Energy Requirements and CO_2 Mitigation Potential of PV Systems*

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ABSTRACT: In this paper we investigate the energy requirements of PV modules and systems and calculate the Energy Pay-Back Time for two major PV applications. Based on a review of past energy analysis studies we explain the main sources of differences and establish a “best estimate” for key system components. For present-day c-Si modules the main source of uncertainty is the preparation of silicon feedstock from semiconductor industry scrap. The best estimates of 4200 respectively 6000 MJ (primary energy) per m² module area are probably representative for near-future, frameless mc-Si and sc-Si modules. For a-Si thin film modules we estimate energy requirements at 1200 MJ/m² for present technology. Present-day and future energy requirements have also been estimated for the BOS in grid-connected roof-top systems and for Solar Home Systems. The Energy Pay-Back Time of present-day grid-connected systems is estimated at 3-8 years (under 1700 kWh/m² irradiation) and 1-2 years for future systems. The specific CO_2 emission of these systems is 60-150 g/kWh now and 20-30 g/kWh in the future. In Solar Home Systems the battery is the cause for a relatively high EPBT of more than 7 years, with little prospects for future improvements. The CO_2 emision is now estimated at 250-400 g/kWh and around 200 g/kWh in the future. This leads to the conclusion that PV systems, especially grid-connected systems, can contribute significantly to the mitigation of CO_2 emissions.

1. INTRODUCTION

The energy pay-back time or the energy requirement of PV systems has always been an issue receiving a great deal of public attention. Rightly so, because the energy requirement is a very good indicator of the net potential for CO_2 mitigation. The latter constitutes on its turn an important political motivation for PV technology development.
My objective in this paper is to review existing knowledge on energy requirements for manufacturing PV systems and give some example calculations for the energy pay-back time and the CO_2 emissions.
Over the past decade a number of studies on energy requirements of PV modules or systems have been published, among others by the author of this paper [1-12]. I have reviewed and compared these studies and tried to establish on which data there is more or less consensus and how observed differences may be explained. Based on this review of available data I have established a ‘best estimate’ of the energy requirement of crystalline silicon modules, thin film modules and BOS components.
Also I will show calculations of the Energy Pay-Back Time and CO_2 emissions for two representative PV system applications, namely a grid-connected rooftop system and a Solar Home System.

Throughout this paper I will present energy data as Equivalent Primary Energy requirements, that is the amount of primary (or fuel) energy necessary to produce the component. So all electrical energy input is converted into primary energy requirements, with an assumed conversion efficiency of 35%. (So 1 MJ of primary energy can supply 0.097 kWh of electrical energy.)
I restrict my assessment to the *production* phase of components because energy demands in the utilization phase are generally negligible for PV systems, and because there is very little data on recycling or other treatments of decommissioned systems.

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2. CRYSTALLINE SILICON MODULES

Present technology

Published estimates [1, 2, 4, 6, 9, 10, 12] for the energy requirement of present-day crystalline silicon modules vary considerably: between 2400 and 7600 MJ/m² for multicrystalline (mc-Si) technology and between 5300 and 16500 MJ/m² for single-crystalline (sc-Si) technology. Partly, these differences can be explained by different assumptions for process parameters like wafer thickness and wafering losses.

The most important source of differences, however, is the energy requirement estimation for the silicon feedstock used to produce PV wafers. Currently the majority of PV cells are made from off-spec silicon that is rejected by the micro-electronics industry. The first source of silicon for PV wafers is a fraction of the poly-silicon material that is produced by the silicon purification process but which has a slightly lower purity than the standard electronic grade material.

The second (and largest) source of PV feedstock are the tops and tails of Czochralsky ingots which are cut off before the ingots are being sawn into wafers. These Cz tops and tails are then remelted to produce ingots for PV wafers, with the result that the silicon in this PV ingot has in fact undergone *two* crystallization steps. We will call these the primary and the secondary crystallization steps.

