Photovoltaic materials and solar power plant optimization design in relation to its environmental impact

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Solar photovoltaic (PV) systems for distributed and concentrated energy production are having at present and will have in the near future an exceptional expansion. Solar energy will possibly contribute to about 1/3 of the whole primary supply by the 2070 decade. In the present chapter we analyze the evolution of photovoltaic materials, the possibility to recycle these non-conventional power plants and the way a PV solar power plant impacts the environment. In particular, we consider: the possibility to place this type of power plants in different places of Argentina (Santa Fe province and near San Juan and Jujuy cities), the solar radiation availability in these sites and the produced annual mean electric energy. Regarding the environmental impact, we show results for the efficiencies in energy use and in reduction of greenhouse gases in the construction phase of a PV solar farm. We present general suggestions: a) Make a flux diagram of input/output and use of energy, inert materials, and contamination; b) Use the Total Quality (or other related) technique and Continuous Improvement model in the activities related to all phases of the PV solar power plant; c) At the designing stage, take into account the largest number of possible problems that will appear in the life cycle of the system and the possibility to reuse or recycle materials and the soil of the PV solar power plant that could be used, for example, as a conventional farm; d) Determine the Carbon footprint of the whole phases of the project and consider different actions for minimizing these footprints. Also, we present specific suggestions for the construction phase: a) Reduce to the minimum the change in soil quality, in order to minimize local economical impact after decommissioning; b) Build the warehouse for material storage, auxiliary elements like inverter and the habitat for the personnel that will make the maintenance of the PV solar plant, considering measures for efficient energy use, renewable energy supply and minimum emission of GHG gases, c) Make an inventory of trees that must be eliminated from the terrain and replace them by a larger number of native species in the near area.

Keywords solar; photovoltaic; power plant; energy; CO2; impact; environment

1. Introduction

Climate change is producing at present and will produce in the future a large impact at global level. The global warming of the Earth was estimated by Piacentini and Mujumdar [1] to have a mean increase of 0.57 ºC the last century and the 2007 Intergovernmental Panel on Climate Change/Working Group I Report [2] estimated a large mean increase of about 3ºC by the end of the present century. The significant increase in the use of renewable energies is one of the possible solutions, at least for mitigation of this global warming.

The conversion of solar radiation into electricity using photovoltaic (PV) cells, had a steady increase in the last decades, with a mean increase of 74% from 2006 to 2011, the largest one with respect to the other renewable energy sources (concentrated solar energy 35%, solar water heating 27%, wind energy 20%, etc.) [3]. Also, a UNEP Report [4] informed that in the period from 1992 to 2010 the rise in photovoltaic solar energy was as high as 30,000 %, even larger than the equivalent rise in wind energy (6,000 %). In 2011, 30 GW of PV systems were installed, leading to a global cumulative installed capacity of 69 GW, which has the possibility to generate up to 85 TWh of electricity per year [5]. Commercial solar cells are in the range of 15-20% efficiency conversion, but solar cell efficiencies as high as 70% have been predicted by using novel photonic nanostructure techniques that captures the infrared part of the solar spectrum [6]. Moreover, Jacobon and Delucchi [7], proposed a complete substitution of the fossil fuels for energy production by around 2030, by renewable (mainly solar, water and wind) energies.

2. PV materials and recyclable systems

In the present work, we will analyze PV materials and systems that are contributing to the described large development of the use of PV solar cells and at the same time, the efforts that has been done, in order to: a) Reduce the number of years a PV module needs to be used for supplying the energy needed to compensate for the energy employed in its production and maintenance and b) Minimize the environmental impacts of PV solar power plants.
2.1. PV materials

There exists a general and reasonable consensus, in the present climate change debate, concerning the advantages of PV technology as a source of clean energy. This is based on the fact that sunlight is supplied all over the world for free, without any costs and emissions. Hence, PV systems occupy a relevant position as candidates to conform an important proportion of the long-term massive electricity generation market [8]. However, nothing is really for free and there are certain environmental impacts associated with PV devices which come from: (i) emissions and water use during manufacturing process, (ii) using hazardous materials during fabrication and (iii) land use, which cause some degree of habitat loss at the installation site. The extent of these impacts depends mainly on the specific technology under consideration (crystalline or amorphous, bulk or thin film), on the material (crystalline silicon, c-Si, amorphous silicon, a-Si, microcrystalline silicon, μc-Si, cadmium telluride, CdTe, copper-indium-gallium selenide or sulfide, CIGS), and on the size of the PV installation (ranging from rooftop arrays to large-scale generation plants in the order of some MW).

