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Global solar electric power potential: technical and ecological limits

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Abstract:
This paper makes a global assessment of the technical and ecological potential of solar electric power.
Despite renewable energies offer a great theoretical potential of energy and most of them are in the first steps of their development and exploitation, their limits should be carefully analyzed. While other methodologies are based in theoretical efficiencies of renewable energies or generous estimations of effective global surface than could be occupied by the renewable infrastructure, our assessment is based on a top-down methodology (Castro et al., 2011) that takes into account present real efficiencies and surface occupation of technologies, land competence and other limits such as mineral reserves.
Although some uncertainties can not be avoid, our estimations for the global potential of solar electrical power are 1,75-4,5 TWe, which implies a hard techno-ecological of solar power potential, much lesser than other assessments.

Key words:

Renewable energy potential; solar energy; global energy assessment;

1. Introduction

Given the limited nature 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 (Zerta et al. 2008, Greenpeace 2010, Jacobson 2009, Jacobson and Delucchi 2011, Schindler and Zittel, 2007, Deng et al. 2010).
The present primary power consumption is 16TW (EIA, 2009); although energy efficiency and the quality of renewable resources could improve over time with respect to non-renewable energies, the expected increases in population and per capita energy consumption mean that the demand for renewable energy, overall, may well exceed 10 electric TW (=10TWe) at the end of this century. Thus, for instance, Nakicenovick et al. 1998, forecast global needs of primary energy of 25-65 TW (for 2100), Nakicenovick et al. 2000, 26-42 TW (for 2050), EIA 2010 roughly 24 TW (for 2035), Schindler and Zittel (2007) more than 25TW with 16TWe from renewables for 2100, and Jacobson and Delucchi (2011) believe that 11.5TWe is possible for 2030 from renewables.

However, the nature of renewable energy flows and their essential use by natural ecosystems make the achievable technical potential of renewable resources other than solar power (wind, biomass, hydro, etc.) limited to values much lower than present consumption of non-renewable energies (Smil 2008). Wind has a technical electric potential of roughly 1TWe (de Castro et al. 2011) and many wind assessments and scenarios are flawed because they take more than 1 TWe, (e.g. Jacobson and Delucchi 2011, Deng et al. 2011, Greenpeace 2010, De Vries et al. 2007, Zerta et al. 2008) as realisable potential during XXI century. Acknowledging the high dispersion of these resources and their role in the energetic and material fluxes of ecosystems, only direct solar power among the renewables has the technical potential to exceed 1 TWe (Smil 2008, present work).

Section 2 reviews the estimations of global PV solar power potential present in the literature. Section 3 and 4 calculate the global technical potential of solar PV energy density at present and in the foreseeable future. In section 5, we make a preliminary estimation of ecological land potential for solar installations. In section 6, we introduce the material limits and their relation with land potential and finally, in section 7, conclusions are extracted.

2. Previous estimations of global solar electric power potential

The power that the sun shines on the Earth is huge (174000TW), 86000TW being over land (Hermann, 2006). Given that the global ice-free land is around 13000 MHa, the theoretically attained power would be about 21840 TW.

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

Current or future geographical technical electric power potential will be: $P_T = S_G \cdot \rho_e$, where ρ_e is 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.

By comparison, solar energy power density has an average of 168 W/m^2 (Hermann, 2006); if it could get all this power density, it would capture about the same on average, effectively and considering all uses of land occupation, as the fossil energy industry (oil, coal and natural gas): more than 150 W/m^2 (Smil, 2008). However, this is impossible. 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. This requires much more land dedicated to photovoltaic energy to provide the same power than is required by the fossil fuels industry.

Biomass for energy (Smil 2010, Smil 2008) is even less efficient in this sense, because typical primary power densities are well below 1W/m^2. If the land extent were the main limit to these energies, their theoretical densities mean that solar power is a better choice than biomass; therefore, the potential for solar power are bigger, at least one order of magnitude, than the biomass power limit if we take the same surface potential S_G.

Solar power densities for photovoltaic (PV) parks are roughly equal to (Smil 2010), or even better (Jacobson 2009) than other solar technologies for electricity production such as CSP (concentrated solar power) systems, which means that the cost per watt installed is much cheaper for PV than CSP, making CSP projects in USA partially change to PV (REN21, 2011). For this reason, in this work, we will concentrate on the PV systems, but we do not exclude CSP technologies.

