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Global solar electric potential: A review of their technical and sustainable limits

Carlos de Castro [a,*], Margarita Mediavilla [b], Luis Javier Miguel [b], Fernando Frechoso [c]

[a] Applied Physics, Campus Miguel Delibes, University of Valladolid, 47011 Valladolid, Spain
[b] Systems Engineering and Automatic Control, Paseo del Cauce s/n, University of Valladolid, 47011 Valladolid, Spain
[c] Electric Engineering, Francisco Mendizabal s/n, University of Valladolid, Spain

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ABSTRACT

Despite the fact that renewable energies offer a great theoretical potential of energy and that most of them have only a small share of global primary and final consumption (less than 2% of final World energy consumption was provided by wind, solar, geothermal, biomass and biofuels together) [1], their limits should be carefully analyzed. While other methodologies are based on theoretical efficiencies of renewable energies, generous estimations of effective global surface that could be occupied by the renewable infrastructure and/or ignore the mineral reserve limits, our assessment is based on a top-down methodology (de Castro et al. [2,3]) that takes into account real present and foreseeable future efficiencies and surface occupation of technologies, land competence and other limits such as mineral reserves.

We have focused here on the net density power (electric averaged watts per square meter, W_e/m^2) and compared our top-down assessment, based on real examples, with other theoretical based assessments; our results show that present and foreseeable future density power of solar infrastructures are much less (4–10 times) than most published studies. This relatively low density implies much bigger land necessities per watt delivered, putting more pressure on Earth than previously thought. On the other hand, mineral reserves of some scarce materials being used will also put pressure on this industry, because there is also a trade-off between solar park efficiencies and mineral limits. Although it is very difficult to give a global limit to the expansion of solar power, an overview of the land and materials needed for large scale implementation show that many of the estimations found in the literature are hardly compatible with the rest of human activities.

Overall, solar could be more limited than supposed from a technological and sustainable point of view: around 60–120 EJ/yr.

Contents

* Corresponding author. Tel.: +34 983423545; fax: +34 983423358.
E-mail address: ccastro@termo.uva.es (C. de Castro).

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Nomenclature

CPV	concentrated PV
c-Si	crystalline silicon
CSP	concentrated solar power
Direct solar power	solar power technologies that capture solar radiation directly
EJ	Exajoules (10^{18} J)
f1	cell efficiency at STC of a solar panel
f2	averaged net PR over solar plant lifetime
f3	solar cell occupation over land occupancy
IPCC	Intergovernmental Panel on Climate Change
Land occupancy	the total land area used by a solar park
LUEI	solar land use energy intensity (m^2 yr/MWh), the amount of land used for a defined amount of utility scale electricity generation in the solar power industry
Mineral reserves/resources	as defined by USGS
m-Si	mono-crystalline silicon
PR	Performance ratio
p-Si	poli-crystalline silicon
P_T	technical electric power potential
PV	photovoltaics
S_G	geographical potential
Solar park	the complete infrastructure (panels, inverters, etc.) of a solar installation
STC	standard test conditions, i.e. irradiance of 1000 W/m^2, air mass 1.5, 25 °C
TW	Terawatts (10^{12} W)
USGS	United States Geological Survey (www.usgs.gov)
ρ_e	electric power density (W/m^2)

1. Introduction

Given the limits of fossil and nuclear resources and the social and environmental problems associated with these energy sources, renewable energies are seen as ideal candidates for a global energy transition that must occur over this century [4–9].

However, any source of energy has impacts and restrictions, and global renewable energy generation, therefore, has a limit. The knowledge of these limits is of great importance to plan and formulate sustainable energy policies. Although these limits depend on many variables, whose time evolution is uncertain, an effort to get a good estimation should be done, and a cautiously conservative estimate may be the most appropriate to avoid serious consequences.