Emissions and water use during manufacturing are a common denominator in practically all human activities and can hardly be suppressed, but they can somehow be optimized. In the case of PV devices, the environmental impact regarding these characteristics can be estimated by the energy payback time (EPBT) parameter and the life-cycle analysis (LCA) used to obtain the greenhouse gases (GHG) emissions of the product. The EPBT is the operating time period needed by the PV device to provide the energy involved in its production, assembly, transport, installation, maintenance and final disposal, while the LCA permits to determine the equivalent amount of CO₂ delivered to the atmosphere through all those stages. The EPBT depends on the type and the location of the PV system. The EPBT of c-Si modules is in the range of 1.5–4.4 years between southern and middle European irradiation conditions [9]. In turn, for CdTe solar cells it lays between 0.8–1.1 years [10] and 1.5–2.8 years for CIGS modules, as was determined in 2007 [11], depending on the installation. Sherwani et al. [12] have reported an EPBT of 2.5–3.2 years for a-Si modules at different installations around the world. Because of the continuous improvements on production processes and material utilization, the EPBT has been decreasing over time [13]. In the case of c-Si modules installed on rooftops in Southern Europe (1700 kWh/m²/year), the EPBT has decreased from 3.3 years in 1990 to 1.75 years in 2009, and continues to diminish. The thickness of c-Si wafers has also been dropping with time, from ~ 400 μm used in 1990 to less than 180 μm used now. The utilization of thinner cells and the increase in efficiency caused that the amount of material needed to produce a given amount of energy has also been declining steadily, from more than 16 g/Wp in 2004 to ~ 6 g/Wp presently [14]. Figure 1 compares the EPBT of different technologies for the same geographical location (Southern Europe), taking into account all the contributions to the PV system [15]. These EPBT’s approximately double for a location with a lower solar irradiance, like Central Europe (Germany).

![Energy payback time of different PV](image)

Fig. 1 Energy payback time of different PV systems installed on-roof in Southern Europe with an optimum inclination of the modules. Data from 2009, with the following module efficiencies: c-Si (mono) = 14%, mc-Si (multi) = 13.2%, ribbon Si = 13.2%, CIGS = 10.5%, CdTe = 10.9%, amorphous Si (a-Si) = 6.6%, micromorph Si (μm-Si) = 8.5%. For a-Si and μm-Si the contribution to the EPBT of take back and recycling is not yet considered.

Data taken from Ref. [15].

Regarding GHG emission estimations, most results for PV systems are between 0.03–0.08 equivalent (this and other GHG) CO₂ kg/kWh, which is far below the GHG emissions values for natural gas (0.3–0.9 equivalent CO₂ kg/kWh) and coal (0.6–1.6 equivalent CO₂ kg/kWh) [16]. Generally, the lifetime of these technologies is in the range between 20 and 30 years. Therefore, from an energetic and environmental point of view, the advantage of PV technologies in this aspect has been proven. Figure 2 shows the evolution of energy delivered by a typical house rooftop PV installation, with 2 years of EPBT, during its whole life cycle and covering half of a common household electrical consumption. A net energy gain is evidenced with a subsequently reduction in CO₂ emissions [17].
The use of hazardous materials is also common to all PV technologies. The manufacturing process requires cleaning and purifying the surfaces of semiconductors and substrates. These chemicals include, among others, hydrochloric acid, sulphuric acid, nitric acid, hydrogen fluoride, 1,1,1-trichloroethane and acetone. The amount of chemicals used depends upon the cell type, the cleaning level that is needed, and the size of the device [18]. Nevertheless, if PV manufacturers attain to the corresponding regulations and procedures, the risks of exposure and the problems of waste processing can be substantially reduced. In relation to active materials in PV devices, both CdTe and CIGS solar cells possess the disadvantage of incorporating semi-toxic or toxic elements like Cd and Se. Si based solar cells also present the problem of exposure to Si dust inhalation, but being a much more manageable issue than toxicity of other elements.

Land occupation can raise concerns regarding habitat degradation or loss. Total area requirements vary depending on PV technology, site topography and solar irradiation. An estimation of the average occupation area per generated power for PV systems is between 6–30 × 10^2 m^2/MW (i.e., between 1 and 5 soccer fields per MW). However, the environmental impact due to the requirement of land occupation turns to be minor since mid- or large-scale PV installation’s site can generally be chosen at lower-quality areas, like brownfields, unused mining lands or even existing transportation corridors [19]. Smaller PV systems can, in turn, be built on the roof or sides of houses and buildings, reducing further the land use impact.

From all the above, it clearly becomes a difficult task to decide which kind of PV technology has a better or worse score on the discussed aspects. Some studies conclude that a-Si appears as one of the most environmentally innocuous technologies, with µc-Si solar cells at the second place [20]. Other projections, based on today’s viewpoint, incline towards PV devices consisting of a-Si and c-Si layers in tandem configuration as having the potential to conform PV installations on a large-scale of several terawatts (TW) level [21]. CIS, CIGS and CdTe based PV devices are behind those based on Si mainly because they use toxic elements or heavy metals, some of which are rather scarce and whose production will eventually decay.

