
30. Skilhagen SE, Dugstad JE, Aaberg RJ. 2008. Osmotic power—power production based on the osmotic pressure difference between waters with varying salt gradients. *Desalination* 220(1–3):476–82

31. Johansson TB, McCormick NL, Turkenburg W. 2004. *The potentials of renewable energy*. Themat. Backgr. Pap., Int. Conf. Renew. Energ., Bonn, Ger. **https://ren21.net/Portals/0/documents/irecs/renew2004/The%20Potentials%20of%20Renewable%20Energy.pdf**
32. Sims REH, Schock RN, Adegbululgbe A, Fenhann J, Konstantinaviciute I, et al. 2007. Energy supply. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the 4th Assessment Report of the Intergovernmental Panel on Climate Change*, ed. B Metz, OR Davidson, PR Bosch, R Dave, LA Meyer, pp. 251–322. Cambridge, UK/New York: Cambridge Univ. Press
33. Dupont E, Koppelaar R, Jeanmart H. 2020. Global available solar energy under physical and energy return on investment constraints. *Appl. Energy* 257:113968
34. Dupont E, Koppelaar R, Jeanmart H. 2018. Global available wind energy with physical and energy return on investment constraints. *Appl. Energy* 209:322–38
35. Archer CL, Jacobson MZ. 2005. Evaluation of global wind power. *J. Geophys. Res.* 110:D12110
36. Jacobson MZ, Delucchi MA. 2011. Providing all global energy with wind, water, and solar power. Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy* 39(3):1154–69
37. Capps SB, Zender CS. 2010. Estimated global ocean wind power potential from QuikSCAT observations, accounting for turbine characteristics and siting. *J. Geophys. Res.* 115:D09101
38. de Castro C, Mediavilla M, Miguel LJ, Frechoso F. 2011. Global wind power potential: physical and technological limits. *Energy Policy* 39(10):6677–82
39. Miller LM, Gans F, Kleidon A. 2011. Estimating maximum global land surface wind power extractability and associated climatic consequences. *Earth Syst. Dyn.* 2:1–12
40. Jacobson MZ, Archer CL. 2012. Saturation wind power potential and its implications for wind energy. *PNAS* 109:15679–84
41. Miller LM, Kleidon A. 2016. Wind speed reductions by large-scale wind turbine deployments lower turbine efficiencies and set low generation limits. *PNAS* 113(48):13570–75
42. Ivanescu C, Fox R. 2021. *Global offshore wind technical potential*. Data Set, World Bank, Washington, DC. **https://datacatalog.worldbank.org/search/dataset/0037787/Global-Offshore-Wind-Technical-Potential**
43. Kleidon A. 2021. Physical limits of wind energy within the atmosphere and its use as renewable energy: from the theoretical basis to practical implications. arXiv:2010.00982 [physics.ao-ph]
44. Stefánsson V. 2005. *World geothermal assessment*. Paper presented at World Geothermal Conference 2005, Antalya, Turk., Apr. 24–29
45. Pelc R, Fujita RM. 2002. Renewable energy from the ocean. *Mar. Policy* 26:471–79
46. Nihous G. 2005. An order-of-magnitude estimate of ocean thermal energy conversion resources. *J. Energy Resour. Technol.* 127(4):328–33
47. Nihous G. 2007. A preliminary assessment of ocean thermal energy conversion resources. *J. Energy Resour. Technol.* 129(1):10–17
48. Kuleszo J, Kroeze C, Post J, Fekete BM. 2010. The potential of blue energy for reducing emissions of CO_2 and non-CO_2 greenhouse gases. *J. Integr. Environ. Sci.* 7(Suppl. 1):89–96
49. Gunn K, Stock-Williams C. 2012. Quantifying the global wave power resource. *Renew. Energy* 44:296–304
50. Rajagopalan K, Nihous G. 2013. Estimates of global ocean thermal energy conversion (OTEC) resources using an ocean general circulation model. *Renew. Energy* 50:532–40
51. Rajagopalan K, Nihous G. 2013. An assessment of global ocean thermal energy conversion resources with a high-resolution ocean general circulation model. *J. Energy Resour. Technol.* 135:041202
52. Rajagopalan K, Nihous GC. 2013. An assessment of global ocean thermal energy conversion resources under broad geographical constraints. *J. Renew. Sustain. Energy* 5:063124
53. Jia Y, Nihous G, Rajagopalan K. 2018. An evaluation of the large-scale implementation of ocean thermal energy conversion (OTEC) using an ocean general circulation model with low-complexity atmospheric feedback effects. *J. Mar. Sci. Eng.* 6:12
54. Jacobson MZ, Delucchi MA, Cameron MA, Coughlin SJ, Hay CA, et al. 2019. Impacts of Green New Deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries. *ONE Earth* 1(4):449–63
55. Hossain J. 2014. *World wind resource assessment report*. Tech. Rep., World Wind Energy Assoc., Bonn. Ger.

