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

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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

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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).

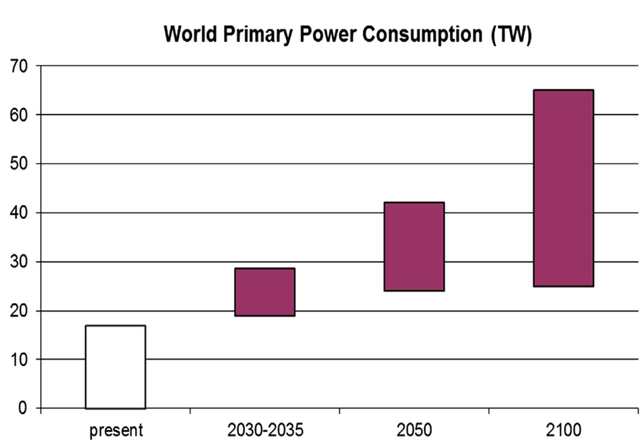

Fig. 1. Some BAU ranges of World primary power consumption (see text for sources).

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 amount of fertile land and suitable locations and their role in the material fluxes of the ecosystems [18]; while, in previous work [2], we concluded that the technological limit of wind energy is around 30 EJ/yr (1 TW_e). Therefore, the potential of individual renewable resources other than solar power seems to be limited to much lower values than the present final energy consumption of non-renewable energies [18].

Acknowledging the limits of these resources, direct solar power seems to be the best candidate among the renewables to have the technical potential to greatly exceed 30 EJ/yr (1 TW_e) [2,18].

This paper reviews some of the technological assumptions for previous estimations of the global technical potential of solar energy found in the literature. Some new considerations lead us to the fact that some of the common assumptions related to solar park efficiency and land occupancy are overestimated, and some important restrictions, such as mineral reserves, are usually not taken into account when potentials are calculated.

Section 2 reviews the estimates of global PV solar power potential present in the literature. Sections 3 and 4 calculate the global technical potential of solar PV energy density at present and in the foreseeable future. In Section 5 we offer an overview of the land and materials needed for the implementation of solar power on a large scale and the interaction with other human activities. In Section 6 we offer a rough estimation of a sustainable limit for global solar power, and finally, in Section 7, conclusions are extracted.

2. Previous estimations of global solar electric power potential

The average power that the sun shines on the Earth is a huge 174,000 TW, 86,000 TW of that over land. Given that the global ice-free land is around 13,000 MHa, and taking into account the power that finally reaches the surface, the theoretically attained power would be about 21,840 TW [19].

Most published studies that calculate the technically feasible potential exclude much of the soil needed for other uses (e.g. forests) or which are impractical (e.g. high mountains with steep slopes). They calculate what fraction of each region and type of land would be possible for the development of solar power. This surface is called the geographical surface potential (S_G).

Defining ρ_e as the current or future electric power density, the net electric power produced by the solar industry divided by the total land occupation that this industry needs to deliver this power, we arrive at the dimensional expression for the current or future technical electric power potential

$$P_T = S_G \rho_e$$

This expression marks the relevance of the ρ_e parameter for renewables, because if it has a low value, the land necessities, S_G, will have a high value and could be the main limit for any estimation of P_T [2,31,2]. This is why the estimates of P_T in the technical assessments of solar potential found in the literature use this expression. We will follow this path, but we will also consider other potential limitations such as the limits imposed by mineral reserves.

Solar energy power density has an average of 168 W/m^2 [19]; however, not all of this power can be captured and turned into electricity.

In theory, as published in different assessments, the solar parks capture and turn into electricity between 12 and 25 W_e/m^2 (see Table 1), i.e. an energy density an order of magnitude below what fossil energy provides (over 150 W/m^2 for oil, coal and natural gas industry as stated by Smil [18]). Thus, apparently, much more land has to be dedicated to photovoltaic energy infrastructures to provide the same power as is required by the fossil fuels industry. In any case, indirect land occupation by the fossil energy industry could be greater than solar if we consider, for instance, the "ecological footprint" that they use [19].

Biomass for energy is even less efficient in this sense, because typical primary power densities are well below 1 W/m^2 [3,18,20,21]. If the extent of land were the main limit to these energies, their theoretical densities mean that solar power is a better choice than biomass. The potential for solar power is therefore bigger, by at least one order of magnitude, than the biomass power limit, if the same surface potential S_G is taken into account.

Solar power densities for photovoltaic (PV) parks are roughly equal to [20], or even better [6,7], than other solar technologies for electricity production, such as CSP (concentrated solar power) systems; Jacobson and Delucchi [7], for example, give 25% more occupation. If we use CSP with storage capacities, the power density is even lower because storage increases the land necessities [22]. For this reason, for the solar power density estimates, we will concentrate on the PV systems, without excluding CSP technologies from our assessment.

Table 1 shows the technical global potential of the solar photovoltaic energy and the present and future estimations of its power density as estimated by different authors. To calculate the technical potential, most authors of Table 1 first calculated the geographical potential (S_G) and then assigned the current solar cell and solar park power densities (based mainly on theoretical grounds). Next, they forecasted the future feasible technical potential for the solar PV industry based on future cell efficiency;

Table 1
Technical or sustainable (if indicated) average power potential of solar PV. In some cases, the present and future solar power densities that authors calculate, or that can be inferred by their work, are indicated. In our study we consider net electric power or net density power.

Authors	Power potential (TW_e)	Present power density (W_e/m^2)	Future power density (W_e/m^2)
DeVries [23]	170–490	20	25–50
WWF [9]	57		
IPCC, 2012 [16]	53.5 50–1580 (PV+CSP reviewed range)	21.6	
Grassl et al. [24]	33 (sustainable)	23.5	42
Jacobson [6]	170–340	12.6–16	
Jacobson–Delucchi [7]	340		
Nakicenovic [12]	> 213		
Hoogwijk et al. [25]	53.6	14.4	24.4
Hoogwijk [26]	42.2	18.6	
Hofman [27]	42		
Sorensen [28]	52		
Zerta et al. [4]	23–46 (sustainable)		
This study	**2–4 TW_e (techno-sustainable)**	**~3.3**	**~3.3 (2.5 to 5)**

they did so, once again, by taking the theoretical value potentials and/or extrapolated past or current trends into the future.