In some past studies the energy consumption for the *primary* crystallization step was allocated equally to the PV wafers and the micro-electronics wafers. Because of the very high energy use in Czochralsky growing this can increase the estimate of the total energy requirement for the PV module dramatically. However, the Cz tops and tails are more or less a waste product with a much lower economic value than the wafers produced for the micro-electronics industry. For this reason I hold the opinion, and other analysts now agree on this [13], that full energy accounting of the primary (as well as the secondary) crystallization step gives much too pessimistic a result for silicon-based modules.

	mc-Si		sc-Si		
process	low	high	low	high	unit
mg silicon production	450	500	500	500	MJ/m² module
silicon purification	1800	3800	1900	4100	MJ/m² module
crystallization & contouring #1	-	5350	-	5700	MJ/m² module
crystallization & contouring #2	750	750	2400	2400	MJ/m² module
wafering	250	250	250	250	MJ/m² module
cell processing	600	600	600	600	MJ/m² module
module assembly	350	350	350	350	MJ/m² module
Total module (frameless)	4200	11600	6000	13900	MJ/m² module
Total module (frameless)	*35*	*96*	*47*	*109*	*MJ/Wp*

Table 1: Break-down of the energy requirements for c-Si module production with present-day technology (in MJ of primary energy). The *low* and *high* variants present different approaches with respect to silicon feedstock production.

On top of this "methodological uncertainty" there is considerable variation in the energy consumption estimates for both the silicon purification process (900-1700 MJ/kg) and for the Czochralsky process (500-2400 MJ/kg)[1], which may be real variations or due to assessment errors. Unfortunately I cannot clarify this further due to lack of reliable and detailed data.

To show the total effect of these two sources of uncertainty I will give here two estimates for silicon modules (table 1). The low estimate is based on the lower end value for silicon purification and does *not*

[1] *Note that the table expresses all energy values in MJ per m² module area. Under our assumptions 2.0 -2.4 kg of poly-silicon feedstock is needed per m² module.*

consider the primary crystallization step, while the high estimate assumes the high end value for Si purification and includes 2400 MJ/kg for the primary crystallization step.
From the silicon scrap material which comes out of the primary crystallization process, the PV industry subsequently prepares a multi- or single-crystalline ingot, which can be sawn into wafers. Assumed were a 64% (mc-Si) resp. 60% (sc-Si) ingot yield, and for both technologies a 350 µm wafer thickness and a 60% wafering yield. Energy use in the secondary Cz step was assumed to be considerably lower (1100 MJ/kg) than in the primary Cz step, because of the smaller ingot size (6") and lower quality required for PV material.

Regarding the energy requirements for the remainder of the solar cell production process there is less controversy. Our best estimate is that about 600 MJ/m² is added in cell processing and some 350 MJ/m² during module assembly, assuming standard screen printing technology and glass/tedlar encapsulation. The main uncertainty in the energy data concerns the 400 MJ/m² estimate for overhead energy that is used for functions like lighting and climatization of the module production plant and for environmental control. Taking into consideration also the production yields of cell and module processing (95% resp. 97%) we obtain total energy requirements for c-Si modules in the 4200-13900 MJ/m2 range. Note that for the cell and module processing our assumptions are the same for all four variants of table 1. Finally, we can remark that only a few percent of this total energy requirement is used in a non-electrical form.

If we now assume encapsulated cell efficiencies of 14 resp. 15.5% and module packing factors of 0.87 resp. 0.82 for mc-Si and sc-Si modules (cf. table 2) we can evaluate the energy requirements on a Wp basis (last row of table 1). We see that despite their higher efficiency sc-Si modules are slightly in the disadvantage over mc-Si modules. This is mainly due to the higher energy consumption for the sc-Si crystallization process.

It is unsatisfactory to have such a large uncertainty in the energy estimates. However, as I have stated above, the high estimate gives in my view too pessimistic a result, because it *fully* includes the primary crystallization step. So the actual value in the present situation will be closer to the lower estimate than to the higher one.

Future technology
In the near future (1-2 years) the supply of off-spec silicon will quickly become insufficient to meet the demands from the PV industry so that other feedstock sources will have to be drawn on. Because standard electronic-grade silicon is to expensive for PV applications, dedicated silicon purification routes will be needed. For this reason too, the lower energy estimates of table 1 are probably most representative for near-future c-Si technology.

