ENERGY PAY-BACK TIME OF PHOTOVOLTAIC ENERGY SYSTEMS: PRESENT STATUS AND PROSPECTS

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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 three 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. Therefore a low and a high estimate are presented for energy requirement of c-Si. The low estimates of 4200 respectively 6000 MJ (primary energy) per m² module area are probably most 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 array field systems, rooftop systems and Solar Home Systems. The Energy Pay-Back Time of present-day array field and rooftop systems is estimated at 4-8 years (under 1700 kWh/m² irradiation) and 1.2-2.4 for future systems. 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.
KEYWORDS: Environmental effects - 1: c-Si - 2: Thin film - 3

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.
Our 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.

Over the past decade a number of studies on energy requirements of PV modules or systems have been published, among others by the authors of this paper [1-12]. We 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 our review of available data we have established a 'best estimate' of the energy requirement of crystalline silicon modules, thin film modules and BOS components.
Also we will show calculations of the Energy Pay-Back Time for three representative PV system applications, namely a grid-connected array field system, a grid-connected rooftop system and a Solar Home System.

Throughout this paper we 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.). Our
We restrict our 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.

2. CRYSTALLINE SILICON MODULES

Published estimates [1, 2, 4, 7, 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.
It is now a quite difficult methodological question how the energy consumption of the silicon purification process and from the primary crystallization process (the CZ pulling) should be allocated to what is more or less a waste product, i.e. the off-spec poly-Si respectively the CZ tops and tails. One line of reasoning is that only part of the energy for purification and none of the energy for the primary crystallization should be taken into account for PV feedstock. A more conservative approach is to account both processes fully. There is no easy way to identify the best approach in this matter, and it may remain a source of controversy as long as the PV industry relies on off-spec material from the micro-electronics industry.

	mc-Si		sc-Si		unit
process	**low**	**high**	**low**	**high**	
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 we cannot clarify this further due to lack of reliable and detailed data.

For this reason we 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* 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 unfortunate and unsatisfactory to have such a wide range in the energy estimate, but in the context of this paper we cannot resolve this partly methodological uncertainty. However, the authors have now reached the opinion that *full inclusion of the primary crystallization step* in the energy account gives *too pessimistic* a result for c-Si PV modules.

Moreover, in the near future (1-2 years) the supply of off-spec silicon will 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 will be to expensive for PV applications, dedicated silicon purification routes will be needed. For this reason too, the lower energy estimates are probably more representative for near-future c-Si technology than the higher values.

It is clear that the major determinants for the energy requirement of c-Si modules 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. Therefore 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

[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.*

of silicon feedstock to 600-1100 MJ/kg 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 our own, independently performed studies [2, 4, 7] we 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 we expect that with similar technology improvements a total energy requirement for the module may be achieved around 3200 MJ/m² [4].
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

3.THIN FILM MODULES

Concerning thin film modules most published studies on energy requirements deal with amorphous silicon technology [1, 2, 7, 8, 10, 11] and two with electrodeposited CdTe modules [2, 6]. 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] we 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.
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 req. (MJ/m² module)	Share (%)
cell material	50	4%
substrate + encaps.mat.	350	29%
cell/module processing	400	33%
overhead operations	250	21%
equipment manuf.	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.

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 we expect the energy requirement of thin film modules to decrease with some 30%, to 900 MJ/m², in the next ten years [cf. 2, 7]. If concurrently the module efficiency can be increased to 9%, the energy requirement on a Wp basis may reach the 10 MJ level.

4. BALANCE-OF-SYSTEM COMPONENTS

Recently, the results of a detailed analysis of the primary energy content of present application of PV systems in buildings has been published (5). The study has taken into account several applications on rooftops and building facades. It also has included the analysis of a large power plant, namely the 3,3 MW power plant in Serre, Italy, for comparison. The results show that the primary energy content of a PV power plant is in the range of 1900 MJ/m^2, while most of the systems in buildings have a total primary energy content of around[2] 600 MJ/m^2. The high value for power plants is caused by the high amount of concrete and steel needed for this kind of installation in open fields. It is not expected to drop significantly in the future. On the contrary, PV applications in architecture profit from the existing building structures. The analysis also has shown that in the future the primary energy needed to install building-integrated systems might well further drop down to around 400 MJ/m^2 for tilted roofs and 200 MJ/m^2 for facades. These improvements can be obtained by reducing absolute quantities of materials and/or using large fractions of recycled materials (especially in the case of aluminium). Lowest and highest values of present and expected future energy requirements for BOS components and module frames are summarized in Table 4. For the energy pay-back time calculations we have used the mean values of 700 MJ/m² respectively 500 MJ/m^2 for present and future rooftop systems.
Cabling has not been included in these analyses, but is expected to have a small to negligible impact in most systems.

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

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 [13-16]. 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 [15, 16]. 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 our further analyses we will assume the mid-range value of 0.9 MJ/Wh. Furthermore we assume that within the next ten years no significant improvements in battery technology or battery energy requirements will occur.

