REVIEW AND ASSESSMENT OF SUSTAINABLE LIMITS TO THE GLOBAL SOLAR ELECTRIC POTENTIAL

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Contents

Summary

This chapter is dedicated to the assessment of sustainable limits which solar energy for electricity generation may undergo in the future given its expected substantial increase in the next few decades globally. Published global potentials to date are mostly technical and report: very high potentials for land-based photovoltaic (PV) (ranging between hundreds and thousands of EJ/year); lower potentials for concentrated solar power (CSP), especially when energy return on energy investments (EROI) constraints are taken into account; while solar rooftop PV is generally found to be able to cover from a very low to moderate share of the current electricity consumption.

Solar energy based electricity generation represents a clear opportunity to de-carbonize the electricity sector and reduce chemical pollution. However, due to their low power density, its unplanned widespread deployment can drive the occupation of very large natural areas with significant impacts in terms of biodiversity conservation and habitat fragmentation. Current solar technologies are very dependent on a set of critical minerals, whose future availability will be very dependent on the future demand by the

rest of the economy. Given the low current recycling rates of most of these elements, solar deployment will hence tend to noticeably expand the extractive frontier globally and the related socio-environmental conflicts during the energy transition.

All the impacts identified in this review will tend to be aggravated in a society where (1) population and energy per capita continue to grow, and (2) a likely reduction of the EROI of the system is expected. Hence, it is recommended to focus energy transition policies first in the rationalization of energy consumption (actively dealing with potential rebound effects which may require switching to a postgrowth/degrowth paradigm), followed by the full occupation of urban areas (notably rooftops) and degraded lands, and only as last use natural land-based PV.

In the light of this review, we can conclude that no study in the literature has estimated the global sustainable potential of solar energy taking into account all the factors potentially implied. The estimation would certainly be very complex, but the evidence gathered here suggests that its estimation would significantly lower the published technical estimates up to date.

1. Introduction

Most governments are developing policy frameworks to promote the penetration of renewable energy sources (RES) to improve energy security, increasingly threatened by the depletion of conventional fossil fuels (FFs), and mitigate emissions to limit anthropogenic climate change and other impacts related to the use fossil fuels. Among renewables, wind and solar forms of energy are estimated to have the greatest potential, with projections often assuming that the resource base provides no practical limitation if adequate investments are forthcoming in a suitable regulatory framework.

RES have four fundamental biophysical-chemical properties radically different to FFs which need to be specifically taken into account in the assessment of their global sustainable potentials:

1. While fossil fuels represent concentrated deposits of energy and thus can be exploited at high power rates (100-10,000 W_e/m^2 (1 W_e = 8760 Wh/year)), the technologies harnessing renewable sources are characterized by power densities several orders of magnitude lower (see Figure 1). Hence, for delivering the same gross power, RES are substantially more land intensive. While wind farms are partially compatible with other uses (e.g., agriculture) or can be located offshore, biomass plantations, solar farms and to a lesser extent hydroelectric reservoirs (e.g., water supply management), tend not to allow double uses, that is, in practice they monopolize the occupied land. Figure 1 also shows that the power density of modern uses (cities, industry and houses) is above the power density levels of RES, which implies a greater effort to concentrate and transport them to the consumption points than for FF.
2. Variability of generation of those RES with more potential globally (wind and solar). This implies: (1) a lower capacity factor of RES vs FFs energy generation systems, and (2) given, that modern human societies depend on reliable and dispatchable (i.e., manageable) source of energy on demand, additional effort and resources will have

to be devoted to the management of this variability in energy systems with high RES share (including additional facilities as well as demand-management).

