RURAL ELECTRIFICATION BY PV IN TERMS OF CARBON TRADING

Stefan C. W. Krauter

Federal State University of Ceará (UECE), Department of Physics
Av Paranjana 1700, Fortaleza 60740-000 CE, Brazil
Tel./Fax. ++55-85-2992804, e-mail: krauter@uece.br, info@rio4.com

Abstract - A comprehensive CO_2-balance within the life-cycle of a PV power plant requires examination of the CO_2 sinks and sources at the sites and under the conditions of production, during transport, installation and operation, as well as at the location 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. In the examples of Brazil and Germany, the effective CO_2 reductions are derived, including the variables of possible interchange scenarios for production and operation of the PV systems, as well the carbon dioxide intensity of the local electrical grids. In the case of Brazil off-grid applications and the partial substitution of Diesel generating sets by photovoltaics are also examined. CO_2 reduction may reach 26,805 kg/kW$_p$ 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 considerably reduce the specific carbon dioxide emissions of the country. To find out the exact amount of reduction, a detailed analysis was developed that considers the carbon dioxide balance of the entire life-cycle of PV power plants, including production, transport installation, operation, and dismantling.

Several authors have discussed energy requirements for the production of photovoltaic solar energy conversion systems and their energy pay-back-time (Alsema 1998; Keoleian and Lewis 1997). Some publications also mention the reduction of CO_2-emissions by using PV systems to substitute conventional energy generating sets (e.g. Alsema, 2000). System limits of the life-cycle-analysis (LCA) of energy systems are very often set to national borders (as Tahara *et al.*, 1997). 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.*, 1996), 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 of PV

While the specific electrical energy requirements do not vary notably for most of modern manufacturing facilities of PV components, the specific CO_2 emissions depend very much on the power plants (nuclear, hydro, fossil etc.) producing the electricity to run these PV production facilities. The CO_2 intensity of different kinds of electrical power plants may vary considerably (between 17 and 1140 g of CO_2/kWh$_{el}$), 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 1).

Table 1. Composition of power plants for electrical energy generation in different countries.

Country	Fossil fuels (%)	Nuclear (%)	Renewables incl. hydro (%)	CO_2 intensity (g/kWh_{el})
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, Schaefer 1993 (in Brauch 1997), and Tahara *et al.* 1997.

The use of recycled materials has a major effect on the energy requirement and CO_2 emission of materials. E.g. for aluminum energy savings can reach 95% - recycled aluminum requires less energy than new steel (Czichos, 1996). Table 2 shows 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 in the available data, the separation between thermal and electrical energy used was not maintained (see overview by Alsema, 1998), which is essential to determine specific carbon dioxide emissions. Aside from the energy required in the production process, the demand for building the production facilities must also be considered.

Table 2. Sectors of energy consumption and CO_2 emission for the production of PV power plants.

Type	Electricity		Fuels			NEC	
Type of PV	Energy [a)]	CO_2 D [b)]	CO_2 BR [b)]	Energy [c)]	CO_2 [b)]	Energy [c)]	CO_2 [b)]
sc	5,144	2,726	360	1,152	346	226	52.4
mc	2,530	1,341	177	1,630	489	450	103.5

a) in kWh_{el}/kW_p b) in kg/kW_p c) in kWh_{prim}/kW_p
sc: single- or mono- crystalline, mc: multi-crystalline
NEC: Non-energy consumption
D: in Germany, BR: in Brazil, data by (Krauter, 1998).

2.2 Operation

The electrical energy output of a PV system depends on local solar irradiance, the angle of the sun's incidence, the irradiance spectrum, the operating temperature and electrical matching. Due to these factors, when compared with standard test conditions (STC) at which PV modules are rated, the actual power output can be up to 40% lower, as can be seen in the monitoring results of Germany's 1000 PV-Roofs Program. Krauter 1993; Krauter and Hanitsch 1996 describe a model for an accurate loss analysis, allowing a precise computation of PV output. 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 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 in the question of differing locations of production occurs on the sites of application: substituting a diesel-generator (0.9 to 1.05 kg CO_2/kWh_{el}) for a PV system could avoid the emission of 0.85 to 1 kg CO_2/kWh_{el}, while a grid-connected PV system in a “clean” electrical grid (e.g. Brazil at 0.07 kg CO_2/kWh_{el}) will not substantially contribute to CO_2 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_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 increase the average CO_2 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).