[2]*The retrofit PV cladding facade at the University of Northumbria has a much higher value of 1800 MJ/m2. However, this is an exception caused by an excessive use of primary aluminium.*

	Unit	Present energy req.	Future energy req.
Module frame (Al)	MJ/m²	300-770	0
array support - field	MJ/m²	1900	1800
array support - roof integrated	MJ/m²	500-1000	350-700
array support - facade	MJ/m²	600-700	200-550
inverter (3.3 kW)	MJ/kW	0.5	0.5
battery (lead-acid)	MJ/Wh	0.6-1.2	0.6-1.2

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

5. ENERGY PAY-BACK TIME OF PV SYSTEMS

Figure 1 shows the energy pay-back time for three major PV system applications, namely grid-connected rooftop systems, grid-connected array field 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.
As a matter of fact, in the present mc-Si high case the energy pay-back time is around eight years, even in the middle-good insolation conditions of 1700 kWh/m^2/yr. However, as already mentioned, we 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, we think that the low case is more representative for the near-future situation.
If the high mc-Si case is excluded, the BOS contribution is significant already today: the energy pay-back time of present array field (around 4 years) is reduced down to 3.4 years in the case of rooftops. In the latter case it is worth noticing that the contribution of aluminum frames is of the same order of magnitude of the one of BOS.
Due to lower efficiency, larger surface needed and consequently higher BOS requirements, the advantages of present amorphous modules are cancelled by the BOS. In the case of the array field, the energy pay-back time of a-Si is even higher than the one of mc-Si (low case).
The expected future energy pay-back time for array fields is slightly higher than 2 years for both multicrystalline and amorphous silicon. As the contribution of modules decreases, differences in BOS count proportionally more. Therefore the application of PV systems in buildings is expected to further reduce energy pay-back times by 30% (down to 1,7 years) and 50% (1,2 years) for mc-Si and a-Si respectively.

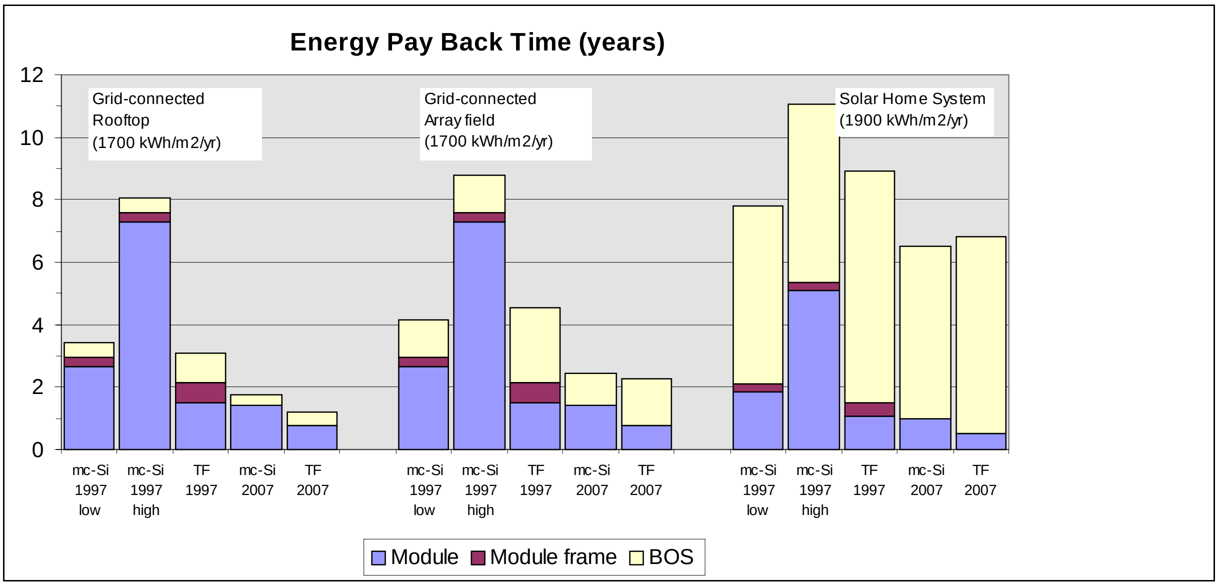

Figure 1: The Energy Pay Back Time (in years) for three major PV applications, both for present-day (1997) and future (2007) PV technology. For system-specific assumptions see table 5.

We think that these are very interesting values. In other words, we think that future rooftop PV systems (and slightly less, future PV array field power plants) will definitively be able to save a significant amount of net conventional energy over their life-cycle by substituting electricity production from fossil fuels, thus giving a significant contribution for the mitigation of CO2 emissions.

This is not straightforward the case for our third PV application, 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.
One consequence of this result is that one should be careful when attributing a 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.

	Unit	Grid conn.	SHS
irradiation	kWh/m²/yr	1700	1900
Final yield	kWh/Wp/yr	1.28	1.3
battery size	Ah (@12V)	0	70
# of batt. sets required over system life		n.a.	5
Energy eff. of altern. supply option	%	35	25

Table 5: Assumptions for the Energy Pay Back Time calculations.

6. CONCLUSIONS

We have reviewed energy requirement data for PV modules and BOS components. We 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).
We think that this difficulty mostly explains 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 integration of PV systems in buildings brings benefits in comparison to array field power plants already today. These benefits will further increase in the future, since as the contribution of modules decreases, differences in BOS count proportionally more. As a consequence, the energy pay-back times of PV rooftops are expected to drop down to 1,7 years and 1,2 years for mc-Si and a-Si respectively. These values indicate that such future systems will definitively have a high net fossil energy substitution and CO_2 mitigation potential.

This is not straightforward the case for Solar Home Systems, for which energy pay-back times of more than 7 years were found. 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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