3. The two above factors imply that the construction of power plants to harness, transform and transport RES imply a much higher material intensity by capacity installed (kg/MWh) with relation to FFs (from double to up to two magnitude orders higher depending on the material); additionally, RES power systems tend to require a higher diversity in the use of minerals. Moreover, the management of RES variability implies additional infrastructures for energy transmission, storage, conversion, etc. which hence tend to increase the overall material intensity of energy systems with high RES share.
4. RES are in fact (1) energy flows which put into motion the biosphere, and/or (2) energy stocks which, as in the case of bio-energy, form part of the biosphere. If the co-optation of RES by humans is "low", the impacts on the biosphere functioning will be low/negligible (albedo change, wind regime change, etc.). But, if the renewables are scaled to levels where the requirement of natural resources competes/co-opts a substantial part of the biosphere which hosts us all, this may put in danger the whole system. This appropriation is already reaching substantial shares with relation to biomass since it is estimated that humans globally were appropriating around 25% of vegetation's potential net primary production around the year 2000, and around one-third of potential aboveground vegetation growth. Excepting for biomass, this subject is understudied in the literature.

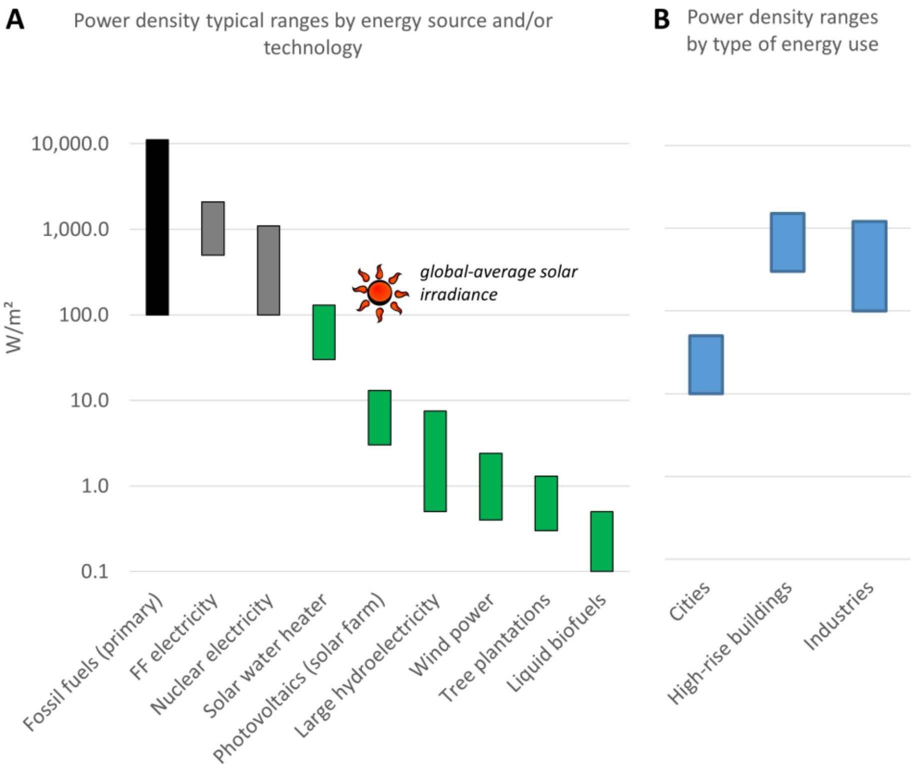

Figure 1. Gross power density typical ranges of fossil energy conversions and renewable energies by: A) energy sources and/or technology and B) type of energy use (cities, houses and industry).

Power density levels include the whole land footprint, i.e., land occupied by primary energy extraction and refining facilities, eventually buffer zones (nuclear) or adjacent cooling lakes, land occupied by transport networks, etc. Note that the given ranges are indicative typical numbers and the spread including particular cases is very large. Still, only in some very exceptional cases do some renewable energy conversions (most notably those involving alpine hydro stations with high heads and small reservoirs) can reach similar power densities to fossil fuels-fired electricity (in worse case conditions such as e.g., coal-fired stations burning low-quality fuel from surface mines with a high overburden to seam ratio).

Source: own work from data from Smil (2015). W/m^2 stands for power density in final energy terms (electricity, heat of liquid fuel) excepting for "Fossil fuels (primary)".

So, a key question nowadays is which level of energy can be sustainably obtained from the biosphere.

