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ENVIRONMENTAL IMPACT OF PV SYSTEMS: EFFECTS OF ENERGY SOURCES USED IN PRODUCTION OF SOLAR PANELS

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ABSTRACT: The international expansion of the PV industry can affect the range of indirect environmental impacts, and mostly the CO_2 equivalent emissions, of the solar electricity produced in any country. We demonstrate a clear trend towards high variation in the global warming potential of solar electricity produced in France by PV installations which use modules produced with different electricity mix. The variation is somewhat less important when looking at the Energy Payback Time (EPBT) of the PV installation. In any studied case, the transportation between countries has a low effect compared to the choice made on the source of electricity used during the different steps involved in the fabrication of modules for any technology.
Keywords: Environmental effect, Module Manufacturing & Energy Options

1 INTRODUCTION

Previous life cycle analyses (LCA) of photovoltaic (PV) systems have created a representative database of the fabrication steps of this rapidly developing industry [1-5]. These previous studies have brought a better understanding of the critical parameters influencing the indirect solar electricity environmental impacts. Even if technological improvements are an important goal to both minimize the cost and environmental impacts of solar electricity there are other significant parameters like the irradiation received by a PV installation [3,6]. In many of the past researches it has been shown that the electricity consumed during PV manufacturing was high and, hence, responsible for a large proportion of the indirect impacts linked with the global warming potential and non-renewable primary energy consumption. Because the PV industry is widespread around the world, its high electricity consumption brought forward a new question. What is the effect of different energy sources or mixes on the final environmental impacts of solar electricity?

To address this issue, we compared the results of a life cycle sensitivity analysis with values from previous researches. To do this, we have used a type of installation that has been commonly used for PV LCA. We then modified the most recent LCA database on PV systems (EcoInvent) [7] by varying the electricity sources and transportation distances. The changes in transportation distances seemed necessary to make a balance comparison between PV manufacturing sites. The results show expected trends providing some guidance to the PV industry to a more efficient development highlighting its indirect environmental impacts.

2 SYSTEM AND HYPOTHESIS

2.1 Scope of study

The goal of this study is to evaluate over the life cycle direct and indirect environmental impacts of the electricity produced by different integrated 3 kW_p PV installations (which we call solar electricity). The choice of this specific installation size was made to enable the comparison of our results with previous works. The main difference between each of the analyzed PV installation is the source of electricity used to manufacture the PV modules. Such sensitivity analysis on electricity source has been conducted for 6 main PV technologies: amorphous silicon (a-Si), CdTe, CIS, multicrystalline silicon (mc-Si), ribbon silicon (ribbon-Si) and monocrystalline silicon (sc-Si). Two different models of manufacturing electricity have been considered. The first one involves single sources like Nuclear, Coal, Hydro, Wind and PV. The second model involves a more complex, but more realistic source, which is the energy mixes of different countries. We have chosen electricity mixes from 4 countries with a large PV industry (China, Germany, Japan and the US) and European countries with special electricity production characteristics (Switzerland and France). To elaborate on the perspective of the international PV market we also have considered different transport distances to bring the modules from the site of manufacturing to the site of the installation (France).

The manufacturing structure references for all the verified technologies are issued from the EcoInvent model [7]. Some of the relevant life cycle inventories have been update in 2009 but the data is mainly based on 2005 information. The fabrication methods presented in the database are mainly used by European or American companies. For our analysis, modules manufacturing steps are covering all the steps involved between the purification of metal grade silicon up until the creation of a PV module. Figure 1 presents the list of specific steps with the input of electricity. Note that thin-film technologies require only one module fabrication step in the database we have used.

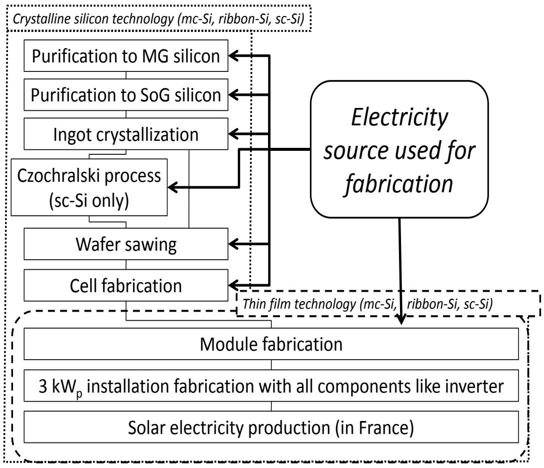

Figure 1: Description of the steps involved in the fabrication of PV modules and their need for electricity

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2.2 Hypothesis

Many hypotheses are necessary to evaluate the life cycle environmental impacts of solar electricity. Most of them are necessary to evaluate the quantity of electricity produced over the lifetime of a PV installation. Here we state that the lifetime of any installation is 30 years. With a production performance averaged from the 2005 values for each technology we assumed an electricity production of 82 980 kWh for any 3kW$_p$ installation. This electricity production can be seen as a low estimate but was necessary for comparison to the results from the analysis of the EcoInvent database.

In this study we also have made some hypothesis on the transportation distance between countries. Table 1 presents those distances.