For a view on the longer-term potential (up to 2007) we have to look first at the major determinants for the energy requirement of c-Si modules.
Our analysis above shows that these determinants are: 1) the inclusion or not of the primary crystallization step, 2) the energy consumption for Si purification and 3) the silicon content of the cells. For sc-Si cells the Czochralsky process is also a large contributor.
So it will be clear that future improvements in wafer production technology may bring down the energy requirements of Si modules. Technologies like EFG or other methods which eliminate the losses from wafer sawing, could have significant advantages.
A major factor determining future energy requirements will be the way silicon feedstock is produced. The introduction of a solar-grade silicon process might reduce the energy content of silicon feedstock to 600-1100 MJ/kg [1, 6] and make the discussion about one or two crystallizations obsolete. Because of the latter fact the values for future Si technology may be less uncertain than those for present-day technology.

Based on a number of independently performed studies [2, 4, 6] I expect that future mc-Si production technology may achieve a reduction in energy requirements to around 2600 MJ/m², assuming innovations like a dedicated silicon feedstock production for PV applications (solar grade or advanced Siemens) delivering material with an energy requirement of about 1000 MJ/kg, and furthermore improved casting methods (e.g. electromagnetic casting) and reduced silicon requirements per m² wafer. This kind of technology will probably become available in the next ten years.
For single-crystalline silicon modules a total energy requirement around 3200 MJ/m² [4] may be achieved with similar technology improvements.
If we further make a conservative assumption for future cell efficiencies of 16% resp. 18% (cf. table 2) we obtain energy requirements per Wp of 18.8 resp. 21.6 MJ for future mc-Si and sc-Si technology.

	Present (1997)		Future (2007)	
	cell	module	cell	Module
mc-Si	14	12.1	16	13.8
sc-Si	15.5	12.7	18	14.8
thin film	n.a.	6	n.a.	9

Table 2: Assumptions for encapsulated cell and module efficiencies for different cell technologies

CO_2 emissions
Because more than 95% of the energy for Si module production is used as electricity the CO_2 emissions due to module production can be estimated rather quickly[2]. Assuming a CO_2-emission of 0.57 kg per kWh produced electricity[3] (0.055 kg/MJ_{prim}) we obtain specific CO_2-emissions of 1.9 kg/Wp for near-future mc-Si and 2.6 g/Wp for near-future sc-Si. For year 2007 technology our estimates are resp. 1.0 and 1.2 kg/Wp. In our system assessment below we will calculate the CO_2 emission per kWh of delivered energy.

3.THIN FILM MODULES

Present technology
Concerning thin film modules most published studies on energy requirements deal with amorphous silicon technology [1, 2, 6, 8, 10, 11] and two with electrodeposited CdTe modules [2, 7]. Although estimates for the total energy requirement of a frameless a-Si module range from 710 to 1980 MJ/m², many of the differences may be explained by the choice of substrates and/or encapsulation materials, and the consideration or not of the energy requirement for manufacturing the production equipment. A remaining factor of uncertainty, which cannot be explained so easily, is the overhead energy use for functions like lighting, climatization and environmental control (estimated range 80-800 MJ/m²).
On the basis of a careful comparison and analysis of published energy estimates [3] I come to the best estimate for energy requirements of an a-Si thin film module, as given in table 3.

From table 3 we can see that the semiconductor and contact materials constituting the actual solar cell contribute only very little to the module's energy requirement. Low deposition efficiencies (<10%) in combination with high purity requirements, however, may drive up this value.

[2] *CO_2 emissions from the silica reduction process are also quite small, about 0.1 kg/Wp[14]*

[3] *This is an approximate value within the UCPTE region, i.e. continental W-Europe [15]. In this region about 50% of the electricity is produced by nucleair and hydro power plants.*

The materials used for the substrate and encapsulation constitute about 1/3 of the total energy input, assuming a glass/glass encapsulation. A polymer back cover will reduce the energy requirement with some 150 MJ/m². On the other hand, if not one of the glass sheets of the encapsulation is used as substrate, but an extra substrate layer is added, this will increase the energy requirement considerably (e.g. with 150 MJ/m² in case of stainless steel foil).

