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Considerations for the calculation of greenhouse gas reduction by photovoltaic solar energy

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Abstract

A CO_2 comprehensive balance within the life-cycle of a photovoltaic energy system requires careful examination of the CO_2 sinks and sources at the locations and under the conditions of production of each component, during transport, installation and operation, as well as at the site of recycling. Calculations of the possible effect on CO_2 reduction by PV energy systems may be incorrect if system borders are not set wide enough and remain on a national level, as can be found in the literature. For the examples of Brazil and Germany, the effective CO_2 reductions have been derived, also considering possible interchange scenarios for production and operation of the PV systems considering the carbon dioxide intensity of the local electricity grids. In the case of Brazil also off-grid applications and the substitution of diesel generating sets by photovoltaics are examined: CO_2 reduction may reach 26,805 kg/kW_p in that case. Doing these calculations, the compositions of the local grids and their CO_2 intensity at the time of PV grid injection have to be taken into account. Also possible changes of the generation fuel mix in the future have to be considered: During the operation time of a PV system, different kinds of power plants could be installed that might change the CO_2 intensity of the grid. In the future also advanced technologies such as thin films have to be considered.

Keywords: Carbon dioxide reduction; Solar energy; Photovoltaic; Dislocation; Life-cycle analysis

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Nomenclature

a-Si	amorphous silicon
BR	Brazil
D	Germany
GJ_{el}	electrical energy in 10^9 J
kW_p	electrical power output of PV generator under Standard Test Conditions (irradiance of 1000 W/m^2, solar spectrum equivalent to a relative air mass of 1.5, solar cell temperature 25 °C)
kWh	energy (equivalent to 3.6 MJ)
kWh_{el}	electrical energy (equivalent to 3.6 MJ_{el})
kWh_{prim}	primary energy (equivalent to 3.6 MJ_{prim})
MJ	energy in 10^6 J
m-Si	mono-crystalline silicon
p-Si	multi-crystalline silicon (formerly known under the name of 'polycrystalline' silicon)

1. Introduction

Several authors have discussed the energy requirements for the production of photovoltaic (PV) solar energy conversion systems and their energy pay-back-time [1–3]. Some publications also mention the reduction of CO_2 emissions by using PV systems to substitute conventional energy generating sets [4]. System borders of the life-cycle analysis (LCA) of energy systems are very often set to national borders (as Tahara et al. [5]). These results may be helpful to improve national CO_2 balances, but they often will not meet concerns about suitable measures in order to reduce the Earth's atmosphere carbon dioxide contents on a global scale.

With very few exceptions (e.g. Komiyada et al. [6]), all of the CO_2 balances made are neglecting the fact that the locations of production, of operation, and of recycling of a PV system are rarely the same in a global market. This could lead to vast deviations of calculations from the actual effect of PV on the reduction of greenhouse gases.

2. Calculations

2.1. Production

While the specific electrical energy requirements do not vary notably for most of modern manufacturing facilities of PV components all over the world, the specific CO_2 emissions depend very much on the power plants (nuclear, hydro, fossil etc.) producing the electricity to operate production facilities of PV and system components. The CO_2 intensity of electrical power plants and of national electrical grids may vary considerably (between 17 and 1140 g of CO_2/kWh_{el}), as can be seen in Tables 1 and 2.

Table 3 gives an overview of the primary energy requirements and the resulting CO_2 emissions of different materials in Germany. As can be seen, recycling has a major effect on the energy requirement and CO_2 emission of materials. For aluminum the savings can reach 95%, while recycled aluminum requires less energy than new steel.

Table 4 shows the energy requirements to manufacture PV modules and presents the resulting CO_2 emissions for Germany and Brazil. The use of PV modules based on thin film technology could not be considered, because of the data available the separation between thermal and electrical energy used was not kept (see overview by Alsema [1,2]), which is essential to calculate specific carbon dioxide emissions.

Aside from the energy required at the production process, the demand for building the production facilities (production halls, equipment) has to be considered as well.