The present primary power consumption is greater than 530 EJ/yr (equivalent to an averaged primary power consumption of 16.9 TW) [10]. The expected increases in population and per capita energy consumption mean that the final overall demand for renewable energy may grow substantially. Thus, for instance, Nakicenovic et al. [11] forecast global primary energy needs of 790–2050 EJ/yr (25–65 TW) (for 2100); Nakicenovic et al. [12] forecast 26–42 TW (for 2050), the U.S. Energy Information Administration [13] forecasts roughly 24 TW (for 2035), while Schindler and Zittel [8] forecast more than 25 TW (for 2100). A review of 8 BAU (Business as usual) forecasts give a range of 31–55 TW for 2100 [14]. An overview of all these forecasts is shown in Fig. 1: all of them imagine a future energetically richer than the present time (1.5–3.8 times for 2100).

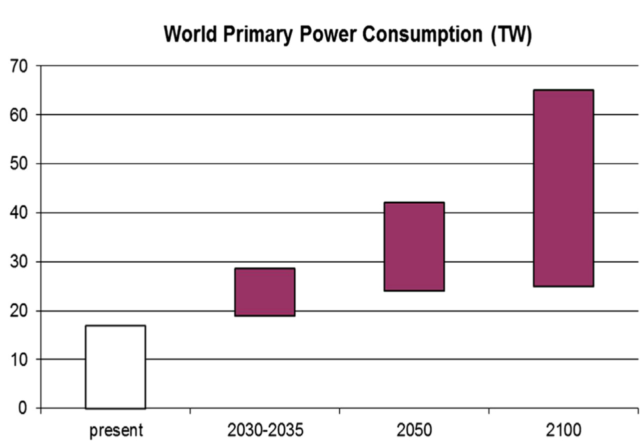

Fig. 1. Some BAU ranges of World primary power consumption (see text for sources).

Many authors believe that the potential of renewable energies is enough to cover a good share, if not all, of this demand. For example, for the final energy delivered from renewables, Schindler and Zittel [8] forecast 500 EJ/yr (16 TW) (for 2100), for Greenpeace [5], in their "Advanced Energy [r]evolution scenario", 284 EJ/yr (9 TW) is possible in 2050. The U.S. Energy Information Administration [13] forecasts 125 EJ/yr (4 TW) in 2035 from renewables, and Jacobson and Delucchi [7] believe that 360 EJ/yr (11.5 TW) is possible for 2030, mainly in the form of electricity from renewables. The range of scenarios contemplated by the IPCC in their special report on renewable energy [16] is very big, but more than 50% of them give more than 5.5 TW, while some give more than 12.5 TW from renewables for 2050.

Most scenarios that contemplate a renewable transition see wind and solar power as the two main sources from renewables [7,15]. These scenarios are supply-demand driven and could be named "Business-as-usual" (BAU) scenarios that assume energy transition to renewables by economically driven policies or "ecological" (ECO) scenarios that add strong policies on demand to save energy and improve efficiencies. For example, BAU transition scenarios like that of Schindler and Zittel [8] give 4.7 TW from wind and 10 TW from solar power; while scenarios like that of Jacobson and Delucchi [7] give 5.75 TW from wind and 4.6 TW from solar power as early as 2030. Among the ECO scenarios, Greenpeace [5] (in their ADV[R]) assume 1.2 TW from wind and 1.8 TW from solar power to be realizable for 2050; while the WWF [9] give 1 TW from wind and 1.9 TW from solar power for 2050 (from a deployable potential in 2050 of 4.6 TW and 8 TW respectively). All scenarios found do not see any technical limitation to reaching the respective forecasts or attainable power by wind or solar. As reviewed in IPCC2012 ([16], pp. 23): "all scenarios assessed confirm that technical potentials will not be the limiting factors for the expansion of RE [renewable energies] at a global scale". The IPCC report gives the same technological potential range for solar as Rogner et al. [17] (50–1580 TW), although this work actually gives a geographical primary power potential that is in reality much greater than the technological one.

However, we think that there are several geographical and technological restrictions that have been underestimated in most of the literature and might lead to lower limits for the achievable global renewable energy. Renewable resources other than solar power (hydro, biomass, wind, etc.) are much more limited than solar power on both theoretical and technological grounds. Hydro electricity and biomass limits are evident because of the limited