To calculate the geographical potential (S_G), some authors, like Hoowijk [26] and Hoowijk et al. [25], exclude urban, forest and natural reserve soils, assign 5% occupancy by the solar power industry to extensive grasslands and hot deserts and 1% to the rest of the soils. However, Hofman et al. [25], also exclude high step mountains, agricultural areas and low irradiance sites (<120 W/m^2), but allocate 5% for the remaining land occupation. Others, like DeVries [23], Nakicenovik [12], etc., use land models similar to those used in the IPCC [16] scenarios. De Vries [23], for instance, assigns at least 1000 MHa for abandoned cropland in 2100 in their scenarios and uses 80–90% of this abandoned land for new renewables based on estimates by other authors.

3. Estimation of current technical power density potential of solar PV, ρ_e

The net electric power density from the current PV plants (ρ_e) is the average solar irradiance (sunlight power density) on the PV modules (I), limited by some factors (f_i) that take into account the energy that cannot be transformed into electricity.

We could describe the net electrical power density as

$$\rho_e = I f_1 f_2 f_3 \quad (1)$$

where I is the average solar irradiance on the modules. f_1 is the conversion efficiency of solar radiation into electricity in the PV cells. f_2 is the remaining energy factor after subtraction of the loss of solar radiation energy in the PV modules, in power converters, due to cell degradation, failures, etc. In the technical literature this is known as PR or performance ratio. f_3 is the actual occupation of PV cells on the total land occupation of the solar photovoltaic industry.

In this section, we calculate all the terms of Eq. (1) and conclude that the recruitment and ongoing transformation of solar energy density into electricity on current solar plants is much lower than the theoretical studies shown in Table 1.

We estimate ρ_e by means of the detailed study of some very big photovoltaic parks and also through the entire Spanish case. We then make the hypothesis that both cases are representatives of the present or near future tendencies of the global PV industry and then we take a greater number for the average expected ρ_e at the World scale because we acknowledge some pessimistic caveats for the two examples chosen.

Table 2
The largest solar PV power plants operative in November 2010. Surface, solar panel efficiency and expected production data from solar companies that own the plants and from the manufacturers of photovoltaic modules as found on their respective websites. The percentage of radiation transformed into electricity is the theoretical electricity power density expected from the total average solar irradiance at the PV modules, calculated from the "Photovoltaic geographical information system (PVGIS) of the Joint Research Center (JRC) of the European Commission" (European plants) and the "NASA Surface meteorology and solar energy developed by the Prediction of Worldwide energy resource project" (Canada plant).

Solar PV plants	Expected production (GWh/yr)	Solar panel efficiency (%)	Surface occupation (Ha)	Power density (W_e/m^2)	Radiation % converted into electricity
Finsterwalde (Germany)	74	15	198	4.26	3.32
Sarnia (Canada)	120	9.1	365	3.75	2.11
Olmedilla (Spain)	87.5	14.5	180	5.55	2.54
Strasskirchen (Germany)	57	15	135	4.82	3.15
Lieberose (Germany)	53	9.1	162	3.71	2.67
Moura (Portugal)	93	15	250	4.24	1.39
Total	**484.5**	**12.5**	**1291**	**4.28**	**2.22**

Table 3
Expected average density and solar conversion to electricity of the largest solar parks. See text for explanations. We take the same f_3 for the solar parks as in Table 2, but the Lieberose park is corrected according to Fig. 2. If we correct the rest of the parks according to the maximum footprint criteria (see text) that we found, then we will get less than 2.9 W_e/m^2 for the net average density power, and if we discard instead the Sarnia (little f_1), Lieberose (little f_1) and Moura (little f_3) parks, we get 3.55 W_e/m^2.

Solar PV plants	f_1	f_2	f_3	ρ_e W_e/m^2	Radiation % converted into electricity
Finsterwalde (Germany)	0.15	0.65	0.272	3.40	2.45
Sarnia (Canada)	0.091	0.70	0.231	2.44	1.47
Olmedilla (Spain)	0.145	0.65	0.219	4.45	1.91
Strasskirchen (Germany)	0.15	0.65	0.243	3.64	2.19
Lieberose (Germany)	0.091	0.70	0.181	1.53	0.81
Moura (Portugal)	0.15	0.65	0.118	3.50	1.15
Total average	**0.125**	**0.67**	**0.207**	**3.33**	**1.75**

Firstly, we do an extensive study of the six largest photovoltaic parks, rated by nominal power, in operation worldwide as at November 2010. We chose these six parks because we could retrieve from the manufacturers' web-pages all the data that we need and also because we could compare the reported land occupation with satellite photographs by means of free web sites.

The parks are PV fixed mounted modules (see Table 2), except the Moura plant that has a one-axis solar tracking technology; this represents around 20% of the installed power of the six parks as against 6.4% of the tracked PV systems worldwide installed in 2012 [29]. Sarnia and Lieberose have thin film (Cd–Te) cells, Olmedilla m-Si cells and the rest p-Si cells. Sarnia and Lieberose represent around 40% of the installed power of the six parks as against around 15% of the thin-film global market share in recent years [1].

The manufacturers expect power conversion efficiencies per unit of area occupied by their park facilities of well below 10 W_e/m^2.

Although with Table 2 we could conclude that many assessments probably overstate the density power attained by present parks, we take a step forward and recalculate Table 2 using Eq. (1) for our own estimations (see Table 3) of the net average power that the plant will give to the society over the expected park lifetime.

1. f_1: conversion efficiency
   We will take f_1 as the solar cell efficiency at STC (standard test conditions) as reported by their manufacturers.
2. f_2: Averaged Performance Ratio over the park's life-cycle
   The net electricity generated in these parks is lower than expected because the solar companies assume an overstated performance ratio (PR) [30], not taking into account in their calculations of expected production some factors such as
   - the average degradation of the photovoltaic cells over the expected plant life time;
   - the electrical losses from the current meter to the connection to the country's electricity grid;
   - the losses due to failures of modules or inverters (availability losses averaged over the plant lifetime);
   - energy self-consumption (other than electric) for the maintenance of the solar park installations.

   There are many performance ratios calculated in the scientific literature and which are reviewed, for instance, in Mondol et al.

[31] and Eltawil [32] (see also [33–35]). The range of values found is typically 0.4–0.8. In Germany, the monitoring results of 250 grid connected PV systems gave a mean of 0.67 [36]. Jahn and Nasse [36] gave an average of 0.66 for parks in 1983–1995 and 0.70 for 1996–2002. Eltawil and Zhao [32] give a range of 0.55–0.76 with an average of 0.72 for well-maintained parks. Some PR studies for grid connected parks do not take into account losses in the evacuation line to the electric network because the “net” electrical output is often measured before. Sometimes, the difference between the reported PR and the measured PR is due to the fact that the actual power of the installed PV arrays is below the rated power declared by the manufactures [30]. PR calculations found (all but Prieto and Hall [30]) disregard future availability losses because they take the current availability of new or relatively young parks and future failures such as severe corrosion of the structures, aging of installations, etc. can be expected. Proof of this is that modules, inverters, trackers and auxiliary equipment are guaranteed much lower than the power output of the modules. Another test is that the reported PR average of the same installations by Jahn and Nasse [36] decreases over time.