2.2. Operation

Electrical energy output of a PV system is depending on local solar irradiance, angle of sun's incidence, irradiance spectrum, operating temperature and electrical

Table 1
Comparison of specific CO_2 emissions (in g/kWh_{el}) for different kinds of electrical power plants

Fuel of electrical power plant	Emission of CO_2 (g/kWh_{el})	References
Lignite	1140.1	German Government [16]
Coal	915.8	Tahara et al. [5]
Oil	755.6	Tahara et al. [5]
Gas (natural)	420.1	Kaltschmitt and Wiese [17]
Wind (5.5 m/s)	17.3	Voß [18]
Hydro	16.9	Tahara et al. [5]
PV (m-Si)	259.2[a]	Voss [19]
	190.1[a]	Kaltschmitt and Wiese [17]
	74.9[a]	Sørensen [15]
PV (p-Si)	317.2[a]	Kaltschmitt and Wiese [17]
	265.0[a]	Brauch [20]
	51.1[b]	Frisson et al. [10]
	10.1[c]	Frisson et al. [10]
	60.0[d]	Alsema [4]
PV (a-Si)	37.5[a]	Hagedorn [21]
	42.2[a]	Kaltschmitt and Wiese [17]
	11.9[a]	Sørensen [15]
	50.0[d]	Alsema [4]

[a] For conditions in central Europe.
[b] For tropical conditions.
[c] For tropical conditions, recycled solar cells.
[d] Produced in Europe, irradiance: 1700 kWh m^{-2} a^{-1}.

Table 2
Composition of power plants for electrical energy generation in different countries (data by Geller et al. [22], Mauch [23], and Tahara et al. [5])

Country	Fossil fuels (%)	Nuclear (%)	Hydro power and other renewables (%)	Carbon dioxide intensity of electricity production (g/kWh_{el})
Great Britain	76.9	20.9	2.2	
Former USSR	74.7	12.4	12.9	
Japan	61.1	28.2	10.5	439
Germany	57.5	37.5	4.9	530
France	12.8	74.7	12.5	
Brazil	6.0	0.8	93.2	70
Sweden	4.2	45.8	50.0	34
Norway	0.4	0	99.6	16
Iceland	0.1	0	99.9	15
Mix of aluminum exporting countries				139
Mix of copper exporting countries				572

matching. Compared to standard test conditions (STC) at which PV modules are rated, the actual power output can be up to 40% lower, as observed at Germany's 1000-PV-roofs program, due to these factors. Krauter [7] and Krauter and Hanitsch [8] describe a model for an accurate loss and yield analysis.

Table 3
Materials used for the manufacturing of PV power plants (without solar cells) in Germany, their energy and CO_2 intensity

Material	Energy requirements (kWh_{prim}/kg)	CO_2 emissions (kg/kg)	References
Aluminum (new)[a]	53.0–245.0	15.1–18.8	Umweltbundesamt [30], Mauch [23]
Aluminum (50% recycled)	31.4	6.7	Kaltschmitt and Wiese [17]
Aluminum (100% recycled)	3.3–5.6		Czichos [24] Alsema [1,2]
Concrete	0.17	0.14	Hantsche [25]
Copper (new)	26.4		Wagner [26]
Copper (40% recycled)	24.6	5.08	Kaltschmitt and Wiese [17]
Copper (100% recycled)	7.2		Wagner [26]
EVA	20.8		Alsema [1,2], valid for USA
Glass (new)	4.1	0.54	Hantsche [25]
Glass (100% recycled)	1.0		German Government [16]
PVT (Tedlar®)	31.9		Alsema [1,2], valid for USA
Steel (new)	8.3	3.0	Kaltschmitt and Wiese [17]
Steel (40% recycled)	5.6	1.7	Kaltschmitt and Wiese [17]
Steel (100% recycled)	2.8–5.0		Czichos [24]

[a] Due to a large participation of hydropower in the energy mix of the main aluminum (new) processing countries, such as Norway and Iceland, the definition of the primary energy consumption for production becomes difficult. Czichos [24] is therefore giving energy requirements of just 44–67 kWh/kg of new aluminium, probably not considering the (rather theoretical) conversion to primary energy requirements. The value of 18.8 kg/kg of CO_2 emissions for new aluminium includes all greenhouse gases [30].

Table 4
Sectors of energy consumption and CO_2 emission for the production of PV power plants (by Krauter [27])

Type	Electricity			Fuels		Non-energetic consumption	
Type of PV	Energy (kWh_{el}/kW_p)	CO_2 in D in (kg/kW_p)	CO_2 in BR (kg/kW_p)	Energy (kWh_{prim}/kW_p)	CO_2 (kg/kW_p)	Energy (kWh_{prim}/kW_p)	CO_2 (kg/kW_p)
Mono-crystalline	5144	2726	360	1152	346	226	52.4
Multi-crystalline	2530	1341	177	1630	489	450	103.5

For operation in Germany (yearly irradiance in Berlin on an optimal tilted plane is 1050 kWh m^{-2} a^{-1}, the electrical energy yield for a 1 kW_p PV system is in the vicinity of 770 kWh_{el} a^{-1}, in Rio de Janeiro (yearly irradiance 1750 kWh a^{-1} m^{-2}) average electrical power output of a 1 kW_p PV system is about 1138 kWh_{el} a^{-1}.