56. Bertani R. 2009. *Geothermal energy: an overview on resources and potential*. Paper presented at International Geothermal Days: Slovakia 2009 Conference and Summer School, Častá Papiernička, Slovak., May 26–29
57. Jacobson MZ, Delucchi MA, Bauer ZAF, Goodman SC, Chapman WE, et al. 2017. 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world. *Joule* 1:108–21
58. AE Solar. 2022. *History and development of photovoltaics*. Fact Sheet, AE Solar, Koenigsbrunn, Ger. **https://ae-solar.com/history-of-solar-module/#:∼:text=Solar%20Energy%20in%20the%201900's,an%20efficiency%20of%204%25%20only**
59. IRENA (Int. Renew. Energy Agency). 2022. *Renewable Energy Statistics 2022*. Abu Dhabi: IRENA
60. Sahu A, Yadav N, Sudhakar K. 2016. Floating photovoltaic power plant: a review. *Renew. Sustain. Energy Rev.* 66:815–24
61. Dinesh H, Pearce JM. 2016. The potential of agrivoltaic systems. *Renew. Sustain. Energy Rev.* 54:299–308
62. Alsema E, van Brummelen M. 1993. *Het potentieel van PV-systemen in OECD landen*. Rep., Utrecht Univ., Utrecht, Neth. (in Dutch)
63. IEA (Int. Energy Agency). 2001. *Potential for building integrated photovoltaics*. Rep. PVPS T7-4, IEA, Paris
64. Melius J, Margolis R, Ong S. 2013. *Estimating rooftop suitability for PV: a review of methods, patents, and validation techniques*. Tech. Rep. NREL/TP-6A20-60593, Natl. Renew. Energy Lab., Washington, DC
65. Aalborg CSP. 2022. *History of concentrated solar power (CSP)*. Fact Sheet, Aalborg CSP, Aalborg, Den. **https://www.aalborgcsp.com/business-areas/solar-district-heating/csp-parabolic-troughs/history-of-csp**
66. NREL (Natl. Renew. Energy Lab.). 2022. *Concentrated solar power basics*. Fact Sheet, NREL, Washington, DC. **https://www.nrel.gov/research/re-csp.html**
67. EIA (Energy Inf. Adm.). 2022. *Wind explained: history of wind power*. Fact Sheet, EIA, Washington, DC. **https://www.eia.gov/energyexplained/wind/history-of-wind-power.php**
68. IRENA (Int. Renew. Energy Agency). 2022. *Wind energy*. Fact Sheet, IRENA, Abu Dhabi. **https://www.irena.org/Energy-Transition/Technology/Wind-energy**
69. Clarke L, Wei Y-M, de la Vega Navarro A, Garg A, Hahmann AN, et al. 2022. Energy systems. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the 6th Assessment Report of the Intergovernmental Panel on Climate Change*, ed. PR Shukla, J Skea, R Slade, A Al Khourdajie, R van Diemen, et al., pp. 613–746. Cambridge, UK/New York: Cambridge Univ. Press
70. Hahmann AN, García-Santiago O, Peña A. 2022. Current and future wind energy resources in the North Sea according to CMIP6. *Wind Energy Sci.* 7:2373–91
71. Volker PJH, Hahmann AN, Badger J, Jørgensen HE. 2017. Prospects for generating electricity by large onshore and offshore wind farms. *Environ. Res. Lett.* 12:034022
72. Ørsted. *Making green energy affordable*. White Pap., Ørsted, Fredericia, Den. **https://orsted.com/en/about-us/whitepapers/making-green-energy-affordable/1991-to-2001-the-first-offshore-wind-farms**
73. Díaz H, Soares CG. 2020. Review of the current status, technology and future trends of offshore wind farms. *Ocean Eng*. 209:107381
74. Ørsted. *Hornsea 2*. Fact Sheet, Ørsted, Fredericia, Den. **https://hornseaprojects.co.uk/hornsea-project-two**
75. Ørsted. 2020. *Hornsea Project Two offshore wind farm safety zone application*. Doc. 037767092, Ørsted, Fredericia, Den. **https://orstedcdn.azureedge.net/-/media/www/docs/corp/uk/hornsea-project-two/how02offex-safety-zone-application-03767092a.pdf?rev=1952f1fa61904a7eba9e30abcc5a4e28&hash=A640A9DCCB9F1ABA07A229035B884D08**
76. Principle Power. 2022. *Kincardine offshore wind farm*. Fact Sheet, Principle Power, Emeryville, CA. **https://www.principlepower.com/projects/kincardine-offshore-wind-farm**
77. T&D World. 2021. Floating offshore wind farm linked to Scotland's power grid. *T&D World Blog*, Oct. 19. **https://www.tdworld.com/distributed-energy-resources/article/21178796/floating-offshore-wind-farmlinked-to-scotlands-power-grid**
78. Mathern A, von der Haar C, Marx S. 2021. Concrete support structures for offshore wind turbines: current status, challenges, and future trends. *Energies* 14:1995