PR calculations do not take into account future losses due to further cell degradation (they take the current cell degradation). Cells often degrade over time at rates of about 0.5–1% per year, with an average of roughly 0.7% [37–39]. If the lifetime of a solar park is extended to 30 years, considering that defective materials and modules will be replaced if necessary, a 0.6%/yr of cell degradation for the surviving cells means a net electricity loss of 8% averaged over the entire lifetime.

Other factors do not improve PR estimations, for instance, module washing, monitoring, surveillance and maintenance are part of the self-consumption that requires energy and surface occupation. For instance, an estimate of 15 m^3/MW-yr of water for washing results in a 0.2% of self-consumption solely for this purpose [30].

Our f_2 calculations will be lower than some PR estimations mainly because we consider a prorated degradation of the cells and panels over the entire life cycle of the park and we estimate some factors, like self-consumption and maintenance (that also tend to grow with the age of the solar park), that other assessments do not consider. For instance, Kymakis et al. [40], for a modern park in Crete, give a PR of 0.71:4.54% for availability and grid connection losses, 6% for internal network and other losses, etc., but consider only the present PV degradation losses (5%) not the prorated ones, and they do not take into account other losses such as self-consumption, future maintenance, etc.

For silicon cell modules, we take the following PR subfactors: 0.88 for temperature, spectral and angular losses (the estimated average losses due to temperature and angular losses using the PVGI tool (see Table 2) for the Finsterwalde, Olmedilla, Strasskirchen and Moura parks is 12.1%), 0.92 for cell degradation (see above), 0.95 for availability (averaged over the life park), 0.95 for dust, snow and other shadings and 0.85 for captured and other system losses (losses in wiring and protection diodes, poor module performance at low irradiance, module mismatch, inverter inefficiencies, losses from inverter to grid, non-optimum module angle with respect to irradiance, operation of the array at a voltage other than its maximum power point). Then

$$f_2 = 0.88 \times 0.92 \times 0.95 \times 0.95 \times 0.85 = 0.62 \tag{2}$$

For the case of the entire PV system of Spain, an extensive study by Prieto and Hall [30] finds a PR of 0.655, taking into account the future degradation of the cells, but ignoring availability and self-consumption, shading and other losses.

Taking all these considerations into account, we take an f_2 of 0.65 for the parks of Table 2 based on silicon and 0.70 for Cd–Te technologies (Lieberose and Sarnia) because thin-film has a slower degradation of the cells than silicon cells; in Eq. (2), if we delete the degradation factor, we reach a PR of 0.67, therefore our final choices are slightly optimistic when compared with Eq. (2) because we consider no degradation of these cells.

3. f_3: actual occupation of PV cells

The f_3 factor is estimated for each solar park by calculating the actual solar cell occupation divided by the total land area occupied by the solar parks as estimated by the manufacturers, or by us based on satellite maps. This is a low estimation (and therefore optimistic) because only the solar field or the area occupied by the fencing surrounding the park is reported, but the actual park footprint is larger. For example, in the PR calculation of a solar park in Crete [40], the authors take an active solar area (total PV cell surface) of 1142.4 m^2, covering a total surface area of 3784 m^2 and giving an apparent f_3 of 0.30. But a simple examination of the park's footprint, using the Google maps tool, shows that the total area occupied is greater than 5000 m^2 ($f_3 < 0.23$).

For the solar parks in Table 2, the reported occupation in the Lieberose park is 162 Ha, but this is only the direct occupation of the PV panels. As can be seen in Fig. 2, the plant occupation is

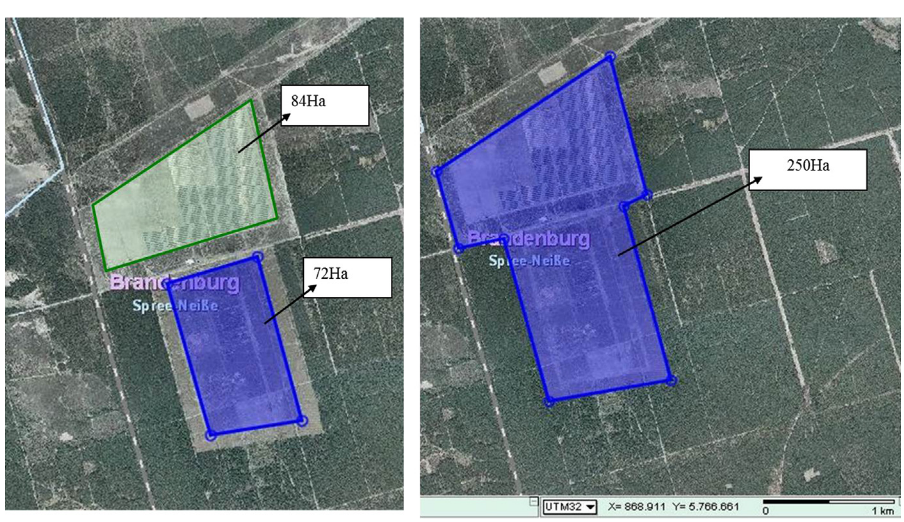

Fig. 2. Lieberose solar park as seen from http://www.geodatenzentrum.de. On the left, the direct solar PV modules occupation. On the right, the total land occupancy.

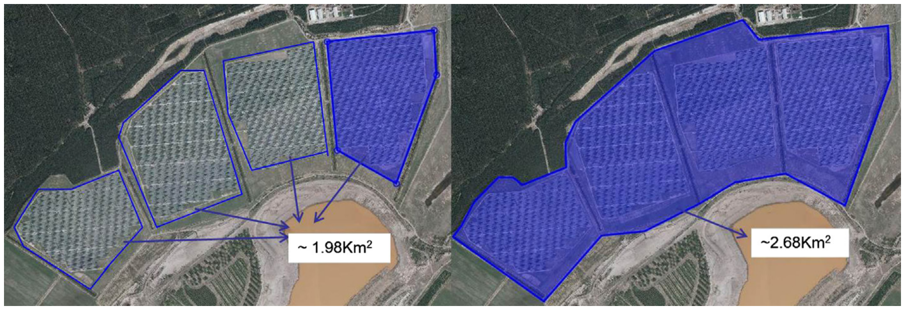

Fig. 3. Finsterwalde park. The reported park occupation is 198 Ha, which is the sum of the four areas of the figure (left). But the total installation footprint is greater (the area not suitable for other purposes and/or the total area acquired by the manufacturers). The blue area of the right-hand figure is 268 Ha. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