Authors	Technical Power potential (TWe)	Present power density (W_e/m^2)	Future power density (W_e/m^2)
DeVries 2007	170-490	20	25-50
Deng et al 2010	57		
Rogner et al 2000	50-1580	17	
Grassl et al 2003	33 (sustainable)	23.5	42
Jacobson 2009	170-340	12.6-16	
Nakicenovick 2000	>213		
Hoogwijk et al. 2008	53.6	14.4	24.4
Hoogwijk 2004	42.2	18.6	
Hofman 2002	42		
Sorensen 1999	52		
Zerta et al 2008	23-46 (sustainable)		
This study	**1.75-4.5**	**<3.5**	**3.5-4.5**

Table 1. Technical potential of solar PV power. In some cases, the present and future solar power densities that authors calculate, or that can be inferred by their work, are indicated.

To calculate the geographical potential (S_G), Hoowijk (2004, 2008) excludes urban, forest and natural reserve soils, assigns 5% occupancy to extensive grasslands and hot deserts and 1% to the rest of soils. Instead, Hofman et al. 2002, also excludes high step mountains, agricultural areas and low irradiance sites (<120W/m^2), but allocates 5% for the remaining land occupation.
To calculate the technical potential, the authors of table 1 first assigned current solar cell and solar park efficiencies (based mainly on theoretical grounds) and then forecast the future feasible technical potential for the solar PV industry based on future cell efficiency; they do so taking once again the theoretical value potentials and/or extrapolated past or current trends into the future.

3. <u>Estimation of current technical density power potential of solar PV, ρ_e</u>

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

$$\rho_e = I \cdot f_1 \cdot f_2 \cdot f_3 \qquad (1)$$

Where:
f_1 is the conversion efficiency of solar radiation into electricity in the PV cells.
f_2 is the loss of solar radiation energy in the PV modules, in power converters, by cell degradation, failures, etc. In the technical literature this is known as PR, the performance ratio.
f_3 is the actual occupation of PV cells on the total land occupation of the solar photovoltaic industry.

As will be demonstrated using equation (1), the recruitment and ongoing transformation of solar energy density into electricity on current solar plants is much lower than the theoretical studies of the table 1 shown.
In table 2, the six largest photovoltaic plants, rated by nominal power, in operation worldwide (as at November 2010 and with surface occupation data that could be retrieved on manufacturer web-pages) are reported. They expect power conversion efficiencies per unit of area occupied by park facilities well below $10W_e/m^2$.

Solar PV plants	Expected production GW·h/year	Surface occupation Ha	Density power W_e/m^2	Radiation % converted into electricity
Finsterwalde (Germany)	74	198	4.26	3.32
Sarnia (Canada)	120	365	3.75	2.11
Olmedilla (Spain)	87.5	180	5.55	2.54
Strasskirchen (Germany)	57	135	4.82	3.15
Lieberose (Germany)	53	162	3.71	2.67
Moura (Portugal)	93	250	4.24	1.39
Total	**484.5**	**1291**	**4.28**	**2.22**

Table 2. The largest solar PV power plants operative in November 2010. Surface and expected production data from solar companies that own the plants and from the manufactures of photovoltaic modules as found on their respective websites. The percentage of radiation transformed into electricity is the theoretical electricity density power expected on 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). All the parks are PV fixed mounted modules except the Moura plant that has a one-axis solar tracking technology. Sarnia and Lieberose have thin film (Cd-Te) cells, Olmedilla m-Si cells and the rest p-Si cells.

We will recalculate table 2 using equation 1 for our own estimations (see table 3).

1.- f_1: Conversion efficiency

We will take f_1 as the solar cell efficiency as reported by their manufacturers.

2.- f2: Performance Ratio

The net electricity generated in these parks is lower than expected because the solar companies assume an overstated performance ratio (PR), 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
- soiling
- bird droppings over modules, and/or
- energy self-consumption by the maintenance of solar park installations (e.g. module washing).