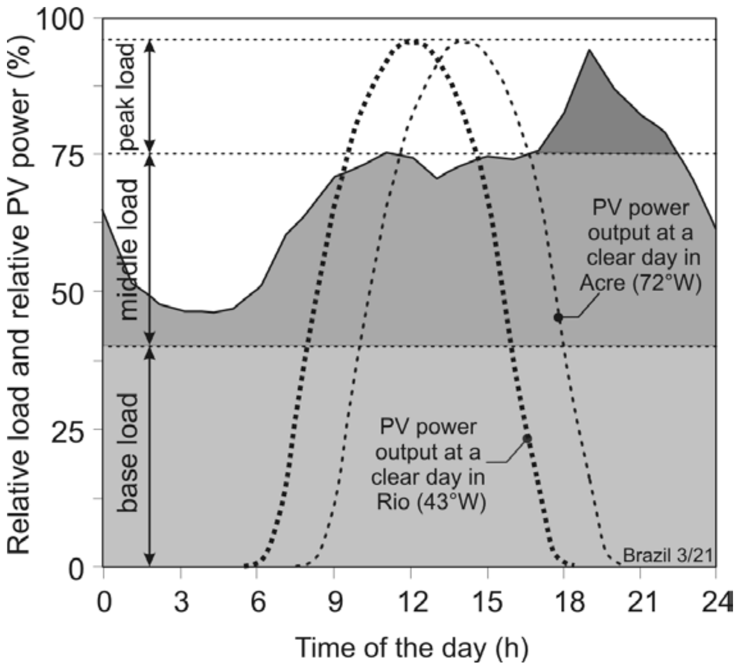

Fig. 1 Relative PV power output and relative electricity consumption for two locations in Brazil at a clear day as a function of time of day (data by Geller *et al.* 1997).

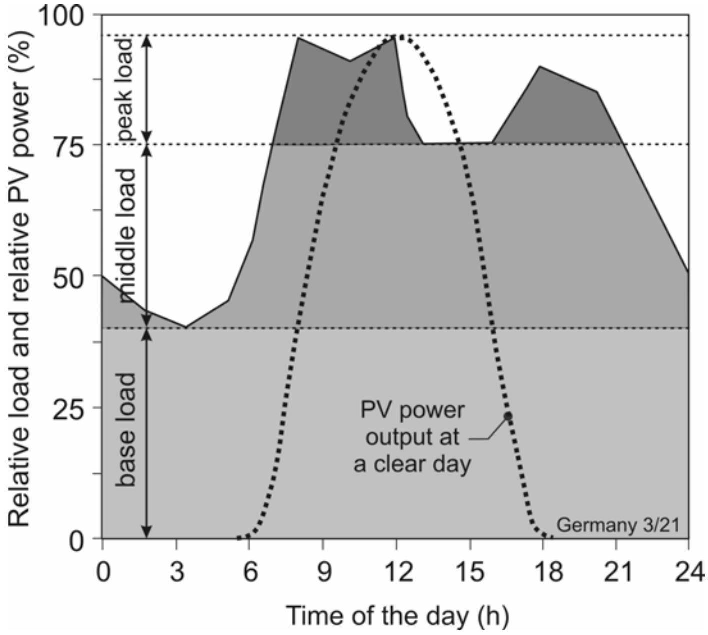

Fig. 2 Relative PV power output and electricity consumption for a clear day in Germany (data by Humm and Jehle, 1996).

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 in the supply of electrical power in Brazil often did not occur due to a lack in the maximum possible power output of the hydro generators, but by the low water levels of dam water. This enables the hydro generators to run at reduced power and allows them to adapt to peak demands. In this instance, PV can contribute substantially in terms of CO_2 reduction by displacing or offsetting water levels in dams for the use during times of peak demand, thus reducing the necessity to start additional peak power plants typically based on fossil fuels.

Furthermore, PV and hydro generation can be regarded as complementary on a seasonal basis, since dam water levels reach critical low values that coincide with higher solar irradiation levels in summer.

In Germany peak load occurs earlier and could be matched in part by PV (Fig. 2). 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_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 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_2 emission savings in the vicinity of 70% (Bruton *et al.* 1994, Frisson *et al.* 1998, Wambach 1998).

2.4 Transport

Table 3 presents the emissions of carbon dioxide for a 1 kW_p 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 3. CO_2 emissions per transported kW_p of a single-crystalline PV power plant between the locations of production and of operation.

CO_2 emissions due to 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

Calculations based on data by Frischknecht *et al.,* 1996: Transporter (< 3.50 t): 1.54 g CO_2/(kg km),
Truck (16 t): 0.35 g CO_2/(kg km), Train: 0.05 g CO_2/(kg km),
Sea freighter 0.001 g CO_2/(kg km)

3. RESULTS

The actual effect of the PV system in terms of net reduction of carbon dioxide is a product of the electrical yield in relationship 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 4 and in Table 5. 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.