	Energy requirement (MJ/m² module)	Share (%)
cell material	50	4%
substrate + encapsulation material	350	29%
cell/module processing	400	33%
overhead operations	250	21%
equipment manufacturing	150	13%
Total module (frameless)	1200	100%
Total module (frameless)	*20 MJ/Wp*	

Table 3: Contributions to the energy requirement of an a-Si thin film module for present-day production technology (in MJ of primary energy).

The actual cell and module processing, comprising contact deposition, active layer deposition, laser scribing and lamination, contributes roughly another 1/3 to the module's energy requirement. Of course significant variations may be found here between different production plants depending on the deposition technology and the processing times.

For other thin film technologies most of the energy contributions will be about the same as for a-Si, except with regard to the processing energy. Electrodeposited CdTe, for example, is estimated to require some 200 MJ/m² less during processing. On the other hand a slightly higher overhead energy use is expected (for environmental control). Also, an polymer back cover would be less desirable for CdTe modules [2]. Although no energy studies for CIS were available we might expect the processing energy for co-deposited CIS modules to be in the same range or possibly higher than for a-Si.

Assuming a 6% module efficiency we obtain an estimated energy requirement of 20 MJ/Wp for an present-day thin film module, which is considerably lower than the values found for c-Si technology. However, as we will see below, high BOS energy requirements may completely cancel out this advantage.

Future technology
Because the encapsulation materials and the processing are the main contributors to the energy input, the prospects for future reduction of the energy requirement are less clearly identifiable as was the case with c-Si technology. A modest reduction, in the range of 10-20%, may be expected in the production of glass and other encapsulation materials. It is not clear whether displacement of the glass cover by a transparent polymer will lead to a lower energy requirement.
The trend towards thinner layers will probably reduce processing time which in turn can lead to a reduction in the processing energy and in the energy for equipment manufacturing. An increase of production scale can contribute to lower processing energy, lower equipment energy and lower overhead energy.
By these improvements I expect the energy requirement of thin film modules to decrease with some 30%, to 900 MJ/m², in the next ten years [cf. 2, 6]. If concurrently the module efficiency can be increased to 9%, the energy requirement on a Wp basis may reach the 10 MJ level.

CO_2 emissions
To estimate the specific CO_2 emission we can again apply the CO_2 emission factor of 0.055 kg/MJ[4], resulting in an emission of about 1.1 kg CO_2/Wp.

4. BALANCE-OF-SYSTEM COMPONENTS

Like in economic analyses of PV systems the Balance-of-System is cannot be neglected in energy analyses. Therefore we will shortly analyse the impacts of array supports, module frames[5] and batteries.
Recently, the results of a detailed analysis of the primary energy content of present applications of PV systems in buildings have been published [16]. This study has considered several applications on rooftops and building facades, as well as a large power plant.
Here I will restrict the BOS considerations to very simple assumptions for grid-connected roof-top systems. I will assume that per m² module area 3.5 kg of aluminium is used for the supports of present roof-top installations, requiring 500 MJ/m² of primary energy and causing an CO_2-equivalent emission of 26.5 kg/m². For future roof-top systems I assume a reduced aluminium use of 2.5 kg/m². The contribution from the inverter is small ([17], cf. table 4), and cabling is not considered here, but presumably it is small too.

It is worth noticing the significant contribution of module frames in present-day systems. Its wide range of energy content (300-770 MJ/m²) in past studies is due to large differences in the amount of aluminium used for the frames. Here I assumed 2.5 kg Al to be used per m² module, requiring 500 MJ of energy input. In any case, PV modules are expected to be frameless for all future applications.

	Unit	Present energy requirement	Future energy requirement
Module frame (Al)	MJ/m²	500	0
array support - roof integrated	MJ/m²	700	500
inverter (3 kW)	MJ/W	1	1
battery (lead-acid)	MJ/Wh	0.9	0.9

Table 4: Energy requirements for Balance-of-System components and module frames.