We will take f_2 as 0.60 for parks with silicon modules and 0.70 for CdTe (thin film modules). There are many performance ratios calculated in the scientific literature and are reviewed, for instance, in Mondol et al. 2006. The range of values found is typically 0.4 to 0.8. In Germany, the monitoring results of 250 grid connected PV systems gave a mean of 0.67 (Jahn & Nasse 2003). Jahn & Nasse (2003), gave an average of 0.66 for 1983-1995 parks and 0.70 for 1996-2002. 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 reported PR and the measured PR difference is due to the actual power of the installed PV arrays being below the rated power declared by the manufactures (Lorenzo 2005). PR calculations disregard the future availability losses because they take the current availability of new or relatively young parks and a growth of availability losses over time due to 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 & Nasse (2003) 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% by year, with an average of 0.7% (Skoczek et al. 2009, Vazquez & Rey-Stolle 2008, Osterwald et al. 2002). If the life time of a solar park is extended to 40 years, considering that defective materials and modules will be replaced if necessary, a 0.6%/year of cell degradation for the surviving cells means a net electricity loss of 12% averaged over the entire life time. The current parks probably have a shorter life expectancy but higher average cell degradation; therefore, the better the cell performance the better the life time of the parks, offsetting each other because cells will be working longer with relatively high cell degradation. If a new solar park has a PR of 0.7, future cell degradation leads to an average PR of less than 0.65.

Other factors do not improve PR estimations, for instance, module washing, monitoring, surveillance and maintenance are part of self-consumption that requires energy and occupation surface. For instance, an estimate of $15m^3$/MW-year of water for washing results in a 0.2% of self-consumption solely for this purpose (Prieto and Hall 2011).

For silicon cell modules, we conservatively 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 Finsterwalde, Olmedilla, Strasskirchen and Moura parks is 12.1%), 0.88 for cell degradation (see above), 0.95 for availability and self-consumption, 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 is: $0.88 \cdot 0.88 \cdot 0.95 \cdot 0.95 \cdot 0.85 < 0.60$.

For Cd-Te thin film technologies, the PR will be better mainly due to lower temperature losses. For Sarnia and Lieberose, with this technology, we will take the PR as 0.70.

For the case of the entire PV system of Spain, an extensive study by Prieto and Hall (2011) finds, conservatively, a PR of 0.65, taking into account the future degradation of the cells, but ignoring availability and self-consumption, shading and other losses.

3.- f_3: Actual occupation of PV cells

The f_3 factor is estimated for each solar park taking the actual solar cell occupation (not the modules) divided by the total land area occupied by the solar parks estimated by manufacturers. This estimate is very conservative (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 (Kymakis et al. 2009), the authors take an active solar area (total PV cells 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 footprint, through the Google maps tool, shows that the total area occupied is greater than 5000 m^2.

For the solar parks in table 2, the reported occupation in the Lieberose park is 162Ha, but this is only the direct occupation of PV panels. As can be seen in figure 1, the plant occupation is greater than 250Ha if we also take into account the deforestation area needed to avoid shading by trees. This means that the f_3 factor for Lieberose is <0.181 instead of 0.280 used in table 3.