Besides climate change, from a broader environmental sustainability perspective, eight other planetary boundaries have been identified: biosphere integrity (biodiversity), climate change, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows (phosphorus and nitrogen), freshwater use, land-system change and novel entities (defined as new substances, new forms of existing substances, and modified life forms that have the potential for unwanted geophysical and/or biological effects). A planetary boundary refers to a specific point related to a global-scale environmental process beyond which humanity should not go if disastrous consequences are to be prevented. This framework reveals the multi-dimensional nature of environmental sustainability; the identification of the individual boundaries is just made to ease conceptual analysis but it should be bear in mind that ultimately, all are interdependent processes. As can be seen in Figure 2, two of them could not be evaluated due to gaps in current knowledge: novel entities and atmospheric aerosol loading. Of the rest, it is estimated that two (biosphere integrity and biogeochemical flows) have already surpassed their planetary boundaries and two (climate change and land-use system change) have been identified as currently lying in the uncertainty zone. This assessment is far from reassuring: although these planetary boundaries are described in terms of individual quantities and separate processes, they are in fact tightly coupled in the non-linear biosphere system through multiple regional processes. This framework will be applied in this chapter to ensure a multi-dimensional assessment of the environmental sustainable limits of concentrated solar power (CSP) and photovoltaics (PV). However, besides environmental sustainability factors, two more critical factors for the sustainability of solar electric technologies over time will be assessed in this chapter: (1) mineral requirements of these technologies (which contrary to RES are not renewable resources) and (2) the net solar energy delivered (energy return on energy invested, EROI) and the implications it may have at system level in the future.

This chapter is specifically focused on the review and assessment of the sustainable limits of the global electric potential of solar CSP and PV. "Potential" is an ambiguous term which need to be specified when referring to energy resources. Depending on the criteria, different categories exist which are reviewed in Section 2. The remaining of the chapter is organized as follows: Section 4 overviews the published global solar potentials, Section 5 reviews their sustainable limits and represents the core of this chapter. Section 6 sheds some light on the potential measures which may be applied to mitigate these sustainability limits, and Section 7 concludes.