Table I: Transportation distances between the PV modules manufacturing country and its installation site.

Traveling distance to France (in tkm) *(for the mc-Si modules)*				
Distance from	By boat	By train	By lorry >16 tonnes	By van < 3.5 tonnes
CH	0	175	45	10
CN	2330	0	580	145
DE	0	220	55	15
FR	0	160	40	10
JP	2910	0	725	180
US	2180	0	545	135

Quality of the results is highly correlated to the quality of the input data collected from PV industry. Quality improvement would be necessary in the future. Transportation distances present also a high level of uncertainty. Because of their low contribution on the final impacts this uncertainty is considered as acceptable but further verifications would mean more precise results.

2.3 Impact analysis

To calculate the CO_2 eq. emissions we have used the Impact 2002+ method [8]. This LCA impact analysis method was also useful to obtain the quantity of non-renewable energy used for the fabrication of a PV installation. Two other impacts categories can be evaluated by this method. They are the Ecosystem Quality and the Human Health. Both of those impacts categories present valid results for Europe and are discarded because our present analysis is not limited to Europe. However these impacts should be investigated for future work.

Energy Payback Time (EBPT) has been calculated with the following definition:

$$\text{EPBT} = \frac{E_p^{\text{fabrication}}}{\text{avoided } E_p^{\text{production}}} \qquad (1)$$

$E_p^{fabrication}$: Non-renewable primary energy used for the fabrication of the installation
avoided $E_p^{production}$: The non-renewable primary energy that is not consumed according to the country mix where the PV is installed over one year because it is produced by the PV installation.

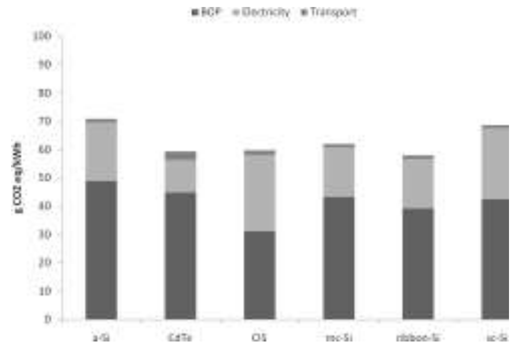
This method of calculating the EPBT gives results that are only valid for the country where the PV modules are installed. In this case, the results are valid for France.

3 RESULTS AND ANALYSIS

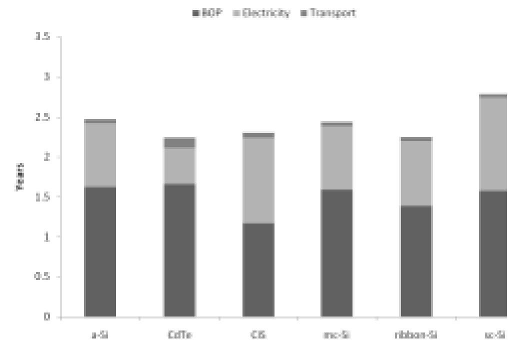
In the next figures, each result is separated in three categories. This separation is important to visualize the link between using a certain type of energy and the level of effect it has on the final impacts of producing solar electricity. The darker section presents the impacts coming from all the different material used for the PV installation. It is called Balance of Processes (BOP). The light grey section presents the level of impact coming from the use of electricity during the manufacturing of PV modules. The dark grey section is linked with the level of impact coming from the transport of modules between the site of their fabrication and the site of the installed PV system.

3.1 Technologies comparison (EcoInvent results)

Figure 2 presents the varying CO_2 eq. emissions per kWh of solar electricity and EPBT for different technologies. In both figure 2(a) and 2(b) the technology with the smallest level of impact presents a value that is about 20% smaller than the value of the technology with the highest level of impact. For both categories of impact the transport has a low importance, the BOP are responsible for a majority of the impacts. The level of importance of the electricity used during the modules manufacturing is different for each technology. Proportionally the CIS is the technology which is affected more by the electricity source used for its manufacturing.



(a)



(b)

Figure 2: Technologies comparison with indications on the influence of the electricity used for fabrication of the PV installation over the final environmental impacts of the solar electricity (CO2 eq and EPBT)

Since this technology comparison is based on the data issued from the EcoInvent database the type of

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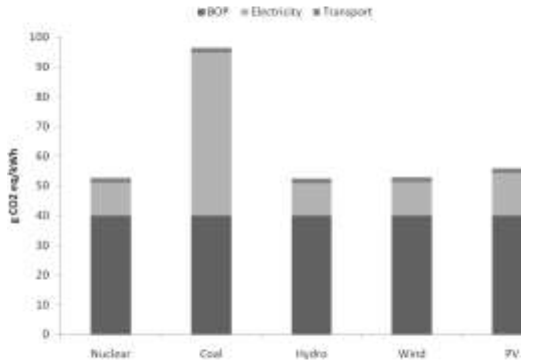
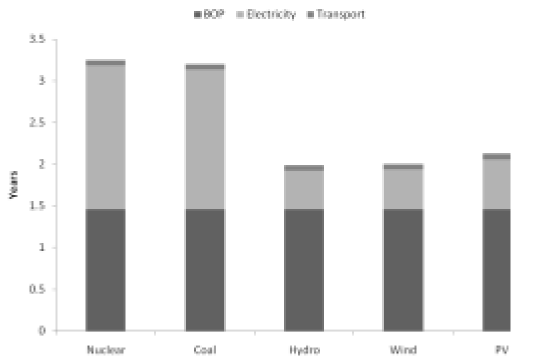
energy mixes used are not exactly the same in each case. But the presented results seem more relevant because they show the average values for solar electricity produced in Europe. **The main outcome for the results presented in figure 2 is the demonstration of the importance of the electricity used for the manufacturing steps of modules in any technology used today.**