Batteries constitute a critical part of autonomous PV systems. Estimates for the energy requirement of lead-acid batteries found in the literature range between 25 and 50 MJ/kg [18-21]. The lower estimates, however, only include the energy requirements for the input materials but not the energy consumed during the battery manufacturing process. This process energy has been estimated at 9-16 MJ/kg [20, 21]. In most estimates the lead input is assumed to comprise a certain fraction of recycled lead (30-50%). Without this lead recycling energy requirements would be higher.
As the specific energy density of a lead-acid battery is about 40 Wh/kg we obtain an energy requirement per Wh of storage capacity in the range of 0.6-1.2 MJ (table 4). For my further analyses I will assume the mid-range value of 0.9 MJ/Wh. Furthermore I assume that within the next ten years no significant improvements in battery technology or battery energy requirements will occur. The CO_2 emission from

[4] *Although thin film modules have lower share of electricity in the total energy requirement (70%), the remaining 30% is used in glass production, where by chance the CO_2 emission is the same 0.055 kg per MJ of used energy.*

[5] *For energy analysis it is convenient to consider the frames separate from the modules, as part of the BOS.*

the battery production I estimate at about 2.4 kg-CO_2 per kg battery which is equivalent to 0.06 kg per Wh capacity (adapted from [20]).

5. ENERGY PAY-BACK TIME AND CO2 EMISSION OF PV SYSTEMS

Grid-connected systems

Figure 1 shows the energy pay-back time for two major PV system applications, namely grid-connected rooftop systems and stand-alone solar home systems. The assumptions taken into account for calculations are summarized in Table 5. Results are reported for multi-crystalline and amorphous silicon technologies. For the reasons explained earlier, the present values for mc-Si are further split into a low and a high case. The difference between the two cases is the most striking result as far as grid-connected systems are concerned.

	Unit	Grid connected	Solar Home System
Irradiation	kWh/m²/yr	1700	1900
Final yield	kWh/Wp/yr	1.28	1.3
system life	yr	30	20
battery size	Ah (@12V)	0	70
# of batt. sets required over system life	-	n.a.	5
Energy eff. of alternative supply option	%	35	25

Table 5: Assumptions for the calculations on Energy Pay Back Time and life-cycle CO_2 emissions