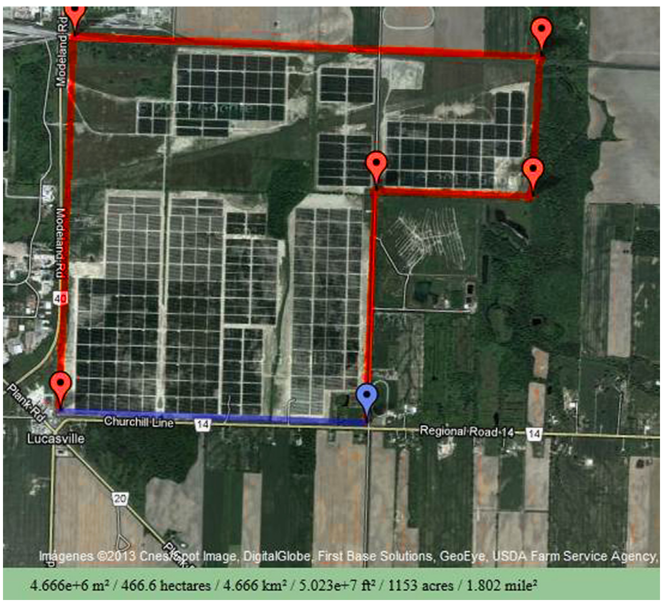

Fig. 4. Sarnia park. The reported land occupation is 365 Ha. The signaled park occupation is around 467 Ha.

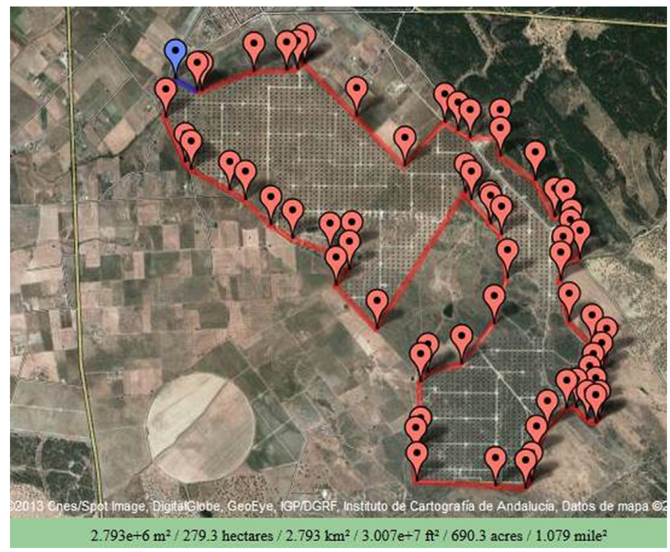

Fig. 5. Moura park. The reported land occupation is 250 Ha. The signaled park occupation is around 279 Ha.

Fig. 6. Part of Olmedilla park. In yellow, one "parcela" or plot (an administrative land measurement in Spain) of the many that must be leased or acquired by the industry. We can appreciate that some internal or surrounding land is unusable or unused. The reported footprint is lower than the total amount of the occupied "parcelas" or plots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

greater than 250 Ha if the deforestation area needed to avoid shading by trees is taken into account. This means that the f_3 factor for Lieberose is <0.181 instead of the 0.280 calculated for 162 Ha.

We have measured the extension of the solar parks with the www.geodatenzentrum.de tool for the German parks, the SIGPAC Spanish tool for Olmedilla (http://sigpac.mapa.es/fega/visor/) and the Google planimeter tool for the Canada and Portugal parks (http://acme.com/planimeter/). Instead of taking only the occupation of the park (often surrounded by a fence) we argue that the total footprint is greater if, inside or surrounding the parks, there are other areas lost for other purposes than the actual present barren use. As we can see in (Figs. 3–5).

We found the same occupation for the Strasskirchen park as that reported in Table 2. For the Moura and Sarnia parks, although the direct occupation is equal to that reported in Table 2, we found an occupation/aquisition of 279 Ha and 467 Ha respectively. For the Olmedilla park, the irregularity of the park makes the estimation difficult, but more than 200 Ha could be estimated if we appreciate the problem of the unused, surrounding or internal lands of some parks (Fig. 6).

Another example, with a different technology, is the reported 650 Ha of the SEGS I-IX installations (CSP parabolic through technology) in the California desert against the actual occupancy of more than 1000 Ha through the Google map tool. 650 Ha is the actual occupation of the solar field mirrors, not the actual footprint, which includes, for example, land treatment units (pools) and other disturbance areas on the site. The calculation for this CSP plant gives around 2% for the solar radiation transformed into electricity. A CSP with storage capacity could increase the footprint of the installations by at least 25% [22], reducing this % of radiation transformed into electricity and confirming that CSP does not improve the electrical power density as compared to PV technologies [6,7]. New developments in CSP, such as the central tower, report good density power; yet, for the Solar Tres (II) project, we estimate from Ref. [41] a 41.9 GWh/yr of net solar electric (not taking into account the natural gas electric production and discounting the self-consumption of the plant) in the reported 142.31 Ha of occupation, with 3.36 W/m^2, and a solar radiation conversion to electricity of 1.42%. This project was finally renamed Gemasolar [42], a bigger project with a reported 195 Ha occupation, but a real occupation of 217.1 Ha (SIGPAC tool). The expected production of this very new Spanish park is 12.55 MW but, if we discount 10% for self-consumption and 15% for natural gas consumption, we get 1.85% of solar radiation to electricity with 100% of availability and no other losses (e.g. aging of infrastructures).

Another way to estimate the net density power, not individual example based (bottom-up methodology), can be done with the top-down analysis of Prieto and Hall for the entire PV sector of Spain: for Spain, the 3.5 GW installed until late 2008 (2.76 GW installed in 2008) gave 685 MW$_e$ after the inverters (but before the grid) in 2009. Prieto and Hall [30] estimate 3 Ha/MW$_p$ in fixed installations, 4.5 Ha/MW$_p$ for one-axis tracking systems and 6 Ha/MW$_p$ for two-axis tracking systems. We make an extensive study of the land occupation of two-axis tracking plants from the solar farm developer OPDE in Spain (www.opde.net). We take the leased land occupation that OPDE gives and, if possible, compare it with a visual inspection of solar parks using the SIGPAC tool (/sigpac.mapa.es/fega/visor/). Our results for 15 two-axis tracking systems gave a real average occupation of land for the plants of around 10 Ha/MW$_p$. Therefore, taking our results for two-axis systems, and accepting Prieto and Hall's [30] results for one-axis and fixed systems (a similar inspection for some fixed and one-axis tracking parks give similar results to those reported by Prieto and Hall [30]), the total land occupation of the PV system in Spain in 2009 was 17,500 Ha. The net power density for the entire PV system of Spain in 2009 is 3.9 W$_e$/m^2. If, for the sake of comparison with Table 3 and Eq. (2), we take the future cell degradation and the availability and grid connection losses, the averaged net power density for the entire PV system of Spain is less than 3.5 W$_e$/m^2, and a percentage of solar radiation converted into electricity $<2\%$, confirming the results of Table 3 for a country with good irradiance and modern PV infrastructure, although with a greater share of tracking technology than the World average.