Table 4. Net-reduction of CO_2 by a PV-System based on single-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_p	10,124 kg/kW_p
Brazil (grid connected: actual generation mix)	- 1,009 kg/kW_p	1,387 kg/kW_p
Brazil (autonomous, instead of diesel generator)	24,408 kg/kW_p	26,805 kg/kW_p

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

For operation in Germany the low irradiance value causes a cutback in the possible effect, but 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 of PV installed.

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_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 kg for off-grid applications in Brazil.

Table 5. Net-reduction of CO_2 (in kg) by a PV-system (in kW_p) 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_p	9,805 kg/kW_p
Brazil (grid connected: actual generation mix)	162 kg/kW_p	1,359 kg/kW_p
Brazil (autonomous, instead of diesel generator)	25,372 kg/kW_p	26,570 kg/kW_p
Lifetime of PV system is 25 years; recycling rate was assumed to be 25%.		

This method of climate control is presently rather expensive when considered in relation to other methods, but in the future CO_2 reduction by PV may become competitive.

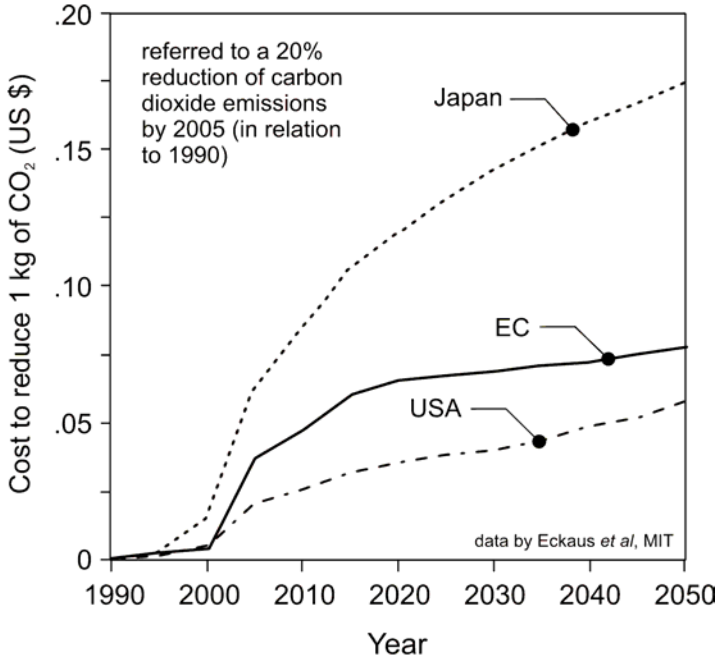

Fig. 3 Costs for carbon dioxide removal, with no backstops and no trade in emissions permits (data by Eckaus *et al*. 1997).

Figure 3 shows the costs to reduce CO_2 (referenced to achieve a 20% reduction of carbon dioxide emissions based on 1990 by 2005) based on data from Eckaus *et al*. 1997 utilizing the least expensive CO_2 removal technologies (without emission trading permit).

4. FUTURE

To carry out a CO_2 analysis for a future time frame (e.g. 20 years ahead), changes of the energy and CO_2 balances have to be taken into account as the mix of generating capacity in an electrical grid as given in Table 1 may alter considerably.

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 (typically natural gas, and oil) due to lack of water, limitations of suitable locations for additional hydro power plants and the increase of electrical energy consumption. To investigate further, one would first consider the future composition of the electrical grid in order to compute the CO_2 balances. Further inquiry would reveal that existing hydro power plants will remain and the increase of consumption only 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 accounted for future non-hydro power plants built during the time period of life expectancy (25 years) of the PV system.

Table 6. Comparison of specific emissions of electrical energy production of different technologies for Silicon based photovoltaic modules (amorphous is thin film technology, all others are thick film) in 1997, 1999 and for 2010 (data by Kuemmel *et al.* 1997 and Alsema 2000 for data of 1999).

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

The optimization of production processes towards low specific emissions, higher recycling rates, and the use of thin film technologies as amorphous silicon may increase the benefit of the use of PV systems in terms of CO_2-reduction. Table 6 is showing values for the specific emissions of .past, present and future silicon solar cell technologies.

5. CONCLUSIONS

Application of PV requires careful examination of the energy and emission flows during the system life-cycle to achieve a considerable effect on carbon dioxide reduction. Substitution of fossil fueled power plants by PV power plants in locations with high irradiance levels would yield the greatest reduction in carbon dioxide emission. In accordance with this, PV is already able to reduce 26.8 metric tons of CO_2 per kW_p installed during its lifetime, using common technology. Improvements in recycling rates and solar cell technology should be able to increase this value to at least 50 to 100 metric tons CO_2/ kW_p within the next 7 years.

The location of PV production, the local power plant composition and its resulting emissions also affect the amount of reduction, but to much a lesser extent than the type of PV use and operation.

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