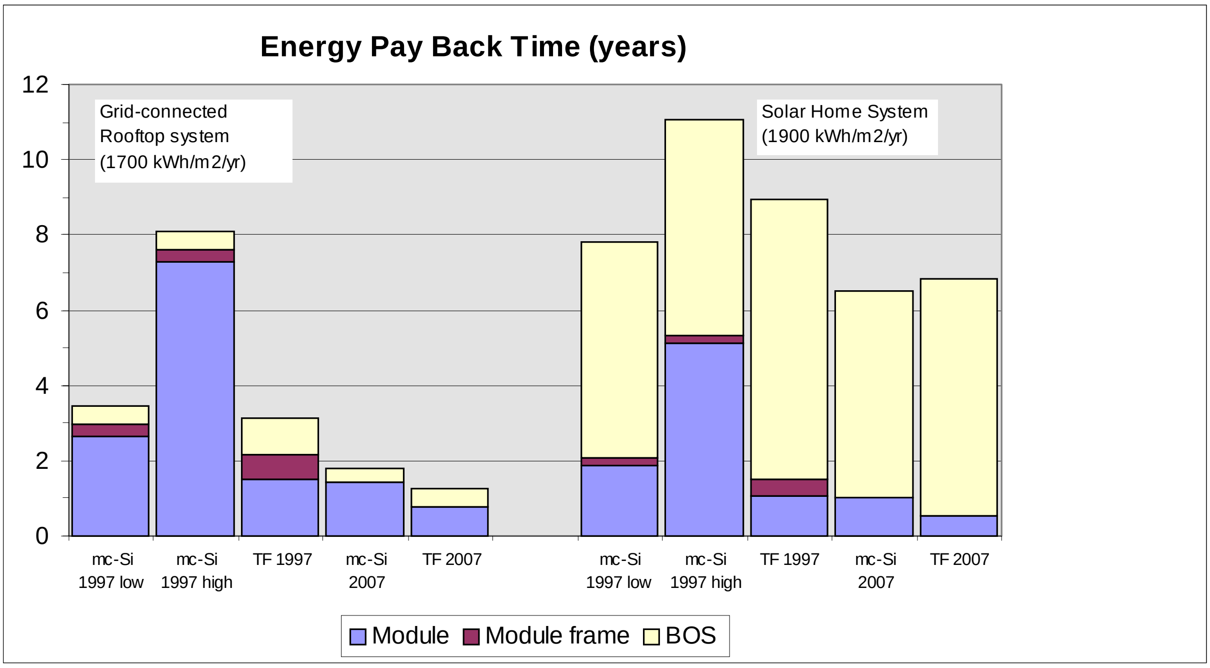

Figure 1: The Energy Pay Back Time (in years) for two major PV applications, both for present-day (1997) and future (2007) PV technology. For system-specific assumptions see table 5.

As a matter of fact, in the present mc-Si high case the energy pay-back time of a PV system is around eight years, even in the middle-good insolation conditions of 1700 kWh/m^2/yr. However, as already mentioned, I believe that this is a rather pessimistic view of present state-of-the art. Given the fact that PV

industry will have to address the issue of feedstock anyway in the next few years, I think that the low case is more representative for the near-future situation.
Further we may note that the contribution from the BOS and frame is significant already today: each causing an increase in energy pay-back time in the order of 0.3-0.5 year in combination with mc-Si cells.
Regarding thin film technology we can see that due to their lower efficiency, larger surface needed and consequently higher BOS requirements, the energetic advantages of present amorphous modules are cancelled by the higher BOS energy.
For future roof-top systems the expected energy pay-back time is 1-2 years both for mc-Si and a-Si technology.

These results show that grid-connected PV systems have considerable potential for saving on fossil-fuel energy production and thus reducing CO_2 emissions. This can also be seen in figure 2 where we have displayed the CO_2 emissions per kWh of supplied electricity for grid-connected PV systems and for a number of conventional power generation technologies. This shows that CO_2 emissions from PV are considerably lower than for fossil-fuel plants and that they will become even lower, around 20-30 g/kWh, in the future.

