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## GREENHOUSE GAS REDUCTION BY PV

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### ABSTRACT

A full CO<sub>2</sub>-balance within the life-cycle of a PV-system requires examination of the CO<sub>2</sub> sinks and sources at the location and under the conditions of production, during transport, installation and operation, as well as at the site of recycling. Calculations of the possible effect on CO<sub>2</sub> 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<sub>2</sub> reductions are derived, including possible interchange scenarios for production and operation of the PV systems considering the carbon dioxide intensity of the local electrical grids. In the case of Brazil also off-grid applications and the partial substitution of Diesel generating sets by photovoltaics are examined. CO<sub>2</sub> reduction may reach 26 805 kg/kW<sub>p</sub> for the case of replacement of diesel generators in Brazil by PV.

### 1 INTRODUCTION

In most cases the use of renewable energies such as photovoltaics (PV) are able to reduce the specific carbon dioxide emissions of the country considerably. To find out the exact amount of reduction, a detailed carbon dioxide balance of the entire life-cycle of PV-power plants, including production, transport installation, operation, dismantling, was set up.

Several authors have discussed energy requirements for the production of photovoltaic solar energy conversion systems and their energy pay-back-time (Alsema 98 [1]; Keoleian and Lewis 97 [2]). Some publications also mention the reduction of CO<sub>2</sub>-emissions by using PV systems to substitute conventional energy generating sets (e.g. Alsema 2000 [3]). System borders of the life-cycle-analysis (LCA) of energy systems are very often set to national borders (as Tahara *et al.* [4]). These results may be helpful to improve national CO<sub>2</sub> 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.* [5]), all of the CO<sub>2</sub>-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 of PV

While the specific electrical energy requirements do not vary notably for most of modern manufacturing facilities of PV components, the specific CO<sub>2</sub> emissions depend very much on the power plants (nuclear, hydro, fossil etc.) producing the electricity to run these PV production facilities. The CO<sub>2</sub> intensity of different kinds of electrical power plants may vary considerably (between 17 and 1140 g of CO<sub>2</sub>/kWh<sub>el</sub>), leading to significant differences in terms of carbon dioxide emissions between the countries, depending on the composition of power plants in their national energy matrix (see Table I).

**Table I.** Composition of power plants for electrical energy generation in different countries.

Country	Fossil fuels (%)	Nuclear (%)	Renewables incl. hydro (%)	CO <sub>2</sub> intensity (g/kWh <sub>el</sub> )
Great Britain	76.9	20.9	2.2	
Ex-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
Al				139
Cu				572

Al: Aluminum exporting countries (mix)  
Cu: Copper exporting countries (mix)  
Data by Mauch 1995 [6], Schaefer 1993 (in [7]), and Tahara *et al.* [4]

The use of recycled materials has a major effect on the energy requirement and CO<sub>2</sub> emission of materials. E.g. for aluminum energy savings can reach 95% - recycled aluminum requires less energy than new steel [9].

Table II shows energy requirements to manufacture PV modules and presents the resulting CO<sub>2</sub> emissions for Germany and Brazil. The use of PV modules based on thin film technology could not be considered, because at the data available the separation between thermal and electrical energy used was not kept (see overview by Alsema [1]), which is essential to achieve specific carbon dioxide emissions. Aside from the energy required at the production process, the demand for building the production facilities has to be considered as well.

**Table II.** Sectors of energy consumption and CO<sub>2</sub> emission for the production of PV power plants.

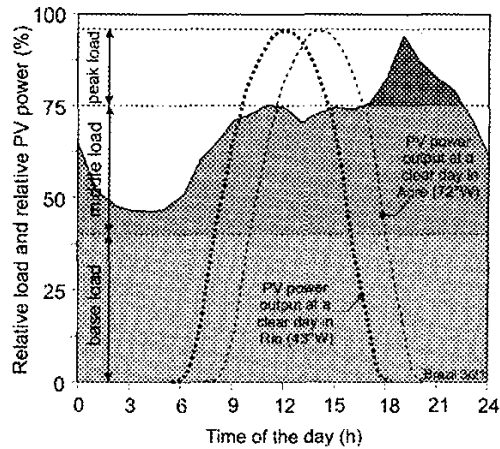
Type	Electricity		Fuels		NEC		
Type of PV	Energy <sup>a)</sup>	CO <sub>2</sub> <sup>D b)</sup>	CO <sub>2</sub> <sup>BR b)</sup>	Energy <sup>c)</sup>	CO <sub>2</sub> <sup>b)</sup>	Energy <sup>c)</sup>	CO <sub>2</sub> <sup>b)</sup>
sc	5,144	2,726	360	1,152	346	226	52.4
mc	2,530	1,341	177	1,630	489	450	103.5

<sup>a)</sup> in kWh<sub>el</sub>/kW<sub>p</sub> <sup>b)</sup> in kg/kW<sub>p</sub> <sup>c)</sup> in kWh<sub>prim</sub>/kW<sub>p</sub>  
 sc: single- or mono- crystalline, mc: multi-crystalline  
 NEC: Non-energy consumption  
 D: in Germany, BR: in Brazil, data by Krauter [8].

