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A COST AND ENVIRONMENTAL IMPACT COMPARISON OF GRID-CONNECTED ROOFTOP AND GROUND-BASED PV SYSTEMS

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ABSTRACT: The environmental impact and total system costs have been investigated for roof-top and ground-based crystalline silicon PV systems by using environmental and cost life cycle assessment.
Greenhouse gas emissions and other environmental impacts from Balance-Of-System components are relatively small, in comparison with those of the total PV system. In-roof systems have lower impact due to credit from avoided roof tiles. With proper design of the mounting structure ground-based systems can have low impacts as well.
Although large ground-based systems use larger weights of mounting structure than small roof-top systems and occupy land, they have lower prices than small-scale roof-top systems due to efficient installation and bulk purchasing.
Keywords: economic analysis, environmental effect, small grid-connected PV systems, large grid-connected PV systems

1 INTRODUCTION

In cost and environmental analyses the contribution of Balance-of-System (BOS) components is often given less attention because its share is smaller than that of the PV modules [1]. However as module costs and environmental impacts decrease, the balance-of system part will become of increasing importance. Also in systems with less efficient modules the contribution of BOS will be higher. Furthermore rooftop systems can have an advantage in BOS costs and impacts over ground–based systems because of the lower material requirements, possible savings on roofing material and multiple area use.

The purpose of this paper is to make a comparison of grid-connected rooftop and ground-based photovoltaic systems, based on an analysis of economic cost and environmental impacts for existing systems in Europe and the USA.

For the cost analysis we will look at the cost for different BOS components and installation requirements for in-roof PV systems, on-roof systems (retrofit above existing roof) as well as a number of large ground-mounted systems in the 0.5-5 MWp range [2,3].

The environmental assessments will be based on a Life Cycle Assessment study for the same type of systems as mentioned above. Among the impact results we will pay special attention to the greenhouse gas emissions.

2 METHODOLOGY

For our analysis we selected a number of photovoltaic systems, which we considered representative for today. The small-scale systems are based on BOS components available in Western-Europe (mainly Germany) and designed as described in section 3. Data on material quantities were collected with the help of mounting system suppliers and other sources of information.

The large-scale systems are actually existing systems: one located in Germany and one in Springerville, U.S.A. The latter system was described in [2,4]. Data for the German system was described in [3] and Phönix Sonnenstrom provided further details.

To determine the environmental impact of the BOS components, an environmental life cycle assessment excluding the end-of-life phase has been done using the software SimaPro 7 with the database Ecoinvent 2.1 (corrections made for list of errors as of 16 March 2006). Since the environmental impact is dominated by the primary energy use, this is calculated by using the Cumulative Energy Demand version 1.03 method. An important environmental effect is the global warming potential, which we estimated by means of the IPCC 2001 GWP 100a version 1.02 method.

3 SMALL SCALE ROOF-TOP PV SYSTEM DESIGN

3.1 PV modules

As a typical example for today's technology we chose for modules incorporating 6 x 10 multicrystalline silicon cells with a size 156 mm x 156 mm. One example of such a module is the SolarWorld SW220 with size 1001 mm x 1675 mm (= 1.68 m^2), 220 Wp, weight 22 kg. Because we focus on BOS aspects in this paper, we restrict our analyses to just this module type; also systems with thin film modules are not considered.

3.2 Array layout and inverter

A 1-phase inverter is chosen with a maximum AC power rating of 5 kW, since this is the largest 1-phase inverter possible in Germany.

Since SMA is the largest European solar inverter manufacturer [5], we calculated the number of the SolarWorld modules possible to a 1-phase SMA inverter with maximum power not exceeding 5 kW, using the SMA Excel tool GenAu.xls version 7.3. This results in 2 strings of 13 SolarWorld modules (area 44 m^2) connected to one SMA Sunny Boy 5000TL HC MS inverter.

Reference houses in the Netherlands have roof surface areas ranging from 47 m^2 to 94 m^2 [6]. Present roofs are dual-pitched, but mono-pitched with optimal orientation and slope for integrating PV modules have been demonstrated [7]. We have multiplied the 2x13 module system by 2 to obtain (1) 4 rows of 13 modules with a total area of 87 m^2 and total PV power of 11.4 kWp and (2) 2 inverters with nominal AC power of 2 x 4.6 = 9.2 kW. The ratio of the inverter power and module power is 0.8. The PV system could be installed on 2 smaller houses with a joint roof or 1 large house, preferable mono-pitched with optimal orientation to the sun.

The modules are oriented portrait, which has the advantage of less accumulation of soil in the profiles and minimizes the amount of mounting material needed related to the total module area as well as the labor needed to install the mounting system. These advantages are also valid for ground-based systems.