Prieto and Hall [30] also give the EROEI (energy return on energy invested) of the Spanish photovoltaic infrastructure with a new methodology (an extended EROEI top-down approach); with their data and collected results, and our estimation of surface occupation, we could get a net electricity power of 2.3 W$_e$/m^2 for the entire Spanish sector.

Palmer [43] writes that conventional EROEI and LCA (Life cycle analysis) do not take much of the energy impact of a PV system. His extended EROEI to PV systems with high penetration (based mainly on Australian rooftop technologies) give even worst EROEIs than Prieto and Hall [30].

We therefore get 2.9 W/m^2 for the six parks analyzed and 2.3 W/m^2 for the Spanish sector, acknowledging that both examples have more than the World average share of technologies with relatively low density power efficiencies (either Cd–Te thin film and/or tracking systems), we will take, the same current net average electric power density as $\rho_e \sim 3.3$ W$_e$/m^2 reflected in Table 3 as being representative of the present World average.

An alternative way to show the relationship between the electricity production and its land needs is the solar land use energy intensity or LUEI, which estimates the amount of land used for a defined amount of utility-scale electricity generation in the solar power industry [44]. The LUEI may be considered as the inverse of ρ_e. The proposed metric for LUEI is square meter-years per megawatt-hour [44] [(m^2 yr)/MWh], which is interesting, although it is more complicated than our ρ (measured as W/m^2) and not an international system unit. A simple conversion of our global averaged ρ (3.3 W/m^2) from W/m^2 to m^2 yr/MWh gives 34.28 m^2 yr/MWh.

4. Future evolution of ρ_e

For the foreseeable future, not only f_1 and the average irradiance I may change (as the authors in Table 1 take into account), but also the factors f_2 and f_3.

Cell efficiencies at STC (standard test conditions) have an average of 12.5% for the six solar plants of Table 3. Although there are cell efficiencies above 20%, and future technologies will improve this efficiency, it is unclear, as is often assumed, whether actual parks to be installed in the future will have better averaged efficiencies than 20%, for instance, because thin film technologies, as evidenced by the Sarnia and Lieberose parks due to their economic advantage, may lead the way in the future. Thin film's share of the global market increased from 14% in 2008 to 17–19% in 2009 for cells [45], although it declined, for the first time since 2005, to 16% in 2010, to 15% in 2011, and to 12% in 2012 [46,47]. Although this recent decreasing trend could continue in the future, there are other opposite trends: the share of very big solar parks is increasing [1] and, of the 10 biggest PV plants in the world, as listed by Wikipedia in July 2013, 5 are Cd–Te thin film technologies, one is a mixture of a-Si thin film with c-Si and the rest are c-Si. This could imply that in the future thin film technologies could again gain share in the market.

Performance ratio will improve in some aspects, mainly in that most closely related to technologies such as inverter efficiencies, but poorer performances can be expected if high irradiance places (such as hot deserts) are chosen, because some losses, such as temperature and soiling losses, longer electric evacuation lines, cell degradation due to higher temperature cycling etc., will grow. For instance, comparing the calculated system losses due to temperature in the Olmedilla or Moura solar parks by means of the PVGIS tool, we have 10.1% and 11.9% losses respectively, but around 7.8% is estimated for the Finsterwalde and Strasskirchen parks (see Table 3).

If 5% of hot deserts were used for renewable energy production, as Hoogwijck [26] and Hofman [27] do in their estimations, then about 45 MHa of the Sahara desert would be occupied, but the electricity produced there would mainly be consumed in Europe, and then thousands of kilometers of new electric lines would be needed (the distance between the center of the Sahara and the center of Europe is roughly 3000 km); but the solar electricity imported from North Africa to northern Europe could have an important loss of power in transmission lines [48]. Delucchi and Jacobson [49] give 1.4–5.3% (depending on the lines) of losses for each 1000 km.

If PV ends up being one of the main sources in the electricity mix, then this industry will need support through storage systems [7,14,43,49–51] (e.g. pumped hydro, compressed air, hydrogen production), requiring more capital investments, more land occupation and a net loss of final electricity being delivered: pumped hydro is the most efficient of these systems with a general loss of 30% [52], compressed air has a loss of 20–80%, and hydrogen losses could surpass 40%: Jacobson and Delucchi [7] give an electrolytic hydrogen efficiency of 70% and the compression and liquefaction efficiency of 89% and 76% respectively, not taking into account transport, long time storage losses and other losses. Moriarty [14] gives 45% of system losses based on hydrogen storage and, at the

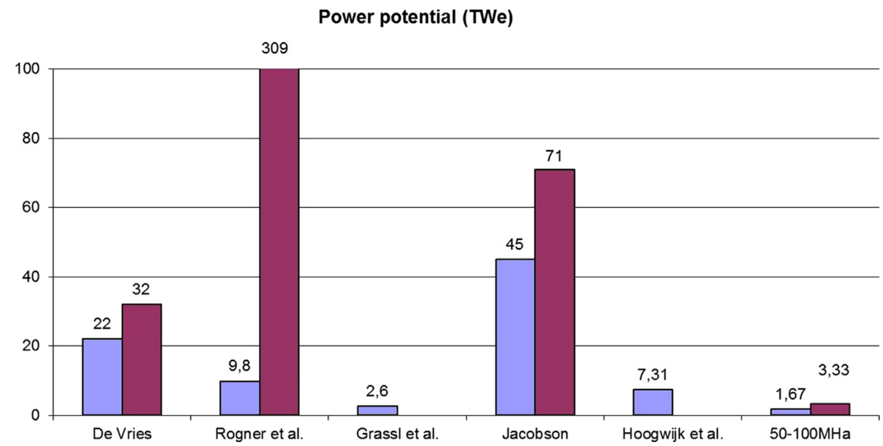

Fig. 7. Solar technological or sustainable power potential using the land surface potential of some authors of Table 1with our density power (3.3 W_e/m^2); the blue column is the reported potential or the minimum of their different scenarios; the red column is the maximum if there are several scenarios. For comparison, we give the potential attained with 50 and 100 MHa of land occupation by infrastructures dedicated to solar industries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