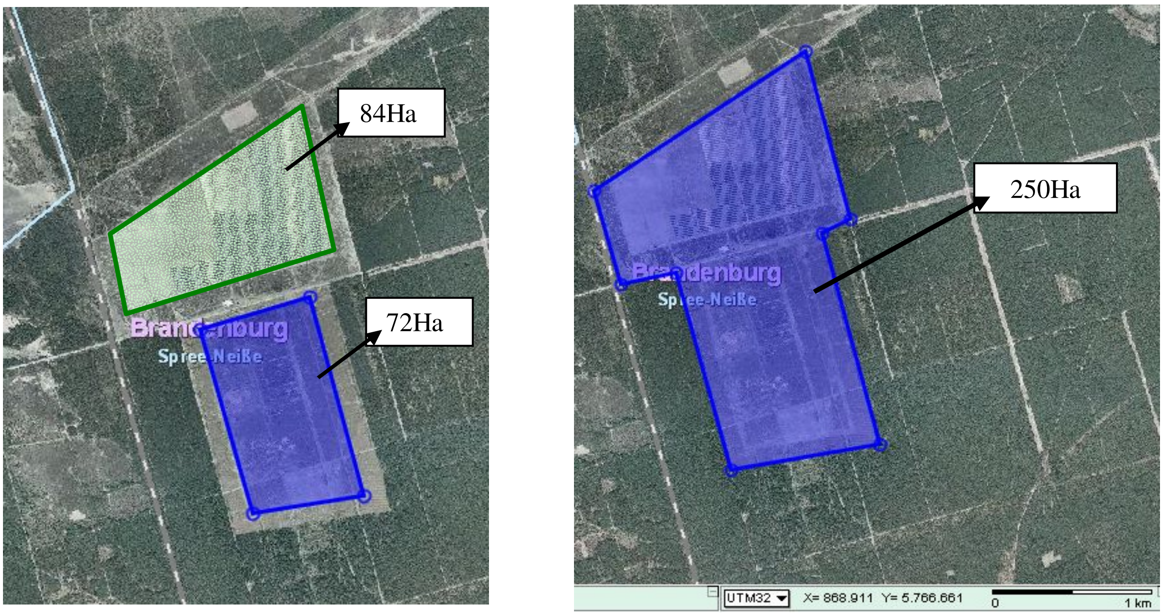

Figure 1. Lieberose solar park as seen from www.geodatenzentrum.de. On the left, the direct solar PV modules occupation. On the right, the total solar field occupation.

Another example, with a different technology, is the reported 650Ha of the SEGS I-IX installations (CSP technology) in the California desert against the actual occupancy of more than 1000Ha through the Google map tool. 650Ha is the actual occupation of the solar field mirrors, not the actual footprint that 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 by at least 25% (Kelly 2005, Jacobson and Delucchi 2011) the footprint of the installations, reducing this % of radiation transformed into electricity and confirming that CSP does not improve the electrical power density compared to PV technologies (Jacobson 2009).

Solar PV plants	f1	f2	f3	ρ_e W_e/m^2	Radiation % converted into electricity

Finsterwalde (Germany)	0.15	0.60	0.272	3.40	2.45
Sarnia (Canada)	0.091	0.70	0.231	2.44	1.47
Olmedilla (Spain)	0.145	0.60	0.219	4.45	1.91
Strasskirchen (Germany)	0.15	0.60	0.243	3.64	2.19
Lieberose (Germany)	0.091	0.70	0.280	2.19	1.78
Moura (Portugal)	0.15	0.60	0.118	3.50	1.15
Total average	**0.125**	**0.64**	**0.221**	**3.40**	**1.77**

Table 3. Expected average efficiency of the largest solar parks. See text for explanations.

In the case of Spain, the 3.5GW installed until late 2008 (2.76GW installed in 2008) gave 685MW_e after the inverters (but before the grid) in 2009. Prieto and Hall (2011) estimate 3Ha/MWp in fixed installations, 4.5Ha/MWp for one-axis tracking systems and 6Ha/MWp 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 10Ha/MWp. Therefore, taking our results for two-axis, and accepting Prieto and Hall's (2011) results for one-axis and fixed systems, the total land occupation of the PV system in Spain is 17500 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, we take the future cell degradation, availability and grid connection losses, less than 3.5W_e/m^2 is the averaged net power density for the entire PV system of Spain and a percentage of solar radiation converted into electricity < 2%, confirming the results of table 3 for a country with good irradiance and very modern PV infrastructure.

We will take, therefore, the global current average electric density power as roughly ρ_e < 3.5W_e/m^2.

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 efficiencies than 15%, because thin film technologies, as evidenced by Sarnia and Lieberose parks due to their economical advantage, may lead the way of the future. Thin film's share of the global market increased from 14 percent in 2008 to 17-19 percent in 2009 for cells (REN21, 2010), although it declined, for the first time since 2005, to 13% in 2010 (REN21, 2011).

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 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 Finsterwalde and Strasskirchen parks (see table 3).
If 5% of hot deserts were used for renewable energy production, as Hoogwjick (2004) and Hofman (2002) do in their estimations, then about 45 million hectares of the Sahara desert would be occupied, but the electricity produced there would mainly be consumed in Europe, and then thousands of Km of new electric lines would be needed; but the solar electricity imported from North Africa to northern Europe will have a 10-15% loss of power in transmission lines (Trieb 2006). This extra loss alone will break all the future technological improvements of PR parks.
If PV ends up being one of the main sources in the electricity mix, then this industry will need support through storage systems (e.g. pumped hydro or hydrogen production), requiring more capital investments, more land occupation and a net loss of final electricity being delivered. 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, although water storage could be used for non-energy purposes, Smil 2008).
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 (Prieto & Hall 2011). It is difficult to predict the future balance sheet of these systems. In recent years, tracking systems have gained share against fixed, and, as is reflected in table 3 for the Moura park (one-axis tracking), the f_3 is much smaller than for fixed systems (it is even lower for two-axis tracking systems, although in theory these systems could have a double use). In table 2, Moura park represents only 20% of the area occupation and the expected production of electricity of the six parks; if one- or two-axis tracking systems gain share in the future against fixed, then f_3 will decrease, not being compensated by the gain in f_1.
If land occupation ends up as a very important factor to be considered in PV projects, then new developments could improve f_3, as some projects are evaluating (e.g. www.solidenergie.com).
The average irradiance on future parks will probably be better than the average optimal (for fixed modules) on parks of table 3 ($177W/m^2$). The average irradiance on parks of table 3 in a horizontal plane is $154W/m^2$. Hoogwijk 2004 estimated $180W/m^2$, considering the average irradiance over the suitable places for PV parks (an increase of 15% with respect to the parks of table 3).