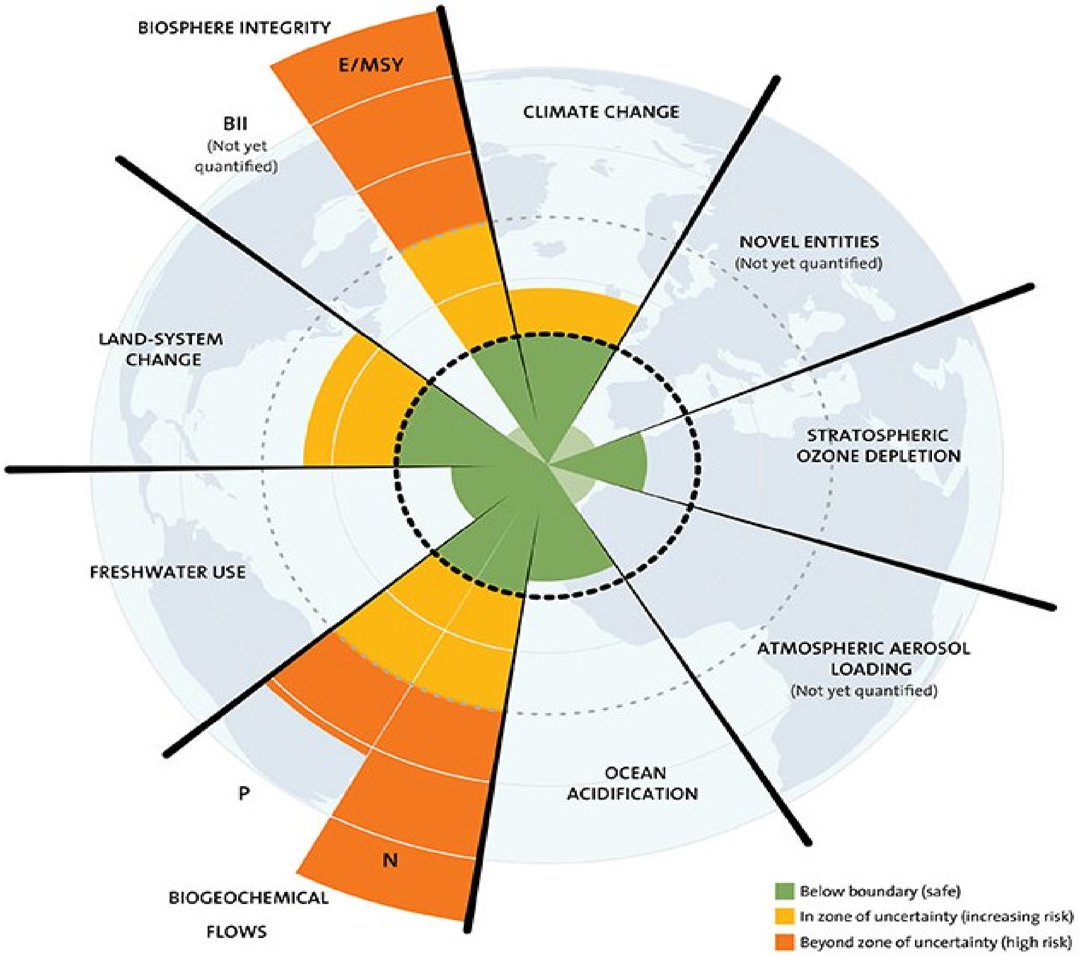

Figure 2. Current status of control variables for seven of the nine planetary boundaries. The green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk), and red is the high-risk zone. The planetary boundary itself lies at the inner heavy circle. E/MSY: extinctions per million species-years; BII: Biodiversity Intactness Index; P: phosphorus; N: nitrogen. Source: (Steffen et al., 2015). Credit: J. Lokrantz/Azote based on Steffen et al. 2015 (https://www.stockholmresilience.org/research/planetary-boundaries.html).

2. Categories of Renewable Energy Potentials

Many categories of RES potentials have been described and applied in the literature. Here we report 5 categories which are typically estimated as being limited by the previous category (see Figure 3):

- The **theoretical potential** is the energy flux theoretically available in the whole Earth (e.g., the energy content of wind speeds or solar irradiation on a global scale) and it consists on the physical upper limit of the energy from a certain source without restrictions,

- The **geographical potential** is the theoretical potential in areas that are considered suitable and available for this production i.e., in areas which are not excluded by other incompatible land cover/use and/or by constraints set on local characteristics such as elevation and minimum average wind speed,
- The **technical potential** is the geographical potential after the losses of the conversion from the extractable primary energy flux to secondary energy carriers or forms (electricity, fuel) are taken into account considering the current and/or foreseeable technologies,
- The **economic potential** is the technical potential up to an estimated production cost of the secondary energy form which is competitive with a specified, locally relevant alternative. This can be given also in form of functions such as supply-cost curves. Some studies distinguish between economic and market potential, the latter including the total amount of renewable energy that can be implemented in the market taking into account the demand for energy, the competing technologies, the costs and subsidies of renewable energy sources and the barriers,
- The **sustainable potential** covers all aspects of sustainability, which usually requires careful consideration and evaluation of different ecological and socio-economic aspects. The differentiation of the sustainable potential is blurred, since ecological aspects may already have been considered for the technological or economic potential, depending on the author. It accounts for sustainability criteria such as biodiversity conservation (typical examples would be the exclusion of protected areas and/or sensitive areas for threatened species) or limiting the associated environmental impacts when up-scaling significantly a given RES technology (e.g., water requirements, local pollution, etc.).

While the theoretical potential can be considered rather constant since it consists in the physical upper limit of the energy, although this may change in the future as a collateral impact of climate change, the rest of potentials are dynamic and affected by an array of factors and particular study assumptions such as: available land, changes in land cover/use, technological changes, energy delivery cost of other RES alternatives which may convert a given RES technology into a more expensive or cheap alternative, the availability of water for irrigating or cooling, the protection of natural areas, etc. In fact, while the potentials are often presented as ‘objective’, they are strongly influenced by assumptions on parameters used (e.g., suitability factors, best practices vs industry averages; future technological changes, etc.). This diversity and even discrepancies in the interpretation of each potential category among different studies prevents a straightforward comparison between studies (see next Section 3 for specific examples). Hence, their representation in Figure 3 separated by clearly separated limits may be considered valid just within each individual study (excepting for the sustainable potential which as aforementioned overlaps).