Figure 3 presents the predicted evolution of the market share of the main energy sources presently available [8]. Oil and gas reserves will unavoidably decay during next decades and renewable energies are expected to increase their integration in the global market share, from an almost negligible relative contribution in 2000 up to more than 1/3 of the total by 2070. Nuclear energy is also expected to participate actively in this projection. However, contaminant radioactive by-products will complicate its expansion, except if nuclear fusion reactors can come to commercial use in the near future. On the other hand, solar energy will present the most marked and steady growth. Feltrin et al. [8] analyzed the future material shortages that will affect the large scale deployment of several PV technologies. The authors have found that, unlike other technologies, classic c-Si and Si-based thin film technologies will be able to reach the required large scale (TW level). Even for these technologies, a fine tuning in some constructing aspects will be needed: finding a substitute for silver, used as front contact in the case of classic c-Si, and replacing indium-tin-oxide transparent conducting oxide, used as front collecting and passivating layer in the case of Si-based thin films solar cells.
Recent advances in chemical and metallurgical routes for production of PV silicon have shown that solar-grade silicon (SoGSi) manufacture can be more energetically efficient than the conventional Siemens process (which uses more than 200 kWh/kg) in a factor of five [22, 23]. Recently, novel Silver® cells made from c-Si wafers have demonstrated the potential for reducing silicon consumption in a factor of 10 to 20 for the same solar module size [24]. Also, these cells have the benefit of requiring from 20 to 40 times fewer wafer starts per MW, in an industrial production environment, than required for conventional wafer-based technologies. Other studies have analyzed the most promising Si-based thin film technologies, which emerged during the last decade like Silver®, hybrid and CSG cells, evidencing that all of them can be scaled-up to an industrial production level [25].

As has been shown, intensive research is being done regarding Si as the main solar material for large scale development of PV systems and installations. Several main advantages raise Si as one of the most important materials to think about, among which are: (i) its abundance, (ii) the maturity regarding its manufacturing processes and (iii) its non-toxicity.

2.2. PV recyclable systems

Although solar cells are known since 1950, the first significant volumes of photovoltaic installations only began in the early 1990s. Considering a lifetime of around 25-30 years for those devices, in the next few years they will start to reach their end-of-life, raising the problem of what to do with used solar modules.

Currently, 90% of the modules that reach their end-of-life are made of c-Si solar cells, while the rest are thin film modules including CdTe, CIGS, a-Si and µc-Si. For c-Si modules, the most ecologically friendly option would be to recover undamaged cells that could be re-used. This concept proved to be possible for solar cells produced in the first stages of the PV industry, for cell thicknesses of around 400 μm [26]. After removing the aluminum frame and the connectors, the process starts with a thermal stage that separates the protecting glass from the metal stripes and the solar cells. The cells then go through a chemical process that leads to wafers that can be re-processed. However, current solar cells have a thickness of around 180 μm – with a tendency to decrease even more – what makes the recovery of complete wafers very difficult. Thus, the recycling objective now changed to recover high-purity silicon, which is then melted and re-crystallized to ingots, from which new wafers are cut [27]. Compared to the production of cells from raw materials, the use of recycled silicon saves a large amount of energy. Table 1 details the approximate composition of a typical c-Si module and the amount of materials that can be recovered from it [28].

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass (kg/m²)</th>
<th>% by mass</th>
<th>Rate recovered (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>10.00</td>
<td>74.16</td>
<td>90</td>
</tr>
<tr>
<td>Aluminum frame</td>
<td>1.39</td>
<td>10.30</td>
<td>100</td>
</tr>
<tr>
<td>Solar cells</td>
<td>0.47</td>
<td>3.48</td>
<td>90</td>
</tr>
<tr>
<td>Polymers</td>
<td>1.37</td>
<td>10.15</td>
<td></td>
</tr>
<tr>
<td>Metal ribbons</td>
<td>0.10</td>
<td>0.75</td>
<td>95</td>
</tr>
<tr>
<td>Adhesives, etc.</td>
<td>0.16</td>
<td>1.16</td>
<td></td>
</tr>
</tbody>
</table>

In the case of thin film solar cells, the amount of semiconductor material that is used is very small (less than 1% of the module mass). The most important materials to be recycled are the glass used as substrate and the metals used for the contacts. For the metals, the same methods used to recycle electronic products can be used.

The viability of a recycling program generally depends on three factors: the geographical concentration of the products, the proximity to the recycling centers, and the market value of the materials that can be recycled. Fthenakis and Mokowith, from Brookhaven National Laboratory (USA), proposed three recycling models for PV panels [29]:

(a) the large users of PV modules (power stations) are responsible for getting the end-of-life modules to the recycling centers. The cost for that would be included in the price of the electricity produced by these large users;

(b) the manufacturers of PV modules are collectively responsible for collecting and transporting the panels to the recycling centers, through the creation of a devoted institution whose operational costs would be covered jointly by the manufacturers;

(c) each manufacturer of PV modules is individually responsible for collecting and transporting the obsolete modules to the recycling centers. The cost of this system would be included in the price that the consumer pays for the modules.