**2.2 Operation**

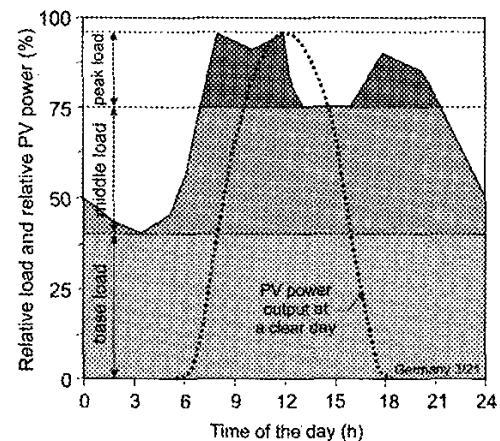
Electrical energy output of a PV system is depending on local solar irradiance, angle of Sun's incidence, irradiance spectrum, operating temperature and electrical matching. Compared to standard test conditions (STC) at which PV modules are rated, the actual power output can be up to 40% lower, see Germany's 1000 PV-Roofs Program, due to these factors. Krauter [10]; Krauter and Hanitsch [11] are describing a model for an accurate loss analysis. For operation in Germany (yearly irradiance in Berlin on an optimal tilted plane is 1050 kWh m<sup>-2</sup> a<sup>-1</sup>, the electrical energy yield for a 1 kW<sub>p</sub> PV system is 770 kWh<sub>el</sub> a<sup>-1</sup>, in Rio de Janeiro (yearly irradiance 1750 kWh a<sup>-1</sup> m<sup>-2</sup>) average electrical power output of a 1 kW<sub>p</sub> PV system is about 1138 kWh<sub>el</sub> a<sup>-1</sup>.

A corresponding issue as for the different locations of production occurs on the sites of application: substituting a diesel-generator (0.9 to 1.05 kg CO<sub>2</sub>/kWh<sub>el</sub>) for a PV system could avoid 0.85 to 1 kg CO<sub>2</sub>/kWh<sub>el</sub> to be emitted, while an electrical grid connected PV system in a "clean" grid (e.g. Brazil at 0.07 kg CO<sub>2</sub>/kWh<sub>el</sub>) will not contribute a lot to CO<sub>2</sub> reduction, especially if a PV system was produced using electricity from a "dirty" grid. In this case its effect could even be negative. Due to different load requirements, the composition of generating sets (and its specific CO<sub>2</sub> 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<sub>2</sub> emissions (and also their substitution value) during these times. Unfortunately, PV power output does not match these peaks in the Brazilian interconnected system as a whole (see Fig. 1).



**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 [17]).

On a local level, however, some grids are showing a good match between power demand and PV generation. 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 irradiance levels in summer. In Germany peak load occurs earlier and could be matched in part by PV (Fig. 2).



**Fig. 2** Relative PV power output and electricity consumption for a clear day in Germany (data by [18]).

The additional power plants operating at peak loads are hydro storage, natural gas, oil and mixed fuel powered plants. Due to the 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<sub>2</sub> 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 kWh/kg to 3.3-5.6 kWh/kg. Numbers for recycling of PV systems used here are conservative estimates (25%), since the latest literature mentions possible energy and CO<sub>2</sub> emission savings in the vicinity of 70% (see Bruton et al. [12], Frisson *et al.* [13], Wambach [14]).

### 2.4 Transport

Table III presents the emissions of carbon dioxide for a 1 kW<sub>p</sub> PV system (based on mono-crystalline solar cells) due to 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 10% higher than for mono-crystalline PV modules. Modules based on amorphous Silicon are therefore expected to cause a 50% higher environmental burden for transportation.

**Table III.** CO<sub>2</sub> emissions per transported kW<sub>p</sub> of a mono-crystalline PV power plant between the locations of production and operation.