other extreme, Trainer [50,51] gives 80–100% losses with the present technologies. For example, pumping water storage requires land occupation that can be as large as the occupation of the solar park (the power density of hydropower is similar to PV [18], although water storage could be used for non-energy purposes). Trainer [50,51] and Palmer [43] show that the difficulty is not only the day–night variability (which CSP with storage could resolve), but the several days in a row intermittencies, such as persistent clouds or winter–summer variability, impossible to deal with without long term storage systems and/or an over-capacity being installed (either solar, other renewable or fossil energy). Although Delucchi and Jacobson [53] recently contested the Trainer [51] critiques, arguing that the intermittence problem is not so high and that it could be resolved with storage systems (mainly hydrogen) and some over-capacity being added, they do not examine the land occupation of these "new" infrastructures in detail. There are also other related issues with the intermittency and the storage problems, reviewed in Palmer [43] and Moriarty [14], who show a lessening of the efficiency (and indirectly, density power) of the PV system when strong penetration occurs.

Both strategies will require more land, decreasing the net and effective power density. For instance, there are frequently several days in the north of Europe, or in Australia in mid-winter, which are cloudy and with almost no wind that could not be compensated for by PV or CSP technologies [43,50], but only with some storage source (pumped hydro, hydrogen, biomass, etc.). These considerations alone imply that ρ_e will probably be less than it is at present. As a concrete example, the expected solar electric generation in Andasol-1 (CSP technology, in Southern Spain) is 4100 MWh and 3100 MWh for January and December, as against more than 25,000 MWh expected for June and July [54], due mainly to solar inclination. Because most land available in the future for solar power will be in the Northern hemisphere, on a global level, this intermittency problem will remain even with a global electricity grid.

The areas of greatest irradiance are hot deserts like the Sahara desert. However, since they are very distant from the main human settlements, they will require new and bigger infrastructures for power evacuation lines, access roads, new settlements for parks maintenance, etc., widening the footprint of installation and therefore lowering f_3 with respect to existing parks (mainly near consumers and without storage systems).

In Spain, 63% of PV parks have fixed modules, 13% are one-axis tracking and 24% two-axis tracking [30]. It is difficult to predict the future balance sheet of these systems. In recent years, tracking systems have gained share against fixed and a rapid increase is projected for the next decade, but at present they represent globally only a modest 6.4% share of the total PV market. Therefore, the Spanish PV sector probably has a worse density power than other countries that also have a good solar radiance.

The average irradiance of future parks will probably be better than the optimal average (for fixed modules) of the parks of Table 3 (177 W/m^2). The average irradiance of the parks of Table 3 in a horizontal plane is 154 W/m^2. Hoogwijk [26] estimated 180 W/m^2, considering the average irradiance over suitable places for PV parks (an increase of 15% with respect to the parks of Table 3).

Therefore, the future global average electric power density is very difficult to estimate, and even though cell efficiencies and the average irradiance will tend to improve, according to previous discussion, we think that the final power density could even be worse than at present. The density of occupation, f_3, will be worse due to the land requirements for storage and the necessary new infrastructures other than the parks, while the performance ratio, f_2, will also be worse than at present due to the added net losses for the storage systems, the overcapacity being installed to deal with the intermittency problems, the entire new electric networks, roads, etc., and the material limits that will probably impose lower efficiencies for the technologies (see Section 5).

Taking all these arguments into account, we estimate the future density of ρ_e assuming the following hypotheses: the average irradiance might improve by 15%. We estimate that f_1 (the cell efficiency) will go from 12.5% (our calculated average for the parks of Table 2) to an average of 15–25%. We estimate (optimistically in our opinion) f_2 to be in the range of 80–90% and f_3 to be in the range of 70–80% of the previous calculated values for f_2 and f_3. With those estimates, the future power density could be roughly in the range of ρ_e=2.5–5 W_e/m^2, which means that the average would be approximately the same as the present one.

In terms of LUEI, our equivalent range is 22.8–45.7 m^2yr/MWh, which is included in the range 5–55 (m^2 yr)/MWh that has been reviewed [44]. However, our estimate is located on the "pessimistic side" of this range, and quite far from other assessments, as reflected in Table 1.

If this density (3.3 W_e/m^2), which we think is more realistic, is used to estimate the global power potential, taking the geographical potential calculated by other authors (as in Table 1), the resulting values are shown in Fig. 7. One can see that these potentials we calculate with our density are significantly lower than the ones estimated by those authors, some of them even being below 10 TW_e.

5. Competition between solar energies and other human activities

The projected growth of human population and the demand of land for settlement, infrastructures and food production may compete for the land with solar energies, and may impose constraints to its expansion. Energy, materials and capital will also be required in the next few decades for the infrastructures of a growing population, as well as for the solar energy industry.

In this section, we compare the needs for land and materials of solar energy with the projected occupation of soil for several uses. Although this comparison does not pose a limit or physical restriction on solar power potential per se, it is an indication of the challenge that the transition to renewable energies poses on humankind (a sustainability criteria).

5.1. Competition for surface area

More than 75% of the Earth's land not permanently covered with ice is altered as a result of human settlements and other land uses [55]. The Earth's surface, therefore, is already highly altered as a result of human population, and solar energy on a large scale could add even more human pressure on it [56].

Present direct land occupation for human settlement and infrastructures is roughly 200–400 MHa [57–59]. The foreseeable growth of land for food for the next few decades (due to population and affluence growth) is projected to be 200–750 MHa [60–63], while the projected growth of new infrastructures because of population and affluence growth is more than 100 MHa. According to FAOSTAT [64], there were 1526 MHa of arable land and permanent crops in 2011. Therefore, in the next decades, between 2000 and 2800 MHa of land surface will be necessary for food production and human settlement. This would imply a decrease of permanent meadows and pastures of between 15% and 39%, if forest land does not decrease.

In most cases, human settlement and solar infrastructures will compete for extra land, because present architectural designs are not very compatible with solar power. Sorensen [28] and La Gennusa et al. [65], for example, estimate that only a small percent ($<2\%$) of cities can be covered today, with enough efficiency, with solar panels, in such places as building roof-top surfaces. Although we could expect a greater compatibility in the future, changes in building infrastructures are very slow.