Therefore, the global future average electric power density is very difficult to estimate. If we estimate that the f_1-f_3 and irradiance variations compensate for each other in one extreme and that, in the future, an overall 30% of increase is attained in the other extreme, then we can take, for the future, ρ_e = 3.5-4.5 W_e/m^2. In any case, this is very far from other assessments, as reflected in table 1.

5. A rough estimation of the geographical surface potential, S_G, for solar energies

Although present direct land occupation, mostly in suitable areas for human settlement and infrastructures, are roughly 200-400MHa (Wackernagel et al. 2002, Young 1999, WWF 2008), more than 75% of the Earth's ice-free land is altered as a result of human settlements and other land uses (Ellis and Ramankutty 2008). The foreseeable growth of land for food for the next decades (due to population and affluence growth) is projected to be 200-750MHa (Schade and Pimentel 2010, FAO 2003, Balmford et al 2005, Rockström et al. 2007), but the new land that we could convert to agriculture is 300-500MHa (Schade and Pimentel 2010), or 400MHa in a sustainable way, reverting abandoned agriculture lands (Rockström et al 2009, Campbell et al 2008). This means that it will be impossible to offer the demand tendency for food if the degraded lands continue to grow because more than 350MHa will be lost if present trends continue (Pimentel 2006, Foley et al. 2005). Therefore, either there will be a strong diminution of population/food demand, or desertification and land degradation must be reversed. On the other hand, the projected growth of new infrastructures because of population and affluence growth is more than 100MHa for the next decades, growth that will need enormous quantities of energy and materials (Schade and Pimentel 2010, Young 1999). This means that the construction of a similar area for solar energy alone will impose an important challenge for humanity. Both necessities (human settlement versus solar infrastructures) will compete for extra land because only a small percentage (<2%) of human settlements and infrastructures could be covered with solar panels, such as building roof-top surfaces (Sorensen 1999, La Gennusa et al. 2011). This implies that useful land for renewable energies could have important limits much lower than authors such as DeVries et al. 2007, Nakicenovick et al 2000 and Jacobson 2009 unrealistically project (more than 1000MHa for some scenarios).

For the very densely populated and developed countries like the Netherlands, the infrastructures occupied are roughly 10%; this means that a much lower occupation than 10% could be reasonably attained in deserts and degraded lands, or even 5%, as the factor occupation, following Hoowijk et al. (2008), Sorensen (1999), and Hofman (2002) (without justification), is a very optimistic assumption because roughly 2% is the present total land occupation for all human infrastructures (Wackernagel et al. 2002, Young 1999, WWF 2008). Therefore, we believe that 2% of hot deserts and very degraded lands is much more reasonable as the density limit that could be attained by solar infrastructures, roughly 30MHa. The rest of the occupation of solar power will compete for other uses as we reasoned before: agriculture and pasture lands, biofuels, bioelectricity, moderately degraded lands that must be reversed for agriculture or ecosystem processes, etc. To dedicate another 20-70 MHa, totalling 50-100MHa, to solar electric power will be an enormous and probably unsustainable challenge. Therefore, we will take S_G = 50-100MHa as the geographical surface limit.