Model (a) would only be suitable for concentrated users, but not for distributed generation in homes or remote locations. Model (b) is now being implemented in Europe through the creation of the non-profit organization PV CYCLE, founded by the PV industry, whose objectives are “to implement the PV industry's commitment to set up a voluntary take back and recycling program for end-of-life-modules and to take responsibility for PV modules throughout their entire value chain” [30]. However, ecologist organizations prefer a model like (c), where the manufacturers are responsible for the entire life cycle of the modules that they produce, including their recycling [31].
The cost in terms of climate change of conventional energy sources is difficult to calculate, but there are some recent works that provide estimations [32, 33]. If the environmental and health costs of conventional energy are taken into account, then the cost of PV electricity would be lower than the cost of some conventional electricity sources. For coal plants, for example, the cost of electricity has been calculated in 2011 to be between 30 and 40 cents of a Dollar per kWh (¢/kWh), taking into account the costs associated to air pollution, human toxicity, climate change, subsidies and land use [34]. For the case of PV electricity, taking also into account all the contributions, the cost would be between 11 and 27 ¢/kWh depending on the solar irradiance [34]. This calculation would make PV electricity very competitive even at the current prices.

3. Minimization of the environmental impacts of a PV solar power plant

In what follows we will describe the ways in which a PV solar power plant (or farm, an excellent name for the present case) must be built, operated and disarmed at the end of its life cycle, in order to reduce to the (possible) minimum its environmental impact.

We make the following general suggestions in order to minimize these impacts in all phases of the PV solar power plant: a) Make a flux diagram of input/output and use of energy, inert materials, and contamination; b) Use the Total Quality (or other related) technique [35] and Continuous improvement model [36] in the activities related to all phases; c) At the designing stage, take into account the largest number of possible problems that will appear in the life cycle of the system, in particular the possibility to reuse or recycle materials (including PV panels as described in item 2.2) and that soil of the solar power plant could be used again, for example, as a conventional farm; d) Determine the Carbon footprint of the whole phases of the project and consider different actions for minimizing these footprints. In particular, for the construction phase we propose the following specific suggestions: a) The flux diagram must contain, at least, a detailed analysis of input/output and use of: i) energy (mainly liquid fuels and gas for logistic and construction), ii) inert materials (construction materials, PV solar modules, panel supports, perimeter fence and any other kind of materials), iii) contamination reducing to the minimum all sources like dust produced by soil removal, GHGs emitted by machinery and noise produced by equipments, etc; b) Reduce to the minimum the change in soil quality in order to minimize local economical impact after decommissioning; c) Build the warehouse for material storage, auxiliary elements like inverters and the habitat for the personnel that will make the maintenance of the PV solar plant, considering measures for efficient energy use, renewable energy supply and minimum emission of GHG gases (see for example, the work of Piacentini et al. [37]); d) Make an inventory of trees that must be eliminated from the terrain and replace them by a larger number of native species to be placed in the near region.

4. Case study: Analysis of a PV solar power plant placed in Argentina

4.1 Solar radiation availability

Renewable energies and in particular solar energy, are having a growing acceptance as a replacement of energy sources that use fossil fuels (oil, gas and coal), due to the rising cost of these fuels and their significant contribution to the global energy matrix. In particular, they contribute over 88% to the Argentina energy matrix (Secretaría de Energía, Argentina 2012, http://energia3.mecon.gov.ar/contenidos/verpagina.php?idpagina=3366). Also, they add to the external dependence on these fuels and the increase in the greenhouse gases (GHG) emission to the atmosphere, which contribute significantly to global warming [2].
Table 2: Photovoltaic solar farm of 10 MW placed in different sites of Argentina with solar PV panels at optimum inclination angle. Column 2: daily annual mean solar irradiation, \( H_{\text{solar}} \) and solar inclination angle of the modules (in parenthesis); column 3: electric energy produced, \( E_{10} \) and column 4: avoided \( \text{CO}_2 \) equivalent emission, \( m_{\text{10CO}_2\text{eq}} \).

<table>
<thead>
<tr>
<th>Site in Argentina</th>
<th>( H_{\text{solar}} ) [\text{KWh/(m}^2\text{day)}] (optimum inclination angle)</th>
<th>( E_{10} ) [\text{MWh}]</th>
<th>( m_{10\text{CO}_2\text{eq}} ) avoided [\text{[TnCO}_2\text{eq}]])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tostado (Prov. of Santa Fe) (29.3°S; 61.8°W; 64 m asl)</td>
<td>5.17 (29.30°)</td>
<td>14,681</td>
<td>7,943</td>
</tr>
<tr>
<td>Villa Minetti (Prov. of Santa Fe) (28.6°S; 61.7°W; 78 m asl)</td>
<td>5.18 (28.60°)</td>
<td>14,635</td>
<td>7,918</td>
</tr>
<tr>
<td>Vera (Prov. of Santa Fe) (29.5°S; 60.2°W; 52 m asl)</td>
<td>5.19 (29.50°)</td>
<td>14,761</td>
<td>7,986</td>
</tr>
<tr>
<td>Garabato (Prov. of Santa Fe) (28.9°S; 60.1°W; 60 m asl)</td>
<td>5.23 (28.90°)</td>
<td>14,804</td>
<td>8,050</td>
</tr>
<tr>
<td>Rosario (Prov. of Santa Fe) (32.9°S; 60.8°W; 25 m asl)</td>
<td>4.97 (32.90°)</td>
<td>14,380</td>
<td>7,780</td>
</tr>
<tr>
<td>San Juan city (31.4°S; 68.4°W; 598 m asl)</td>
<td>5.70 (31.40°)</td>
<td>16,368</td>
<td>8,856</td>
</tr>
<tr>
<td>Jujuy city (24.4°S; 65.1°W; 905 m asl)</td>
<td>6.34 (24.40°)</td>
<td>17,905</td>
<td>9,688</td>
</tr>
</tbody>
</table>