A corresponding issue as for the different locations of production occurs on the sites of application: substituting a small diesel generator (0.9–1.05 kW CO_2/kWh_{el}) by a PV system could avoid 0.85–1 kW CO_2/kWh_{el} being emitted, while an electrical grid connected PV system in a 'clean' grid (e.g. Brazil at 0.07 kW CO_2/kWh_{el}) will not contribute a lot to CO_2 reduction, especially if a PV system was produced using electricity from a 'dirty' grid. In that case the effect in terms of CO_2-reduction could even be negative. Due to different load requirements, the composition of generating sets and its specific CO_2 emissions in an electrical grid may vary during a day. Peak loads (e.g. in Brazil during weekdays between 5 p.m. and 10 p.m. the load factors are reaching 40%) are often served by fossil fuel driven power plants, which are increasing the average CO_2 emissions (and also their value for substitution) during these times. Unfortunately, PV power output does not match these peaks (see Fig. 1) in the Brazilian interconnected grid system as a whole. On a local level, however, some grids are showing a good match between power demand and PV generation (Florianópolis—CELESC). PV can have a greater value for the utility in terms of grid-support in such instances. In the last years limitations of electrical power supply in Brazil have often not been given by the maximum rated power output of the hydro generators, but by the amount of water stored in the dam, so the hydro generators are running at reduced power and can adapt to peak demand. PV can also contribute here by displacing or offsetting water levels in dams for the use during peak demand. Furthermore, PV and hydro generation can be regarded as complementary on a seasonal basis, since dam water levels reach critical low values coinciding with higher solar irradiation levels in summer.

In Germany peak load occurs earlier and could be matched in part by photovoltaics, as shown in Fig. 2. The additional power plants operating at peak loads are hydro storage, natural gas, oil and mixed fuel powered plants. Due to the

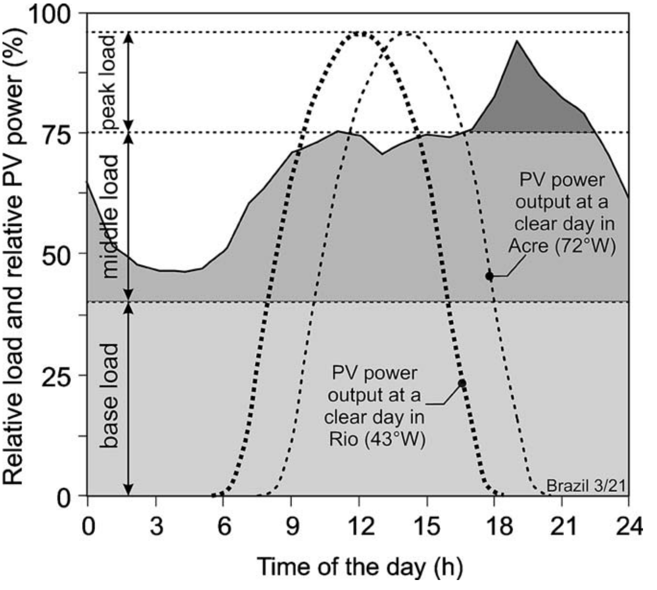

Fig. 1. Relative PV power output and relative electricity consumption for two locations in Brazil at a clear day in Brazil as a function of time of day (data by Geller et al. [22]).

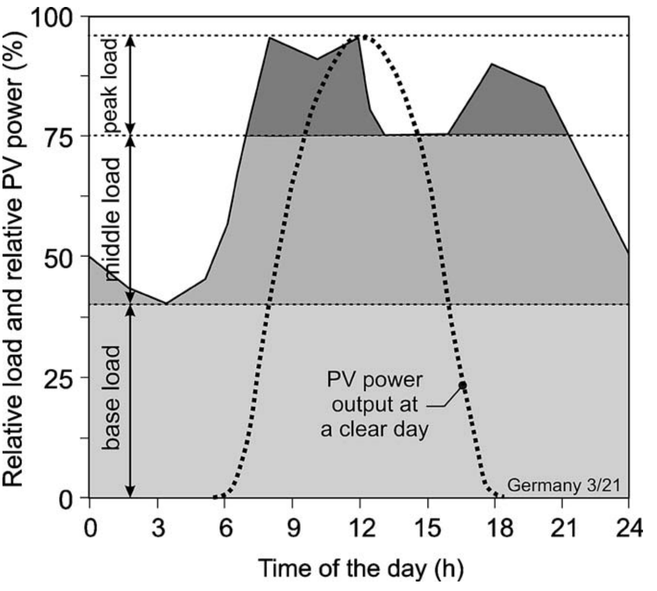

Fig. 2. Relative PV power output and relative electricity consumption at a clear day in Germany as a function of time of day (data by Humm and Jehle [29]).