3.2 Single electricity sources comparison

Figure 3 presents the influence of different electricity sources used for the manufacturing of PV modules on the global impacts of the solar electricity. Here we have taken the mc-Si technology to make the comparison because of it large share of today's market. Using electricity produced by coal (average European production) will bring the highest emission of CO_2 eq. per kWh of solar electricity. It will also consume a large amount of non-renewable primary energy has can be understood by the high EPBT shown for this type of energy source. Nuclear power on the other hand presents low CO_2 eq. emission but the highest non-renewable primary energy use. **Overall the clear trend of figure 3 is that using renewable energy (hydro, wind and PV) for PV modules manufacturing will not only lower the global warming impacts of solar electricity but also minimize its EPBT**.



(a)

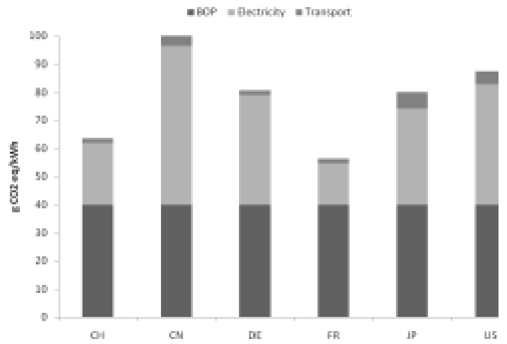


(b)

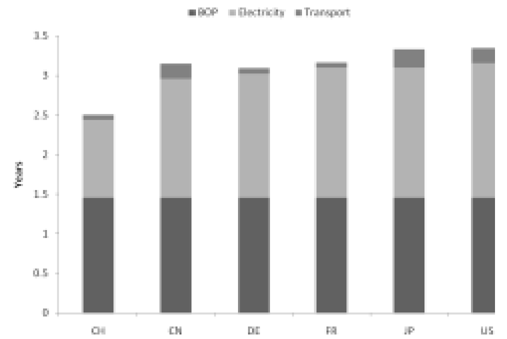
Figure 3: Impacts of solar electricity produced by PV installations fabricated with different source of electricity.

3.3 Electricity mixes comparison

Results from figure 3 bring important information but are rarely representative of the energy used in PV industries. It is more realistic to use the electricity mix from the effective network to manufacture PV modules. This is why we have presented the CO_2 eq. emissions and EPBT for solar electricity produced by PV modules which were entirely fabricated by one type of electricity mix. The transport values are calculated to bring the module from the country were they are manufactured to the French territory where they are installed. **In figure 4(a) we can see that the use of different electricity mixes can bring a large difference in the level of CO_2 eq. emission of the solar electricity**. And this difference is mainly caused by the change in energy mixes and not by the variation on transport distance. On the other hand, the EPBT does not change as much if there is a variation in the electricity mix used even if there is a large amount of renewable in the mix like for the Switzerland case.



(a)



(b)

Figure 4: Impacts of solar electricity produced by PV installations fabricated with different electricity mixes.

4 DISCUSSION

4.1 Industrial perspectives

Within the limit of this sensitivity analysis one outcome can be crucial for understanding the PV industry indirect environmental impacts. As said previously, the PV manufacturing methods of most technologies require a lot of electricity. The search to lower this high energy consumption is important for the industry monetary competitiveness but, environmentally, it does not seem to be the simplest solution. It is, for now, relatively simpler to choose a renewable type of electricity than to find new fabrications techniques which require less electricity consumption. If the manufacturing site does not allow a high renewable production yield then relocation might be an option since the transport should not be a major concern over the entire lifetime impacts of the solar electricity produced. In the future, if renewable sources take a larger portion of the electricity mix in any country this will be less of an issue but for now, the location of

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the PV industry can be a critical parameter in the environmental impacts of the solar electricity.

5 CONCLUSION

The results from our sensitivity analysis clearly demonstrate that the electricity source chosen for the manufacturing of PV modules will have an important effect on the overall environmental impacts of solar electricity. The variation is quite large when looking at the CO_2 equivalent emission of solar electricity produced by PV installations which were fabricated with the use of different electricity mixes. The EPBT will vary less for the same variation in manufacturing electricity use. This observed trend is valid for any technology even if some technologies require less electricity for their manufacturing.. In any studied case, the transportation between countries has a low effect compared to the choice made on the source of electricity used during the different steps involved in the fabrication of modules. The PV industry should consider with great care the source of the electricity mix for the PV manufacturing to limit their indirect environmental impacts.

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