Argentina has a rather high solar radiation incidence over the middle and northern parts of its extensive territory. In Table 2, we present the annual mean daily solar irradiation (solar radiation intensity integrated in the day) for the optimum inclination angle for each indicated place, as determined from the Surface Meteorology and Solar Energy (SSE)/NASA database (http://eosweb.larc.nasa.gov/sse/). This table shows that the Santa Fe province sites have similar solar irradiation (within less than 5%), San Juan has a higher value than the Santa Fe sites and Jujuy present the highest of all values.

4.2 Energy production of a PV solar farm

In order to make a comparative analysis between different sites in Argentina, we present results of the electrical energy that can be produced annually by a photovoltaic (PV) solar plant of 10 MW of power, which is proposed for construction.

Fig. 4 Graphical representation of the fixed 10 MW PV solar power plant modules (at the optimum elevation angle of 28.9°) at the typical place of Garabato (Prov. Santa Fe, Argentina). Note: the panels are oriented to the North and the terrain follows the road orientation which is 10° to the East. The land occupied by the PV solar farm has dimensions of 300 m x 333 m. At bottom left, the grey rectangle indicates the position of the maintenance and housing building (Map source: adapted from Google Earth)

in the province of Santa Fe, Argentina, in particular in the area of highest radiation (Northern Santa Fe), the villages of Tostado and Villa Minetti in the Departamento 9 de Julio, Vera and Garabato in the Departamento Vera, and near Rosario, the most populated city of the province.

In a first analysis, we will perform studies for North Santa Fe region of a photovoltaic power plant for electricity generation that is connected to the electrical system belonging to the Wholesale Electricity Market (MEM) of Argentina, which eliminates the need to incorporate a battery system for accumulation of electricity. To calculate the energy generated and GHG (“\( \text{CO}_2 \) equivalent”) emissions not-emitted, we use the RETScreen software V 4.1 (Analysis
Software Clean Energy Project) developed by Environment Canada, widely used in many universities and institutions of the world (see: http://www.retscreen.net), which employs the climatic and solar radiation SSE/NASA database. In order to run the RetScreen software, the module adopted as a photovoltaic panel is monocrystalline Si with a solar cell efficiency of 19.6%. The normal operating temperature of cells, is considered by the model to that temperature reached when the module is exposed to solar radiation level of 800 W/m², with a wind speed of 1 m/s and an ambient temperature of 20 °C. The temperature coefficient is -0.4%/°C, corresponding to a decrease in efficiency as the temperature rises. Considering a PV solar farm of 10 MW placed at Garabato, province of Santa Fe (Figure 4), the solar collector area needed is 50,970 m², which corresponds to about a little over five hectares. The selected area had 150 trees that are proposed to be planted in a larger number (at least by a factor of 10), in the near region.

In Figure 5 we present a typical situation, considering the necessary separation between the lines of PV solar modules, to avoid almost all the shadow produced by one module over the other (parallel) one and to permit the circulation for maintenance purposes. We made, using the Exotic version 5.5 algorithm, the analysis of this shadowing effect, considering different separations between the modules, with respect to an hypothetical situation where all of them are separated at very large distance one from the other (with almost no shadowing). The results of the mean annual solar irradiation incident on parallel-series array PV solar modules of (2 x 9) 18 panels (1.32 m x 1.66 m) at an inclination angle of 30°, for a PV power plant placed in the Santa Fe province, Argentina and a section of 3 x 9 (= 27) of these arrays, showing the incidence of solar energy over them (see also top and bottom rectangles indicated with arrows) and the available (green) soil for agriculture and animal grows; b. The same section, but showing the daily annual mean photosynthetic active solar radiation (PAR) in units of irradiation, incident on the ground. Note the effect of the shadow of the solar panels on ground (given mainly by the blue color).