Let us compare the needs for land required for solar energy according to the technical potential estimated by the authors of Table 1 and using the solar density we have estimated as realistic. The results can be seen in Fig. 8. The potential estimated by Jacobson and Deluchi [7], for example, equals all the future needs for agricultural land of humankind. Although this is not physically impossible, it is hard to imagine that a surface equal to all the crop fields of the World could be covered with solar panels in the foreseeable future. It is not difficult to imagine that the visual and ecological impact of such a large scale human intervention would be enormous, and the human effort involved in such a huge transformation of the landscape too.

The estimations of some authors [6,25] are based mainly on the hypothesis of the use of desert surfaces for solar power infrastructures. Although this would, a priori, mean that competition with other uses was lower, it does not imply that the building effort and impact on the ecosystems would be less. In any case, we think it is more reasonable to think that solar panels will preferably be located in semi-arid locations with access to water and populated areas where maintenance staff may live, and not too far from the consuming centers.

Even relatively small estimations, such as that of Grassl et al. [24] (which also account for sustainable restrictions), would need a surface similar to 20–40% of today's human infrastructures, which would still have a big impact on the landscape; but this amount, to us, does seem compatible with common sense and any sustainability criteria.

In any case, it would make sense that, prior to making those extraordinary investments, humankind will question whether such energy is really needed [50,56], and it is foreseeable that the answer in most cases will come from a better management of the demand that would significantly reduce the need for new solar infrastructures.

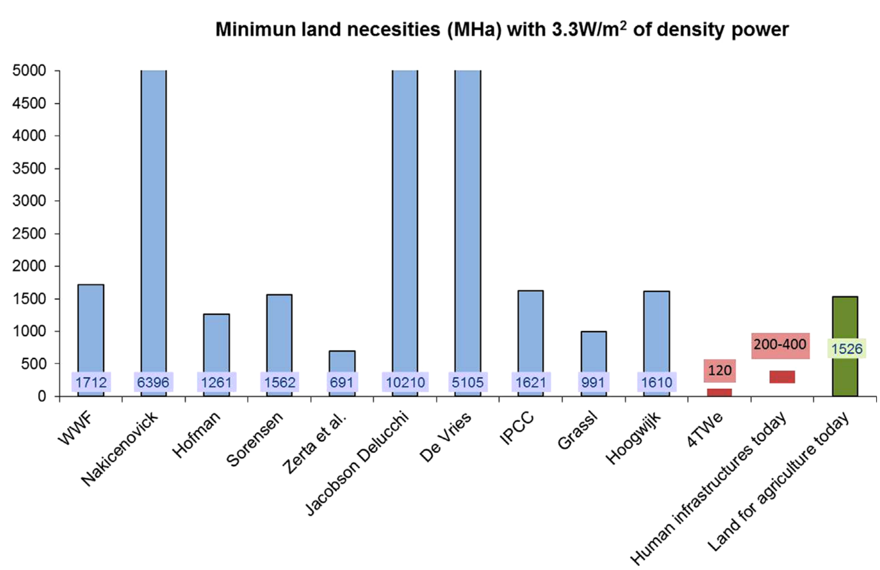

Fig. 8. Minimum land necessities with our estimated power density (3.3 W_e/m^2) to reach the technical potentials of Table 1 (blue columns). For comparison we represent: the land necessities for a net power production of 4 TW_e (red column), the approximate present total human settlements and infrastructures (red bar) and the land dedicated to agriculture today (green column) (see text). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.2. Competition for materials

The building up of large scale solar infrastructures will require large amounts of natural resources like metals and rare elements. Photovoltaic technologies could have less surface area than CSP per TW_e, but at present they have a strong dependence on rare or scarce elements. On the other hand, CSP technologies could compete with PV technologies if they are used with energy storage capabilities.

5.2.1. Photovoltaic technologies

In García-Olivares [66], the materials required to scale-up PV technologies over the TW_e level are studied. They conclude that thin-film technologies, such as Cd–Te or CIGS, cannot scale-up over 0.1 TW_e, due to reserves of tellurium or indium [67]. p-Si technologies cannot scale-up over 0.1 TW_e; with present technologies normally being applied, and with improved efficiency in the use of silver, they will use more than 140,000 t(Ag)/TW_e, making the terawatt level deployment very difficult. Amorphous Si and nano-Si have the same limit as other thin-film technologies because of the indium used, although they can substitute the electrode, using ZnO instead of indium, in which case nano-Si could have the Ag limit of other Si technologies.

In this sense, only a-Si, of the Si technologies, could scale-up well over the 1 TW_e, since they do not use Ag electrodes. However, to overcome their very low cell efficiency, present technologies are using micro- and nano-Si with a-Si that have the Ag limit.

Concentrated solar PV is the other PV technology that has no apparent problems with material resources to scale-up over 1 TW_e, but the land requirements per watt delivered are superior, as they are attached to double-tracking technologies. As we showed earlier in Section 3, the f_3 factor could be 3 or more times lower than that for a fixed panel. Therefore, even with a double efficiency of panels, the ρ_e will be worse. So it seems that overcoming the material limits on solar power technologies implies worsening the present best technological efficiencies being used and, therefore, increasing land necessities.

It is important to note that Feltrin and Freundlich [67] use an unrealistic and generous estimation of the real necessities of minerals for PV application. There are three reasons for this: they suppose a 100% rate of recycling, they suppose that this rate of recovery is free of energy costs and that the PR is only due to 5% of shadowing (PR=95%). However, we demonstrated in Section 3 that the losses are considerably bigger.

5.2.2. CSP technologies

Present CSP technologies use sodium and potassium nitrates as part of the energy storage system, while most present mirrors for CSP are based on silver. These two resources could be the main material limits to CSP expansion.

Scaling-up to the TW_e with this technology would need 855 Mt of sodium nitrate/TW_e and 570 Mt of potassium nitrate/TW_e (extrapolating the necessities of the Andasol CSP plant [66,68]), which is more than the reserves in mines (estimated at 1000 Mt for sodium nitrate and 100 Mt for potassium nitrate [60]). Therefore, synthesis via ammonia and urea using natural gas, as the fertilizer industries actually do, could be an imperative.

Present mirrors for CSP use silver at rates of 1 g/m^2 [69]. Taking the Andasol and SEGS field area and their net solar electric production, 1 TW_e of power would need $2.5–3.5 \times 10^{10}$ m^2 of mirrors, which would require 25–35,000 t of silver.