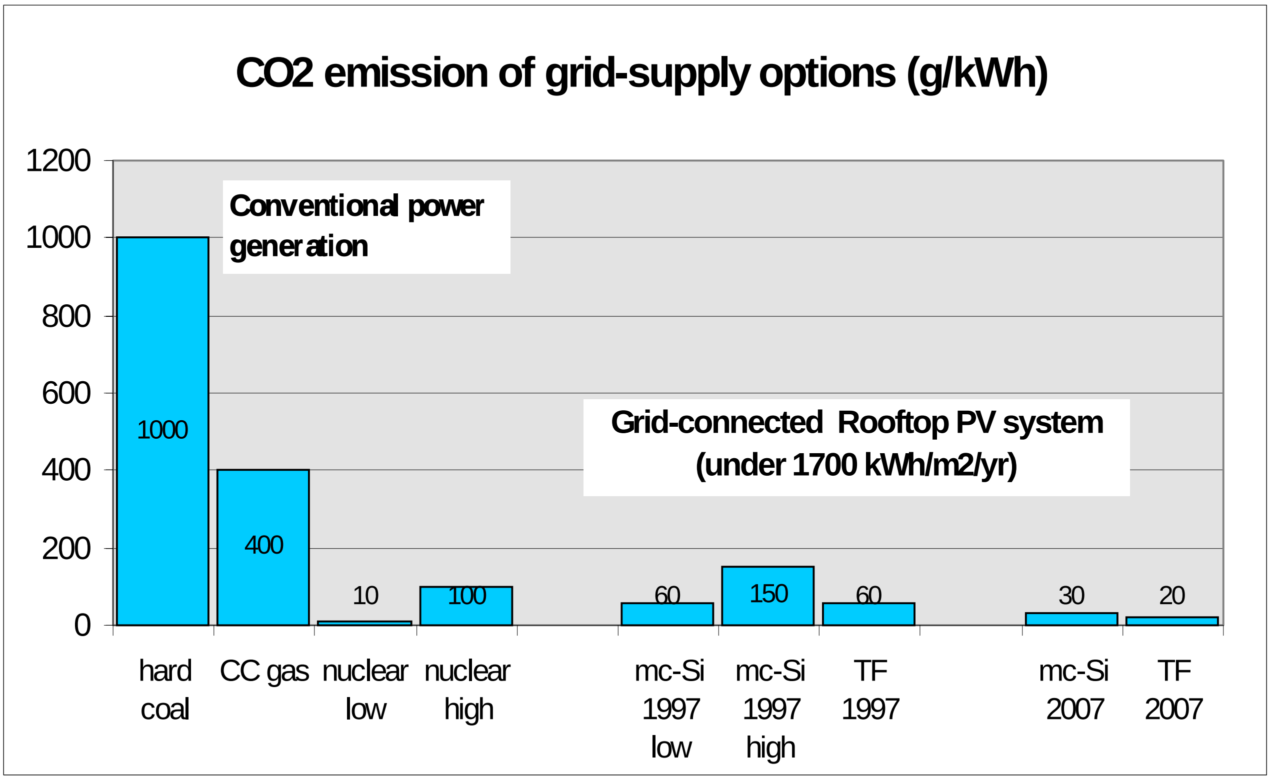

Figure 2: CO_2 emission for grid-connected roof-top PV systems and for conventional power systems (coal, gas, nuclear-low estimates from [15], nuclear-high from [22]).

Solar Home Systems
This potential for CO_2 mitigation by PV technology is less straightforward the case for our second application type, which concerns a Solar Home System, as has been introduced over the past years in many developing countries. A typical SHS as installed in for example Indonesia, comprises a 50 Wp module and a 70 Ah battery. Such a system may have a final yield of 1.30 kWh/Wp/yr under a 1900 kWh/m²/yr irradiation. (Of course actual SHS performance data are heavily dependant on the user load

profile, but we believe our assumption is fairly representative). We further assume a typical life time for the battery of 4 years, so that 5 battery sets are needed over a 20 year system life.
In order to evaluate an Energy Pay-Back Time we will compare the SHS with a diesel generator which converts primary energy (fuel) into electricity at an average efficiency of 25% . (Note that grid supply in a remote area may have a comparable conversion efficiency).
As the results in figure 1 show the EPBT of the assumed SHS configuration would be more than 7 years, even with the low module energy estimates for mc-Si modules. For future PV technology only a modest improvement is expected due to the large contribution of the battery (for which no improvement was assumed) to the system EPBT.

Figure 3 displays the CO_2 emissions per kWh of the SHS application in comparison with one alternative option, namely a diesel generator operating at 25% average conversion efficiency. Transportation energy to get the diesel fuel at the user location has not been accounted.
We see from figure 3 that the CO_2 emission from the PV installation is still considerably lower than for the diesel, although the difference is smaller than for the grid-connected systems.
One consequence of this result is that one should be careful when attributing a *large* CO_2 mitigation potential to SHS's. Some kind of break-through in electricity storage technology will be necessary if we want to improve the CO_2 mitigation potential of this application. In any case, the long-term worldwide contribution of SHS to CO_2 mitigation will always be small in comparison to grid-connected systems. Also one should remember that SHS are very valuable for a different reason, namely providing energy services at remote locations.