In Figure 5 we present a typical situation, considering the necessary separation between the lines of PV solar modules, to avoid almost all the shadow produced by one module over the other (parallel) one and to permit the circulation for maintenance purposes. We made, using the Exotic version 5.5 algorithm, the analysis of this shadowing effect, considering different separations between the modules, with respect to an hypothetical situation where all of them are separated at very large distance one from the other (with almost no shadowing). The results of the mean annual solar irradiation incident on parallel-series array PV solar modules of (2 x 9) 18 panels (1.32 m x 1.66 m) at an inclination angle of 30°, for a PV power plant placed in the Santa Fe province, Argentina and a section of 3 x 9 (= 27) of these arrays, show the incidence of energy over them and the available soil for agriculture and animal growing. We obtained a -4.3% of mean annual solar irradiation with respect to the reference (without shadowing) case, if the separation between the modules is 39% of the horizontal projection of a given module and only -1.3% if it is 75%. Consequently, the needed total area increases by a factor of 1.75 with respect to the original one, being the total area of 8.9 hectares. Another 10% needs to be added for the space corresponding to the perimeter and main circulation roads. So, the total surface is about 9.8 hectares.

We like to point out that the irradiation results shown in Figure 5.a, incident on the module without shadowing is very similar to the corresponding data determined with the RetScreen algorithm. The availability of solar radiation for the agriculture production is shown in Figure 5.b, that describes the daily mean annual mean photosynthetic active solar radiation (PAR) in units of irradiation, incident on the ground. We can see that the lowest PAR value (1.2 MJ/m²day) corresponds to 19% of the total PAR radiation incident on ground without shadowing. It is enough for the growing of grass for animal production (see for example http://discoversolar.co.uk/2012/07/20/renewables-generation-more-than-doubles-its-generation-in-just-one-year/).
Table 2, third column, shows that different sites in Santa Fe province differ in the electric energy production at most in 2.9% (with Garaboto the highest and Rosario the lowest). When they are compared with other possible Argentinian sites in the Andes Mountains, the difference increases up to -9.6% for San Juan city and up to -17.3% for Jujuy city.

Analyzing the electrical energy generated per year for PV solar farms of different powers (10, 20, 50 and 100 MW) at the same Garabato place, we obtained the following linear relation between both quantities

\[
\text{Energy produced annually [MWh]} = \alpha X
\]

where \( \alpha = 0.1E_{10} \) [in MWh/MW], the factor 0.1 comes from the fact that \( E_{10} \) was determined for a PV solar power plant of 10 MW and \( X \) is the electric generation capacity of the PV solar plant [in MW]. For example, a 50 MW PV solar plant at Garabato, Prov. of Santa Fe, Argentina, will produce annually, -applying formula (1), 74 020 MWh, the highest value of all the sites of the same province. The percentage relative difference with respect to the other places of this province is relatively small, within -2.9%.

We also performed different calculations of the energy produced in other regions of the country with large insolation, such as near San Juan and Jujuy cities. The Santa Fe province place with highest solar irradiation (Garabato), has -9.6% difference (essentially due to differences in altitude and latitude) with respect to San Juan and -17.3% with respect to Jujuy. However, it must be pointed out that these differences could eventually be compensated by the electric power loss due to the resistance of the electric grid (wires, transformers system in the about thousand and more kilometers of distance from the Andes region to the Santa Fe province sites), etc.

We made another study considering different possibilities, \( \beta \), for the support (mounting system) of the PV modules: fixed at the optimum inclination angle, uniaxial, biaxial or azimuthal. The corresponding electric energy produced annually by a 10 MW PV solar power plant at Garabato, province of Santa Fe and the corresponding relative efficiencies with respect to the fixed position, are shown in Table 3. Even if the largest gain goes up to 25.1% employing a biaxial mounting system, it must be analyzed in detail if the energy used for the movement of the whole system is much lower than that derived from this gain and also the large increase in costs of the land, since a biaxial movement requires more place than an axial (or fixed) one. These results, within an uncertainty of only several percents, can be extended to the other sites of the Santa Fe province (Villa Minetti, Vera and Rosario).

### Table 3

<table>
<thead>
<tr>
<th>PV module support system (( \beta ))</th>
<th>( E_\beta \text{[MWh]} )</th>
<th>Increase in efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fixed at the optimum inclination angle</td>
<td>14 804</td>
<td>----</td>
</tr>
<tr>
<td>Uniaxial</td>
<td>17 322</td>
<td>17.0</td>
</tr>
<tr>
<td>Azimutal</td>
<td>17 808</td>
<td>20.3</td>
</tr>
<tr>
<td>Biaxial</td>
<td>18 524</td>
<td>25.1</td>
</tr>
</tbody>
</table>

4.3 Reduction in CO2 emission of a 10 MW PV solar farm

We employed the same RetScreen algorithm for the estimation of the reduction in the emission of the greenhouse gas \( \text{CO}_2 \) and others (\( \text{N}_2\text{O}, \text{CH}_4, \text{HFC} \), etc), -which is named “CO2 equivalent”, by using this type of renewable energy. We obtained a similar linear relation between the mass of the avoided to be emitted greenhouse gases, \( m_{\text{CO2,eq}} \) and the power of the PV solar farm, of the following type

\[
m_{\text{CO2,eq}} \text{[in TnCO2,eq]} = \alpha X
\]

where \( \alpha = 0.1m_{\text{CO2,eq}} \) [in TnCO2,eq/MW] and \( X \) the same variable as in formula (1).