dynamic trading of electricity between companies and countries, especially during peak hours, and the difficulty of figuring the kind of energy used to fill the storage dams, an accurate calculation of CO_2 balance for peak conditions is quite extensive and will not be presented here.

2.3. Recycling

Recycling also has an important influence on the balance: e.g. energy consumption of aluminum processing could be reduced from 69.4 to 3.3-5.6 kWh/kW (see Table 3). Numbers for recycling of PV systems used here are conservative estimates (25%), the literature mentions possible energy and CO_2 emission savings in the vicinity of 70% [9–11].

2.4. Transportation

Table 5 shows the specific carbon dioxide emissions of each type of transportation. Exceptional low emissions levels could be observed for sea cargo, even for long distances. Table 6 presents the emissions of carbon dioxide for a 1 kW_p PV system caused by national and international transport for the example of Brazil and Germany. Due to the lower efficiencies of multi-crystalline PV modules, the specific emissions by transport are higher than for mono-crystalline PV modules.

Table 5
Total CO_2 emissions for transport of PV power plants (data by Frischknecht et al. [28])

Way of transportation	CO_2 emissions per km and transported weight ($g\ kg^{-1}\ km^{-1}$)	CO_2 emissions per km and per transported kW_p (330 kg) of mono-crystalline PV power plants ($g\ kg^{-1}\ km^{-1}$)	CO_2 emissions per km and per transported kW_p (363 kg) of multi-crystalline PV power plants ($g\ kg^{-1}\ km^{-1}$)
Transport (<3500 kg)	1.540	508.2	559.0
Truck (16 000 kg)	0.350	115.4	127.1
Train	0.050	16.5	18.5
Sea freighter	0.001	0.3	0.4

Table 6
CO_2 emissions per transported kW_p of a mono-crystalline PV power plant for transportation between the location of production and operation (grid-connected)[a]

CO_2 emissions by transport	PV produced in Germany	PV produced in Brazil
PV plant operated in Germany	52.9 kg/kW_p	95.4 kg/kW_p
PV plant operated in Brazil	230.1 kg/kW_p	158.7 kg/kW_p

[a] Reference data: weight of PV system based on m-Si: 330 kg/kW_p. PV inland transport in Germany: 350 km by truck: 40.4 kg CO_2/kW_p, 50 km by delivery van: 12.5 kg CO_2/kW_p. PV national transport in Brazil: 1050 km by truck: 121.2 kg CO_2/kW_p, 150 km by delivery van: 37.5 kg CO_2/kW_p, (autonomous off-grid systems: double for values transport, batteries are supplied locally). Oversea transport Germany–Brazil or vice versa: 10,000 km by cargo freighter: 31 kg CO_2/kW_p.

Modules based on amorphous silicon are therefore expected to cause a 50% higher environmental burden for transportation.

3. Results and conclusions

The actual effect of the PV system in terms of net reduction of carbon dioxide is the electrical yield related to the local grid minus the production requirements, minus the transport emissions, and plus the value for recycling. The final results are presented in Tables 7–9. It can be seen that a main effect is related to 'dirtiness' of the electricity to be substituted by the PV system. The manufacturing in countries with low specific carbon dioxide emissions is preferable in all cases. For operation in Germany the low irradiance value is reducing the possible effect, on the other hand the substitution of a relatively dirty grid allows a reduction of up to 10.1 tons CO_2 per kW_p or PV installed. For operation in Brazil, the effect can be poor in the case of PV grid injection (especially when the equipment used was manufactured in a country where energy consumption is subject to high carbon dioxide emissions), or considerable in the case when a fossil fuel driven power plant is substituted by PV (up to 27 tons/kW_p). Considering the present costs of a PV system, the costs for CO_2 reduction by photovoltaics are in the vicinity of 0.23 US$ per kW for off-grid applications in Brazil. Related to other methods this way to achieve climate control is rather expensive. Fig. 3 shows the costs to reduce carbon dioxide (referenced to achieve a 20% reduction of carbon dioxide emissions based on 1990 by 2005) based on data from Eckaus et al. [12] by the least expensive CO_2 removal technologies (without emission trading permit).