79. Nunez C. 2019. Hydropower, explained. *National Geographic*, May 13. **https://www.nationalgeographic.com/environment/article/hydropower**
80. US Dep. Energy. 2022. *Types of hydropower plants*. Fact Sheet, Off. Energy Effic. Renew. Energy, US Dep. Energy, Washington, DC. **https://www.energy.gov/eere/water/types-hydropower-plants**
81. WEC (World Energy Counc.). 2016. *World energy resources—waste to energy*. Rep., WEC, London. **https://www.worldenergy.org/assets/images/imported/2016/10/World-Energy-Resources-Full-report-2016.10.03.pdf**
82. Leary D, Esteban M. 2009. How things work: ocean energy making waves. *Our World Blog*, Oct. 5. **https://ourworld.unu.edu/en/ocean-energy-making-waves**
83. IRENA (Int. Renew. Energy Agency). 2020. *Innovation Outlook: Ocean Energy Technologies*. Abu Dhabi: IRENA
84. Panicker NN. 1976. Power resource estimate of ocean surface waves. *Ocean Eng.* 3(6):429–39
85. Marchuk GI, Kagan BA. 1989. *Dynamics of Ocean Tides*. Dordrecht, Neth.: Kluwer Acad.
86. Munk W, Wunsch C. 1998. Abyssal recipes II: energetics of tidal and wind mixing. *Deep-Sea Res. I* 45(12):1977–2010
87. Mørk G, Barstow S, Kabuth A, Pontes MT. 2010. Assessing the global wave energy potential. In *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering*, Vol. 3, pp. 447–54. New York: Am. Soc. Mech. Eng.
88. Kinsman B. 1965. *Wind Waves*. Hoboken, NJ: Prentice Hall
89. Hammons TJ. 1993. Tidal power. *Proc. IEEE* 89(3):419–33
90. Baker AC. 1986. The development of functions relating cost and performance of tidal power schemes and their application to small-scale sites. In *Tidal Power*, ed. AC Baker, pp. 331–44. London: Telford
91. Avery WH, Wu C. 1994. *Renewable Energy from the Ocean: A Guide to OTEC*. New York: Oxford Univ. Press
92. Daniel T. 2000. Ocean thermal energy conversion: an extensive, environmentally benign source of energy for the future. *Sustain. Dev. Int.* 3:121–25
93. Kuleszo J. 2008. *The global and regional potential of salinity-gradient power*. MSc Thesis, Wageningen Univ., Wageningen, Neth.
94. Pathak M, Slade R, Shukla PR, Skea J, Pichs-Madruga R, Ürge-Vorsatz D. 2022. Technical summary. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the 6th Assessment Report of the Intergovernmental Panel on Climate Change*, ed. PR Shukla, J Skea, R Slade, A Al Khourdajie, R van Diemen, et al., pp. 51–147. Cambridge, UK/New York: Cambridge Univ. Press
95. de Castro C, Mediavilla M, Miguel LJ, Frechoso F. 2013. Global solar electric potential: a review of their technical and sustainable limits. *Renew. Sustain. Energy Rev.* 28:824–35
96. Deng YY, Haigh M, Pouwels W, Ramaekers L, Brandsma R, et al. 2015. Quantifying a realistic, worldwide wind and solar electricity supply. *Glob. Environ. Change* 31:239252

Annual Review of Environment and Resources
Volume 48, 2023

Contents

I. Integrative Themes and Emerging Concerns

II. Earth's Life Support Systems

III. Human Use of the Environment and Resources

IV. Management and Governance of Resources and Environment

V. Methods and Indicators

Indexes

Errata

An online log of corrections to *Annual Review of Environment and Resources* articles may be found at http://www.annualreviews.org/errata/environ