In Table 2, we display the avoided \( \text{CO}_2 \text{equivalent} \) emissions for a 10 MW PV solar power plant placed at the different Argentinian sites. In the same way as for the produced electrical energy, the contamination avoided by the power plant placed in the different Argentinian places is determined with the RetScreen algorithm. The coefficient that transform MWh of electricity to Tn of \( \text{CO}_2 \text{eq} \) considering the Argentina electric power matrix, is \( \alpha = 514 \text{TnCO}_2/\text{MWh} 
). The value of this coefficient for other countries (Great Britain, China, India, Brasil, Russia) can be obtained, for example, in the web address of the UK National Energy Foundation (\text{http://www.nef.org.uk/greencompany/co2calculator.htm}). As expected, the site that produce the largest quantity of renewable energy, Jujuy, is also the main contributor to the reduction in GHG emissions. The difference between the Santa Fe province places is at most 3.4%.
4.4 Reduction of the energy consumption

We will analyze the possibility to reduce the energy use (and consequently contaminant emissions), for the PV solar farm to be placed in Garabato, Santa Fe province, Argentina in the three phases (identified with the symbol $\gamma$: construction, operation and decommissioning). So, the total energy used will be

$$E_{\gamma,\text{total}} = \sum_j E_{\gamma,j} = \sum_j \kappa_{\gamma,j} c_{\gamma,j} l_{\gamma,j} \quad \text{[in J], with } j = 1, \ldots, N \text{ (being N the total number of energy systems)} \quad (3)$$

Here, in particular, $E_{\gamma,j} = E_{1,j}$ [used fuels for logistic (transport and storage in a safety place) of building materials preparation, perforation of hole for the basement of the PV modules, etc) [in liter/km or hour] and $l_{\gamma,j}$ is the distance traveled by the vehicles or the working hours [in km or hours].

In order to analyze the efficiency in the reduction of the energetic consumption, we define the reduced energy consumption, adding a * to the corresponding symbols. So, the percentage relative efficiency becomes [38].

$$\eta_{E,\gamma,\text{total}} = 100\left(\frac{E_{\gamma,\text{total}} - E_{\gamma,\text{total}*}}{E_{\gamma,\text{total}}}\right) = \sum_j \eta_{E,j} r_{E,j} \quad \text{[in %]} \quad (4)$$

where $r_{E,j} = E_{\gamma,j}/E_{\gamma,\text{total}}$. If $k \neq c$ are constants, then $r_{E,j} = 1/l_{\gamma,j}/l_{\gamma,\text{total}}$.

In a similar way, we could determine the efficiency in the reduction of CO$_2$ and other GHG gases. We define $m_{CO2,\gamma,\text{total}}$ and $m_{CO2,\gamma,j}$ the total emitted mass and the mass that corresponds to each fuel consumption $j$, respectively. Consequently, the total efficiency becomes

$$\eta_{CO2,\gamma,\text{total}} = 100\left(\frac{m_{CO2,\gamma,\text{total}} - m_{CO2,\gamma,\text{total}*}}{m_{CO2,\gamma,\text{total}}}\right) = \sum_j \eta_{CO2,j} r_{CO2,j} \quad [\text{in %}] \quad (5)$$

being $\eta_{CO2,\gamma,j} = 100\left(\frac{m_{CO2,\gamma,j} - m_{CO2,\gamma,j}*}{m_{CO2,\gamma,j}}\right)$ and $r_{CO2,j} = m_{CO2,\gamma,j}/m_{CO2,\gamma,\text{total}}$. Since the mass of the emitted contaminant is proportional to the quantity of fuels employed in a normal situation ($l_{\gamma,j}$) or in a situation of rational energy use ($l_{\gamma,j}*\gamma_j$) through the coefficient $\lambda_{CO2,\gamma,j}$ [in kg CO$_2$ eq emitted/liter consumed], is $\eta_{CO2,\gamma,j} = 100\lambda_{CO2,\gamma,j}(l_{\gamma,j} - l_{\gamma,j}*)/l_{\gamma,j}$ and $r_{CO2,j} = (l_{\gamma,j} - l_{\gamma,j}*)/l_{\gamma,\text{total}}$. Replacing these quantities in (5), we obtain the total efficiency $\eta_{CO2,\gamma,\text{total}}$.