6. Material limits to solar power energy

Present solar technologies have energy-material limits to scale-up to the TWe production (Feltrin & Freundlich, 2008, Wadia et al. 2009, García-Olivares et al. 2011). Although surface necessities will be bigger than PV, CSP technologies could compete with PV technologies if they are used with energy storage capabilities. Present CSP technologies use sodium and potassium nitrates as part of the energy storage system. To scale-up to the TWe with this technology will need $1425 \cdot 10^6$ Tn of nitrates/TWe (extrapolating the necessities of Andasol CSP plant, Solar Millenium 2008, García Olivares et al. 2011), more than all the reserves in mines. Therefore, synthesis via ammonia and urea using natural gas, as the fertilizer industries actually do, could be an imperative. $1425\cdot10^6$Tn of nitrates is around 8 times the annual fertilizer production (Heffer & Prud'homme, 2011). Therefore, the TWe level deployment means a direct competition with fertilizer production and natural gas that must be taken into account in the future.

Most present mirrors for CSP use silver at rates of 1gr/m^2 (Kennedy 2010). For the terawatt level $5\cdot10^{10}$ m^2/TWe of mirrors is needed (taking Andasol and SEGS field area and their net solar electric production).Therefore, more than 50000Tn/TWe will be needed. Proven reserves are less than 270000Tn and the reserve base (which at present accounts for uneconomical mine deposits) is less than 570000Tn. This would imply strong competition with other uses, the necessity to recycle the silver and the very difficulty of their scale-up to the TWe range based on these silver mirrors. Mirrors based on aluminium do not have this problem, although they have less reflectivity than Ag based mirrors (Kennedy 2010).

PV also has material limits with all the present technologies being applied to grid connected parks. Thin-film technologies, like Cd-Te or CIGS, cannot scale-up over 0.1TWe, due to reserves of tellurium or indium (Feltrin and Freundlich 2008). p-Si technologies have Ag limits stronger than CSP technologies, with present technologies usually being applied, they cannot scale-up over 0.1TWe, and with improved efficiency in the use of Ag, they will use more than 140,000 Tn(Ag)/TWe, making it very difficult the terawatt level deployment. 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, a-Si could scale-up over the 1TWe since they do not use Ag electrodes, but 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 only technology that apparently does not have problems with material resources to scale-up well over 1TWe, but the land requirements per watt delivered are superior, as they are attached to double-tracking technologies. 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. Therefore, 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.

6. <u>Conclusions</u>

In order to obtain the most reliable and realistic estimation of the global potential of the solar electrical power, some technological uncertainties are still present, but we assume, we think, some "common sense" hypothesis. Based on the previous discussion, we considered that the techno-ecological limit for the electric power from solar energy will be: $P_T = S_G \cdot \rho_e <$ 50-100MHa · 3,5-4,5W_e/m^2 = 1,75-4,5TWe

If we want to come closer to the technical limits found here, then the energy density criterion and the material limits criterion should be prioritized simultaneously over other criteria, such as the economic one. Given this, it would call into question any renewable energy with a much lower net energy density than PV (like biomass for electricity or liquid fuels) and also photovoltaic technologies with low efficiency cells and material limits (Cd-Te or CIGS thin film) or large land occupation (tracking systems), etc., especially when competing with other potential uses, such as land suitable for

agriculture and/or strong material limits (use of Ag, In, Te or other rare elements in their panels).
Solar technical potential has been grossly exaggerated (see table 1) by assuming that the power density of the present and the foreseeable future is much higher than what is actually achievable and also because the geographic potential has been evaluated without taking into account factors of future strong competition and limitation for land use or materials.
The present net power production from solar is around 0.008TWe (REN21, 2011); our results imply a bright future based on our calculated limits because the solar industry could expand more than 200 times (if present growth were maintained we will reach the limits in less than 15-20 years). However, although our assessment for the techno-ecological limit that we have estimated is probably larger than the total amount for the rest of renewables (de Castro et al 2011, Smil 2010), it is lower than the current end of use of energy by means of fossil fuels.
Although renewable energy is often used as a synonym for "green", if they are forced to be used on the same scale as the present use of non-renewable energies, due to their low densities in a material and space-constrained world, they may also end up becoming paradigms of unsustainability.
Some assessments or models project that in the next five or six decades, due to geological limits (Zerta et al. 2008) and/or environmental restrictions (Kharecha and Hansen 2007), the non renewable energies will/must decrease at least by half; since economic limits will be harder than the technological ones, the expected energy transition will not be made with only the concourse of renewables, but a change to a lower per capita energy demand will also be required. Adaptation to a scarce energy World will be a technical and ecological imperative.

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