Finally, it has to be taken into account that these potentials can be affected by other factors which may ultimately limit the viable potential of RES, such as mineral availability or ensure sufficiently high EROI levels to be able to sustain the same socioeconomic system which is expected to install the RES power plants, aspects which will be covered in Section 5.2.

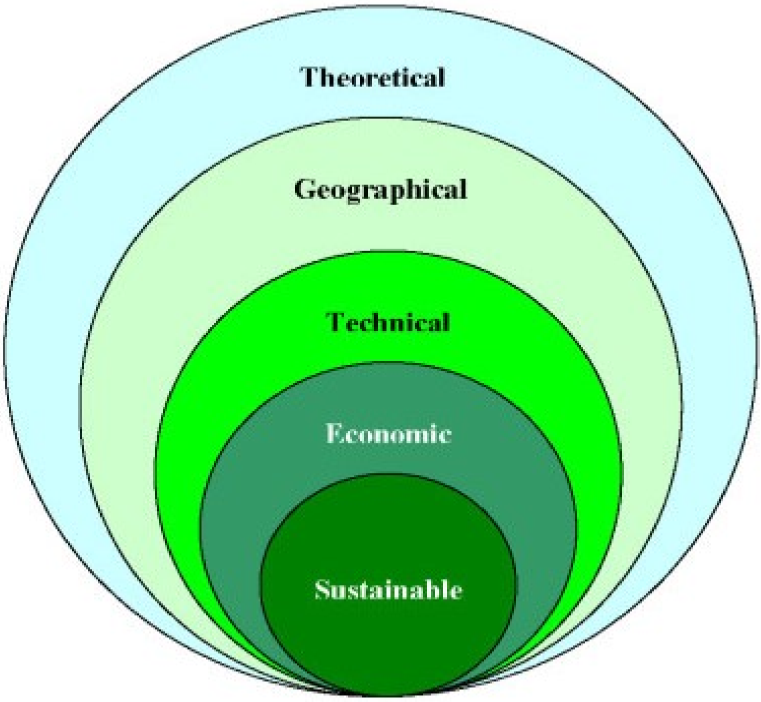

Figure 3. Categories of RES potentials typical in the literature. The limits are clearly set within each study, however different studies may differ on the interpretation to estimate each potential level. Not to scale. Source: own work.

3. Types of Solar Electric Technologies

Two main types of solar electricity generation exist: photovoltaic (PV) and concentrated solar power (CSP).

A solar cell is a device with the primary function of transforming light energy directly into electricity through photovoltaic effect. Its electrical characteristics which includes current, voltage, or resistance, differs with exposure to light energy from any source, whether natural or artificial. Solar cells form photovoltaic modules. Two broad families of PV technologies exist: wafer-based and thin-films. Wafer-based comprises of crystalline silicon (c-Si), example of which are polysilicon (poly-Si) and monocrystalline (mono-Si) silicon. Thin-films are made by depositing one or more thin layers of photovoltaic material on a substrate, such as glass, plastic or metal. Thin-films represent a layer of material ranging from fractions of a nanometer to tens of micrometers (µm) in thickness, which is one order of magnitude lower than crystalline silicon solar that nowadays uses wafers of ~200 µm thick. This allows thin film cells lower in weight and flexible (although they can also be made rigid), and being preferable for some uses where these characteristics are required. Thin-film technology has always been cheaper but less efficient than conventional wafer-based PV technologies. Different technologies exist depending on the materials used: amorphous silicon (a-Si), cadmium Telluride (CdTe), copper indium gallium (di)-selenide (CIGS).

Many other novel technologies are currently being researched. Among them, it is worth highlighting two: (1) perovskites, named this way since they include a perovskite-structured compound, which are cheap to produce and simple to manufacture, and (2) organic cells, which use organic electronics, a branch of electronics that deals with conductive organic polymers or small organic molecules, hence being potentially subject to low production costs. However, they still need to overcome substantial technical barriers in terms of stability and efficiency before entering the market stage.