Table 7
Net reduction of CO_2 (in kg) for a 1 kW_p PV system based on mono-crystalline cells (during its system lifetime of 25 years) for different sites of production and different types of application. Recycling rate of the system was assumed to be 25%

Location of production: site of operation (type):	Germany	Brazil
Germany (grid connected)	7,792 kg/kW_p	10,124 kg/kW_p
Brazil (grid connected, actual generation mix)	−1,009 kg/kW_p	1,387 kg/kW_p
Brazil (autonomous, substitution of diesel generator)	24,408 kg/kW_p	26,805 kg/kW_p

Table 8
Net reduction of CO_2 in kg for a 1 kW_p PV system based on multi-crystalline solar cells (during its system lifetime of 25 years) for different sites of production and different types of application. Recycling rate the PV system was assumed to be 25%

Location of production: site of operation (type):	Germany	Brazil
Germany (in grid)	8,677 kg/kW_p	9,805 kg/kW_p
Brazil (in grid, actual generation mix)	162 kg/kW_p	1,359 kg/kW_p
Brazil (autonomous, substitution of diesel generator)	25,372 kg/kW_p	26,570 kg/kW_p

Table 9
Comparison of specific emissions of electrical energy production by amorphous thin film silicon based photovoltaic modules to mono-crystalline silicon thick film based devices in 1997 and estimations for 2010 [14] and [15] for data of 1999: Alsema [4])

Solar cell technology	CO_2 in g/kWh$_{el}$	SO_2 and NO_x
Mono-crystalline silicon 1997	75	0.3
Amorphous silicon 1997	44	0.2
Multi-crystalline silicon 1999	60	
Amorphous silicon 1999	50	
Mono-crystalline silicon 2010 (estimation)	30	0.1
Amorphous silicon 2010 (estimation)	11	0.04

4. Future

To carry out a CO_2 analysis for a future time frame (e.g. 20 years ahead), also changes of the energy and CO_2 balances have to be taken into account, because the mix of generating capacity in an electrical grid as given in Table 2 may alter considerably. For example, while Brazil currently generates over 90% of its electricity by hydropower, most of its new power plants may be driven by fossil fuels (natural gas, oil) due to lack of water, limitations of suitable locations for additional hydro power plants and the increase of electrical energy consumption. In more detail: at first sight the future composition of the electrical grid system has to be considered

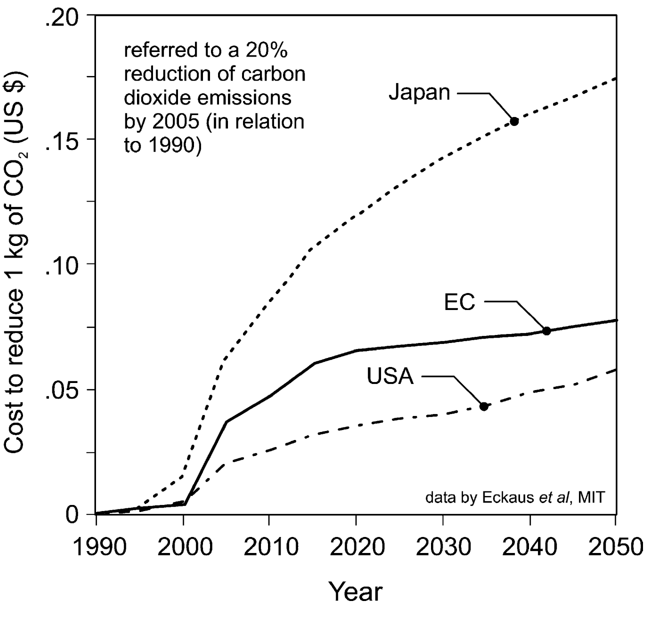

Fig. 3. Costs for carbon dioxide removal, with no backstops and no trade in emissions permits (data by Eckaus et al. [12]).

in order to compute the CO_2 balances. A second look shows that existing hydro power plants will remain and just the increase of consumption will be handled by non-hydro power plants. If electrical grid demand can be reduced by large-scale PV applications, some non-hydro power plants need not to be built. Therefore participation of PV and its substitution value has to be counted for such as the future non-hydro power plants planned within the life expectancy (25 years) of a PV system.

The optimization of production processes towards low specific emissions [13] and higher recycling rates will increase the benefit of the use of PV systems. The use of thin film technologies as amorphous silicon and others promises to reduce specific CO_2 emissions (see Table 9).[1]

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