CO <sub>2</sub> emissions due to transport	PV produced in Germany	PV produced in Brazil
PV plant operated in Germany	52.9 kg/kW <sub>p</sub>	95.4 kg/kW <sub>p</sub>
PV plant operated in Brazil	230.1 kg/kW <sub>p</sub>	158.7 kg/kW <sub>p</sub>

Calculations based on data by Frischknecht *et al.* [15]:  
 Transporter (< 3.50 t): 1.54 g CO<sub>2</sub>/(kg km), Truck (16 t): 0.35 g CO<sub>2</sub>/(kg km), Train: 0.05 g CO<sub>2</sub>/(kg km),  
 Sea freighter 0.001 g CO<sub>2</sub>/(kg km)

## 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 Table IV and in Table V. 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<sub>2</sub> per kW<sub>p</sub> or PV installed.

**Table IV.** Net-reduction of CO<sub>2</sub> by a PV-System based on mono-crystalline solar cells for different locations of production and of operation.

Operation site (type)	Production in Germany	Production in Brazil
Germany (grid connected)	7,792 kg/kW <sub>p</sub>	10,124 kg/kW <sub>p</sub>
Brazil (grid connected: actual generation mix)	- 1,009 kg/kW <sub>p</sub>	1,387 kg/kW <sub>p</sub>
Brazil (autonomous, instead of diesel generator)	24,408 kg/kW <sub>p</sub>	26,805 kg/kW <sub>p</sub>

Lifetime of PV system is 25 years; recycling rate was assumed to be 25%.

**Table V.** Net-reduction of CO<sub>2</sub> (in kg) by a PV-system (in kW<sub>p</sub>) based on multi-crystalline solar cells for different locations of production and of operation.

Operation site (type)	Production in Germany	Production in Brazil
Germany (grid connected)	8,677 kg/kW <sub>p</sub>	9,805 kg/kW <sub>p</sub>
Brazil (grid connected: actual generation mix)	162 kg/kW <sub>p</sub>	1,359 kg/kW <sub>p</sub>
Brazil (autonomous, instead of diesel generator)	25,372 kg/kW <sub>p</sub>	26,570 kg/kW <sub>p</sub>

Lifetime of PV system is 25 years; recycling rate was assumed to be 25%.

For operation in Brazil, the effect can be poor in the case of PV grid connection (especially when the equipment used was manufactured in a country where energy consumption is related to high carbon dioxide emissions), or substantial in case when a fossil fuel driven power plant is being substituted by PV (up to 27 tons/kW<sub>p</sub>). Considering the present costs of a PV system, the costs for CO<sub>2</sub> reduction by photovoltaics are in the vicinity of 0.23 US \$ per kg for off-grid applications in Brazil.

In relation to other methods this way to achieve climate control is rather expensive. Figure 3 shows the costs to reduce CO<sub>2</sub> (referenced to achieve a 20% reduction of carbon dioxide emissions based on 1990 by 2005) based on data from Eckaus *et al.* [16] by the least expensive CO<sub>2</sub> removal technologies (without emission trading permit).

## 4. FUTURE

To carry out a CO<sub>2</sub> analysis for a future time frame (e.g. 20 years ahead), also changes of the energy and CO<sub>2</sub> balances have to be taken into account, because the mix of generating capacity in an electrical grid as given in Table I may alter considerably.

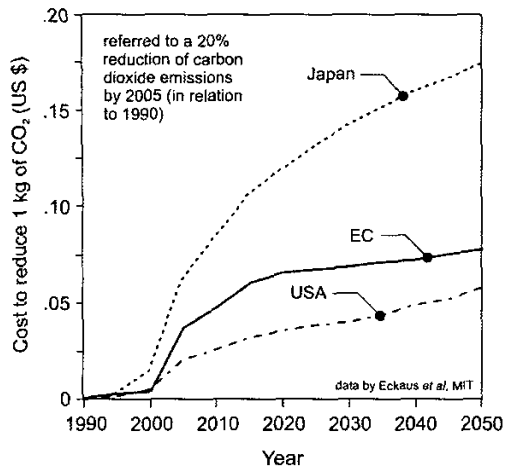


Fig. 3 Costs for carbon dioxide removal, with no backstops and no trade in emissions permits (data by [16]).

For example, while Brazil currently generates over 94% 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. Going deeper into detail: At a first sight the future composition of the grid has to be considered to compute the CO<sub>2</sub> 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 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, higher recycling rates, and the use of thin film technologies as amorphous silicon promises will increase the benefit of the use of PV systems in terms of CO<sub>2</sub>-reduction.

## 6. ACKNOWLEDGMENTS

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