CSP is an electricity generation technology that uses heat provided by solar irradiation concentrated on a small area. Using mirrors, sunlight is reflected to a receiver where heat is collected by a thermal energy carrier (primary circuit), and subsequently used directly (in the case of water/steam), or via a secondary circuit to power a turbine and generate electricity. At present, there are four main CSP technologies: parabolic trough collector, solar power tower, linear Fresnel reflector and parabolic dish systems. One of the main advantages of CSP plants is that it can incorporate thermal energy storage (TES) that can contribute to demand balancing the short-term variability of other RES; however at seasonal level the output has been found to be more variable than for other VRES.

When analyzing solar power plants, a convenient distinction is between the size and location of a solar energy installation. Distributed solar energy systems are relatively small in capacity (e.g., <1 MW). They can function autonomously from the grid and are often integrated into the built environment (e.g., on rooftops of residences, commercial or government buildings; solar water heating systems). Distributed solar contrasts with utility-scale solar energy (USSE) enterprises, as the latter have relatively larger economies of scale, high capacity (typically >1 MW), and are geographically centralized—sometimes at great distances from where the energy will be consumed and away from population centers.

Si-wafer based PV technology accounted for about 95% (2/3 mono-Si and 1/3 poly-Si) of the total production in 2019. The remaining is covered by thin-films technologies, which are dominated by CdTe and CIGS. In the case of solar thermal power, today there are two main commercial possibilities: parabolic trough and central receptor system. In 2019, a similar capacity level was completed for both technologies, representing each around 45% of the total additions, and linear Fresnel plants accounted for the remaining 10%. However, parabolic trough plants continue to represent the majority of total global installed capacity.

A brief review of novel technologies being researched is performed at the end of Section 5.2.1 on “Mineral availability” given that research is being focused towards solar technologies less dependent on critical materials such as perovskites and organic cells than current ones.

4. Overview of Published Global Solar Electric Potentials in the Literature

Taking into account the discussion in the previous section, the comparison between studies reporting estimates of the global solar electric potential must be done with caution and from an approximate point of view.

Different studies estimating different global potential categories of solar electricity have been performed in the last 2 decades applying different methods and focusing on different technologies (utility PV, rooftop PV and CSP) as well as different sub-technologies (e.g., poli-Si PV, mono-Si PV, parabolic CSP, tower CSP, etc.) (see Table 1). The majority of estimates reported in Table 1 was done in the period 2006-2013 (cf. also the review of technical potentials in the Special Report on Renewable Energy Sources and Climate Change Mitigation from the IPCC (2011)).

Work	Type of publication	Solar technology (ies)	Global electric potential (EJ/year)	Type of potential
Sorensen et al 1999	Project report	rooftop PV	20.4	technical
		utility PV	1,646.2	technical
Hofman et al 2002	Ecofys report	PV	1,315.1	technical
		rooftop PV	28.4	technical
		PV	1,343.4	technical
		CSP	249.1	technical
WBGU 2003	WBGU report	PV	~1,000	sustainable (year 2100)
Hoogwijk 2004	PhD thesis	utility PV	1,299.3	technical
		rooftop PV	22.1	technical
		PV	1,321.4	technical
De Vries et al 2007	Scientific article	utility PV	3,380.7	technical (year 2000)
		utility PV	0.0	economic (year 2000)
		utility PV	14,777.8	technical (year 2050)
		utility PV	0-5,758.5	economic (year 2050)
Schindler & Zittel 2007	Scientific article	CSP	233.4	technical
		rooftop PV	94.6	technical
Hoogwijk and Graus 2008	Ecofys report	PV	1,693.5	technical
		CSP	993.4	technical
Jacobson 2009	Scientific article	PV	<1,0785.3	technical
		CSP	3.2-28.4	technical
Krewitt et al 2009	Project report	PV	1,687.2	sustainable
		CSP	8,041.7	sustainable
Trieb et al 2009	Conference paper	CSP	10,785.3	technical
Deng et al 2011	Ecofys report	PV	819.9	economic (long-term)