4.4.1 Practical example of calculation of the efficiencies $\eta_{E,\gamma,\text{total}}$ and $\eta_{CO2,\gamma,\text{total}}$

As a case study, we analyze only the construction phase of the 10 MW PV solar power farm at Garabato, Prov. of Santa Fe, Argentina. From the calculations described in item 4.2, the number of panels needed for producing 10 MW is 34,000. If the panels are of weight 18 kg, the total weight to be transported will be 612 Tn. These panels will occupy a volume of: $(155.9 \times 104.6 \times 3)$ cm$^3$. So, 800 panels can be transported each travel from the production place (La Rioja, Argentina) to the Garabato PV power plant. Then it will be necessary 43 truck trips in a distance of 1000 km. Considering the average yield of a truck in Argentina (0.45 l/Km), the diesel fuel liters consumed in the transportation, will be 19,350 liters. As part of this logistic sub-phase, for personnel transportation from the neighboring town to the ground, every day of the construction period, about 511 liters of diesel will be used. For the construction of the plant (use of machines that perform the task of leveling the land; build access roads to the plant, the modules and the operations center; build the operations area and deposited materials, etc), it will be required 10,696 liters of diesel. Finally, the energy use for all this construction phase will be: $E(10\text{MW})_{\text{const, total}} = E_{\text{const, 1=logistics}} + E_{\text{const, 2=const plant-house}} = (1,118.4 + 299.4) \text{ GJ} = 1,417.8 \text{ GJ}$.

An interesting particular case is the analysis for a polimodal panel transportation system, with the largest possible material transport done by train and the rest by trucks. For the La Rioja-Garabato travel of the panels, 1,310 km need to be made by train and about 70 km by trucks. In this case, a lower energy consumption by the train/truck combination is evident, giving a value of 231 GJ, with respect to 708 GJ for the conventional (only trucks) case. So, the energy efficiency for this particular sub-case will be 67.3%.

We consider that it will be possible to make a 15% (10%) improvement in the number of liters of fuel consumed in truck(or bus for personnel) efficiency in the logistic sub-phase, by taking various measures such as driver training to responsible driving, engine maintenance in optimal conditions, etc. Also we assume a 5% improvement in the construction sub-phase. Accordingly, applying formulas (4) and (5) we obtain: $\eta_{E,\text{const, total}} = \sum_j \eta_{E,j} r_{E,j} = 12.8 \%$ and the same value for $\eta_{CO2,\text{const, total}}$ since the (fuel) energy is proportional to the emitted mass of GHG.
5. Conclusions

Consequently, the obtained results can be summarized as follows:
- Solar PV energy is expected to cover a significant portion of the world energetic matrix in the near future.
- The energy payback time of solar cells has been decreasing in the last years and is expected to continue diminishing.
- Solar modules can be recycled very efficiently, and there is a concern of the PV industry towards environmental aspects of solar energy production.
- A solar power plant can be designed in order to minimize its environmental impact, as the case of the solar PV power plant projected to be placed in Santa Fe Province, Argentina.
- The energy exported annually by a photovoltaic plant of 10 MW, varies from about 14,380 MWh to 17,905 MWh for Rosario and Jujuy, with the value at the reference locality at Northern Santa Fe, Garabato, of 14,804 MWh. The percentage spread between the locations placed in this region (Tostado, Villa Minetti, Vera and Garabato), reaches a maximum value of -1.14%, so we can conclude that the four sites analyzed offer similar export availability of electricity to the MEM grid. Even Rosario, shows a greater difference though, but small compared with Garabato, of only -2.86%.
- The town of San Juan (Jujuy), even if it is at similar latitude than the Santa Fe localities since it is located at a higher latitude, has solar availability conditions only about over 10% (17.3%). These differences are not very high, and eventually can be compensated by losses in the transportation of electrical power to more populated areas with high industrial activity in Argentina, such as the Province of Santa Fe.
- Significant annual reductions in the emission of greenhouse gases (CO₂ and others) can be obtained, with the higher and the lower contributions for Jujuy and Rosario sites, with 9688 TnCO₂eq and 7780 TnCO₂eq, respectively. Other locations in the Northern Santa Fe region are in an intermediate situation, within 3.4% of the TnCO₂eq avoided at Rosario.
- The choice of more sophisticated solar tracking systems could result in higher values of the annual electricity export from 14,803 MWh for the case of fixed scan up to 18,524 MWh for biaxial tracking device, which represents an increase of efficiency of 25.1% in the area under study. However, to decide the incorporation of these systems it should be taking into account the energy consumed by the tracking systems, since mobile devices exposed to external weather conditions undergoes degradation, which in general is often larger than the fixed systems, and should further increase the costs of operation and maintenance of each tracking system, in order to optimize the economic and financial evaluation of each proposal.
- Increased electricity exported to the grid MEM and avoided GHG emissions are linearly proportional to the value of the power generation capacity of the plant. Further study should consider: discrete fixed costs, transport modules that can not always split, etc.
- In summary, we consider that the installation of a photovoltaic power plant in the province of Santa Fe, Argentina, from a technical standpoint, is feasible and can produce an amount of energy which is not much less than what would occur if it were located in areas of high solar radiation intensity, but far from the geographical more populated area of the country. Also, it can reduce significantly GHG emissions.

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