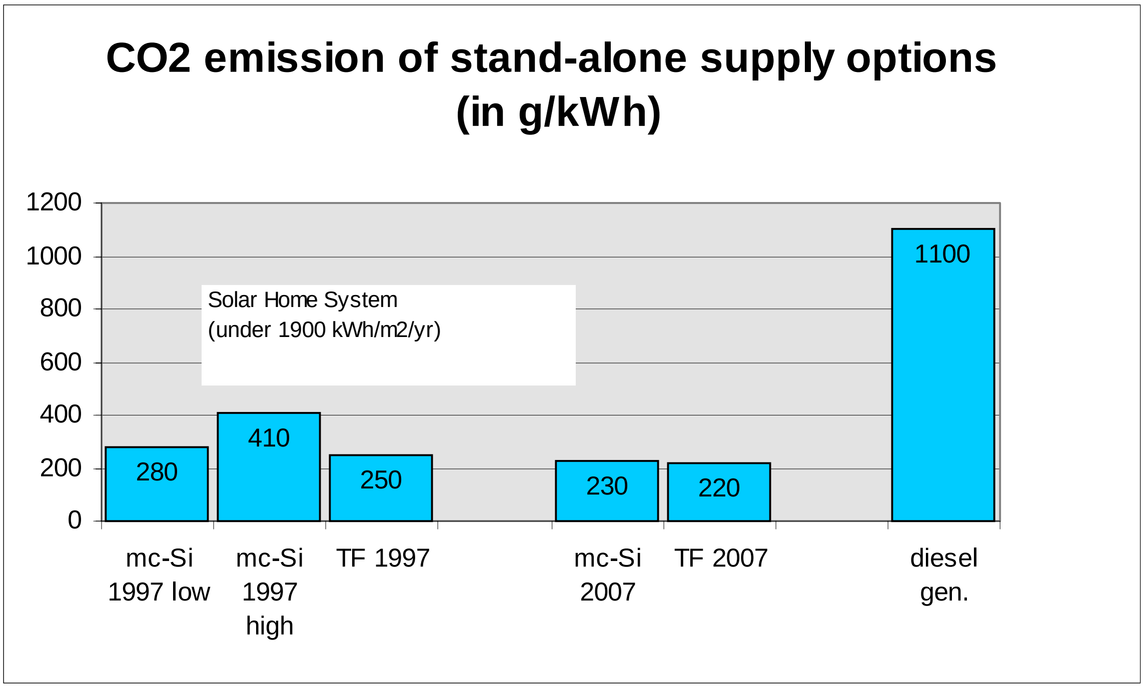

Figure 3: Life cycle CO_2 emissions from Solar Home Systems and from a diesel generator.

6. CONCLUSIONS

We have reviewed energy requirement data for PV modules and BOS components. It was found that there is considerable uncertainty with respect to the energy requirement of c-Si modules, due to accounting difficulties for off-spec silicon and due to lack of reliable data on silicon feedstock production. This is reflected in the large difference between calculated energy pay-back times, which range from around 8 years in the mc-Si high case to 3-4 years in the low case (under 1700 kWh/m²/yr irradiation).
I think that these two difficulties mostly explain the large difference of results which can be found in past literature. However, this will be no longer a major issue in the near future. In any case, dedicated processes for "PV-quality"' silicon feedstock, with a reduced energy requirement, are expected to bring significant improvements in the energy requirement of c-Si modules. The same can be expected from measures to reduce the amount of silicon required per m² wafer.
Thin film modules have a lower energy requirement per m² module area, but on a system level this is offset by their lower efficiency, leading to higher BOS energy requirements and lower energy production. With thin film technology the scope for a future reduction of energy requirements is more limited than for c-Si.
The energy pay-back times of PV rooftops are expected to decrease to less than 2 years both for mc-Si and a-Si module technology. Specific CO_2 emissions from these systems could go down from 60-150 g/kWh now to 20-30 g/kWh in the next ten years. These values indicate that such future systems will definitively have a high net fossil energy substitution and CO_2 mitigation potential.
This is less straightforward the case for Solar Home Systems, for which energy pay-back times of more than 7 years were found. Still, the CO_2 emissions from such systems (250-400 g/kWh) are relatively low in comparison with a diesel generator. In fact, the BOS is the crucial factor determining the energy and environmental profile of these systems and limiting its actual CO2 mitigation potential. Irrespectively of PV technology improvements, some kind of breakthrough in electricity storage means will be needed if we want to improve the over-all environmental effectiveness of Solar Home systems.

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