Work	**Type of publication**	**Solar technology (ies)**	**Global electric potential (EJ/year)**	**Type of potential**
		CSP	977.6	economic (long-term)
		PV+CSP	1,797.6	economic (long-term)
Jacobson and Delucchi (2011)	Scientific article	PV[a]	10,722.2	technical
		CSP	7,568.6	technical
GEA 2012	IIASA report	utility PV	5,991.8-280,039.5	technical
de Castro et al 2013	Scientific article	utility PV+CSP	63.1-126.1	sustainable
Deng et al 2015	Scientific article	utility PV	316-2,815	technical
		rooftop PV	211.0	technical
		CSP	131-1,078	technical
Capellán-Pérez et al 2017	Scientific paper	rooftop PV	2.8-9.5	techno-economic
Dupont et al 2020	Scientific paper	CSP	294	technical (without accounting for PV potential)
		PV	1,194.0	technical (without accounting for CSP potential)
		PV+CSP	1,099.0	technical (maximizing EROI of each technology in each grid cell)
		CSP	0.0	technical (EROI≥9:1)

[a] Not indicated if it includes also rooftop PV.

Table 1. Review of global solar electric estimates by technology published in the literature ranked by published year. See each study for methodological details. “PV” includes both utility and rooftop PV. Source: own work.

Most (~3/4) of the estimated potentials are technical potentials, although with differing assumptions on land-use constraints, horizon years (short-term vs long-term) which in turn affect assumptions on future technological developments, and focus on different solar electric technologies (rooftop PV, utility PV and/or CSP), with a few (15%) studies providing economic and sustainable (10%) potentials. Less commonly, some studies account for the estimated overcapacities due to variable RES intermittency management, the future likely availability of minerals or EROI restrictions.

The most common approach for the estimation of technical potentials is the application of Geographical Information System (GIS) considering geographical and environmental constraints (suitability factors) for utility power plants such as land use or protected areas. Different assumptions on the value or the evolution of technological performance factors are considered depending on the timeframe of the analysis. For rooftop PV, suitability factors are typically estimated considering roof-top area per capita based on population density and GDP data. However, as aforementioned, the interpretation of what is "technical", "economic" or "sustainable" potential differs among studies. Moreover, most studies report single technology potentials and few account for the potential overlapping which in the case of utility PV and CSP has been found to be very large. Another case of overlapping affects rooftops. In practice, there are other uses for rooftops than rooftop PV: daylighting, solar thermal, roof-top gardens or terraces, etc. Although some uses might be compatible with rooftop PV (and sometimes even complementary, e.g., green roofs, hybrid solar collectors, etc.), others will compete for the available roof space, some of these uses also being promoted as sustainable/green practices. For example, solar thermal is a promoted and competitive technology already occupying many suitable locations (including in high latitude regions), and unlike electricity, needs to be close to consumers due to the technical difficulty of transporting heat over large distances without incurring in high thermal losses. Globally, solar thermal already accounts today for ~1.4% of water and space heating in buildings. Thus, studies that do not take into account these competitive uses are likely overestimating the actual surface area available for rooftop PV. The stringency of land constraints has also lead to the research of the potential of spaces such as roads. Pioneer investigations point to modest potential contributions when comparing with current electricity consumption levels.

Hence, the comparison of estimates reported in Table 1 is obviously challenged by this diversity of methods and scopes co-existing in the literature, which delivers more than 2 magnitude orders for the estimates of global solar potentials. Still, some conclusions can be extracted from the overview of the literature:

- Utility PV is in general the solar technology assessed to have a higher potential given that it is a more mature technology and is less subject to geographical and irradiation constraints than CSP (viable in steeper slope, lower irradiance, modular, etc.). The magnitude order of technical potential reported in the literature varies between hundreds and thousands of EJ/year.
- CSP technology is less studied than PV and a high potential is generally reported. However, some works identify a low potential, especially when EROI is taken into account.
- Rooftop PV is the technology with less identified potential given that it is limited to existing urban area and roofs; cities are currently not designed to maximize solar reception. As a consequence, it is generally found that rooftop PV could cover from a very low to moderate share of the current electricity consumption.

- Solar potentials for each technology decrease significantly when accounting for overlapping, i.e., the same area can only be utilized by one technology.

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