Proven reserves are less than 270,000 t and the reserve base (which, at present, accounts for uneconomical mine deposits) is less than 570,000 t [67,71]. The most important aspect to note is that the present rate of consumption of silver is 23,800 t/yr [72] and that less than 5% is for the CSP and PV industries (own calculations). This means that, with this rate of consumption, economic reserves will be exhausted in less than 15 years, and total reserves in less than 35 years [71]. Although strong recycling of silver will be quickly encouraged (up to 80%; at present the USA is recycling 43% [72]) and accepting that 100% of the resource base will be extracted, the peak of silver consumption, following Hubbert's theory, will be in 20–25 years [73], putting pressure on the development of any new Ag-based technology. Therefore, if CSP is based on Ag mirrors, reserve limits would imply strong competition with other uses and the necessity to recycle the silver, which would mean higher costs for this technology.

Mirrors based on aluminum do not have this problem, although they have less reflectivity than Ag based mirrors [70]. Therefore, Al mirrors could lower the power density attained by Ag based CSP.

Phil et al. [74] review the material necessities of CSP technologies (parabolic trough and solar tower) based on two examples. They acknowledge some important problems with both nitrate salts and silver, and also with nickel, chromium and molybdenum, among other metals for the terawatt deployment of CSP technologies. They think that their assessment is a "worst case backdrop situation" that could be overcome with technology and good planning. However, as in the rest of the cases that we analyzed in this paper, they grossly overstate the net density power of these technologies and, therefore, substantially underestimate the real material necessities of these technologies. From their parabolic trough technology with storage calculation, we obtain a density power of 10.62 W/m^2, and 4.24% of the solar radiation being transformed into electricity; for their central tower example, the figures are 14.27 W/m^2 and a 4.6% of the solar radiation converted to electricity. However, as we have discussed before, we get less than 2% of the solar radiation being transformed into net electricity. The 2–3 factor of difference with our calculations is in part due to the greater land necessities (that will require some material necessities like more fences, land movements, etc.) than those usually reported, and because Phil et al. [74] likely ignore the energy self-consumption of these plants and the energy being not for the solar system but for a natural gas co-plant that usually accompanies CSP technologies. Therefore, the material needs are much bigger than those reported in Phil et al. [74] per net watt delivered.

6. Estimations of reasonable global potential

Although all these comparisons do not pose a limit or physical restriction on solar power potential per se, they tend to show that, as reflected in Table 1, other assessments are probably exaggerated. The majority of them take into account neither the Feltrin and Freundlich [67], Wadia et al. [75], García-Olivares et al. [66] discussion nor our above discussion on material limits. Only Jacobson and Delucchi [7] give some credit to this problem and cite Feltrin and Freundlich's work, but without enough detail. Proof of this is that their main scenario is for 2030, when the new technology to overcome the mineral limits has no time to develop. They take, for instance, 2.3 TW from CSP to be delivered in 2030, an average of 0.125 TW/yr from now to 2030 without consideration of Ag and nitrate problems. They also take 2.3 TW from PV when the best technologies to overcome the mineral limits are still in the development phase or have much lower cell efficiencies than they use for their estimations. If there are some difficulties in surpassing 1 TW_e with the present technologies due to material limitations; more than 20 TW_e, as all the authors of Table 1 give as a technologically realizable potential, seems extraordinarily optimistic for the foreseeable future.

If we had to give an estimation of the reasonable global solar potential in the 21st century based on the previous discussion, we would consider the one of Grassl et al. [24], who also estimate a sustainable potential. Correcting their power densities with our 2.5–5 W_e/m^2, they would reach 2–4 TW_e.

This is one or two orders of magnitude less than the technological or sustainable potential estimations given in Table 1 and of the same order as the economic scenarios contemplated by BAU and ECO scenarios with a transition to renewables for 2030–2050. These scenarios mainly address economic and political problems and not technological ones, because they are based on the hypothetical belief that they are far from the demand-supply necessities: for instance, Jacobson and Delucchi [7] see 340 TW as realizable as against a demand for 2030 of 4.6 TW; or WWF [9] see a realizable potential of 27 TW in 2050, but their demand scenario will use around 2 TW.

If the technological-sustainable limit at the end of this century is 2–4 TW_e, the scenarios of transition to renewable energy like the business as usual [4,7,8,76] would be impossible. ECO scenarios [5,9] could also have technological problems to resolve not foreseen in their assessments, although these may not be impossible. If we take into consideration our previous work on the technological limits of wind energy [2], this conclusion is reinforced.

7. Conclusions

Renewable energies are the main hope of substituting the fossil-based energies, which are already entering their decline, and their environmental impact are much lower than that of fossil and nuclear technologies. Despite the uncertainties of technological forecasting, each of the renewable energy sources has a maximum global potential. These limit values are quite difficult to calculate, but an overestimation of them may lead to dangerous policies. An optimistic evaluation of the solar potential might lead, for example, to an underestimation of the needs for improvement in saving and efficiency; or might lead to unreasonable investments on expensive energy-producing infrastructures which might not be profitable, since the high price might reduce energy demand.

This paper develops a top-down method with some considerations that lead to a new estimation of the maximum global potential of solar electric power. Based on a realistic estimation of the energy density of present and future technologies, we consider that the techno-sustainable limit for electric power from solar energy in the 21st century could be 2–4 TW_e (65–130 EJ/yr). This is one or two orders of magnitude less than the technological or sustainable potential of other estimations.

In some previous works about the global potential of solar electric power, several restrictions have not been considered and, therefore, the maximum potential may have been overestimated. The results of this work contribute to a decrease in the growth prospects for global energy consumption.

Although this limit might seem low, present net average power production from solar is around 0.25 EJ/yr (0.008 TW_e) [46]. Therefore, our estimation would imply a huge growth in solar technologies, which could multiply by more than 100 in less than a century.

However, it seems that, in the next few decades, solar and wind energy will be the two main sources of renewable energy which might substitute the decline of fossil fuel extraction, and the limits we estimate for both [2,18,20] are lower than the current final consumption of energy by means of fossil fuels.

Since the studies about the decline of fossil fuel production in this century talk about a 50% reduction or more in their availability by the end of this century (due to geological limits and/or environmental restrictions [77]), and the overall potential of both fossil and renewable energy by this date is lower than present consumption, the expected energy transition could not be made with the concourse of renewables in a business-as-usual scenario alone [43,50,51]. A change to a lower per capita energy demand, as some scenarios contemplate [5,9], will also be required. This has strong political implications, even outside the energy transition debate, for instance, in the political decisions on the climate change problem. The IPCC 2012 on renewables [16] concluded that there are no technological limits to the necessary energy transition to renewables (to avoid dangerous climate change with continuous world economic growth), but our conclusions differ: biofuels [3], wind [2] and solar power (this work) have technological and sustainability limits much closer than thought and therefore scenarios of the future must contemplate them.

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