3.3 Mounting system

We considered two classes of roof-top mounting systems: on-roof mounting, leaving the existing roofing material in place, and in-roof mounting, where the modules take over the function of the roof tiles. In the latter case an actual saving on roof tile material can be accounted. The mounting structures for the roof-top systems that we selected are all suitable for 30^0 sloped roofs and, in the case of the on-roof system, it is compatible with the type of roof tile called Frankfurter Pfanne.

The two on-roof mounting structures analyzed are:

- Schletter Eco05 profile and EcoG roof hooks (the lightest possible)
- Phönix Sonnenstrom TectoSun

The two in-roof mounting structures analyzed are:

- Schletter Plandach 5
- Schweizer Solrif

According to [8] Schletter is the largest solar mounting system supplier for the German market.

As mentioned the modules are mounted on the roof in portrait direction and 4 rows of 13 modules.

3.4 Cabling and connectors

To connect the modules 4 mm^2 DC cabling is used with total length of 188 meter.

To connect the inverter to the grid 6 mm^2 AC cabling is used with total length of 10 meter.

4 ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF PV SYSTEMS

4.1 Modules

The analysis of the multicrystalline silicon modules was in line with our earlier published Life Cycle Assessment of crystalline silicon modules [1]. No update of module production technology was incorporated in this paper.

4.2 Inverters

Detailed data on material use in inverters are not easy to obtain. From earlier studies [9,10] we had at our disposal a detailed bill of materials for a string inverter, the former Philips PSI 300 (P_{nom}= 300 W). Based on that information the material composition for the highly comparable PSI 500 (P_{nom}= 500 W) could be estimated fairly accurately. In the third place we had material data for a somewhat older inverter, the Mastervolt SunMaster 2500 (P_{nom}= 2500 W). All three inverters have wire-wound transformers as major electronic components (by weight).

In figures 1 and 2 you can see that the weight of the inverter in general decreases with the nominal AC power. This effect is strong for very small inverters with a nominal power below 1 kW. Between 2 and 200 kW the weight per kg depends on the inverter choice and is between 5 and 15 kg/kW. Above 400 kW the weight tends to be below 5 kg/kW. For this reason we can expect a lower environmental impact per rated power for inverters for large-scale ground based systems..

Life cycle inventory data for electronic components, like transformers, capacitors and IC's are not available in the standard LCA database that we use (Ecoinvent 2000). Therefore we based ourselves on LCI data for a number of "standard" electronic components that were collected by Andræ [11] [12]. The representativity of these components for inverter electronics could not be verified. Given the relative importance of electronics on the impact results for inverters, this would be a point for further investigation.

The green house gas emissions per rated power of two of our modeled inverters, Sunmaster 2500 and PSI 500, are presented in figure 3.

Figure 3 shows that the impact per rated power of the 500 W inverter is relatively large, mainly as a result of the relatively high amount of electronics and also by the aluminium casing material used for the PSI 500. Quite remarkable too, is the high share of electronics in our modeled inverters. Very often in LCA analyses of inverters, the electronic components are neglected because they are not know or too difficult to model. Our results suggest that this may lead to gross underestimation of the real impacts of inverters.

For inverters in the higher power class, e.g. above 10 kW, one might expect that the relative impact of the electronic components will decrease, as the amount of control electronics will surely not scale with capacity.

For our roof-top system we would need a 4.6 kW inverter. Because no life cycle inventory data for a commercially available 4.6 kW inverter were available, we decided to use scaled-up data for the Sunmaster 2500 instead.

The real impact of a modern inverter in this power class could be different especially if it is transformerless, i.e. if it contains less copper but more electronics. Given the relatively high impacts of electronic components our approach is likely to give an under-estimate of the impacts of a modern inverter.

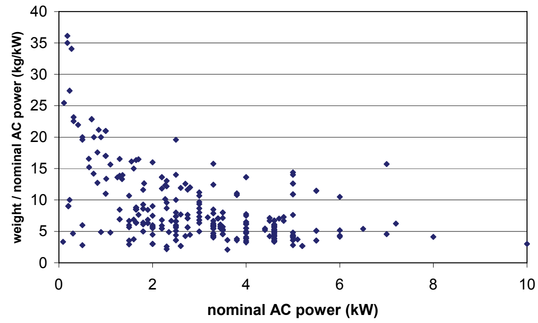

Figure 1: Weight of small inverters (<10 kW)

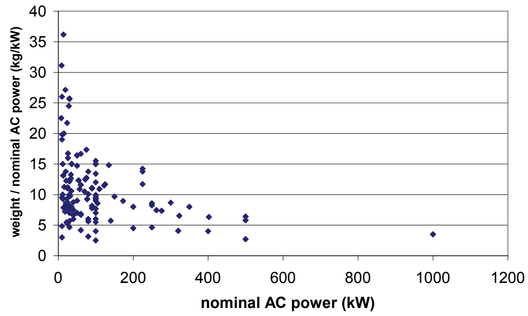

Figure 2: Weight of large inverters (>10 kW)

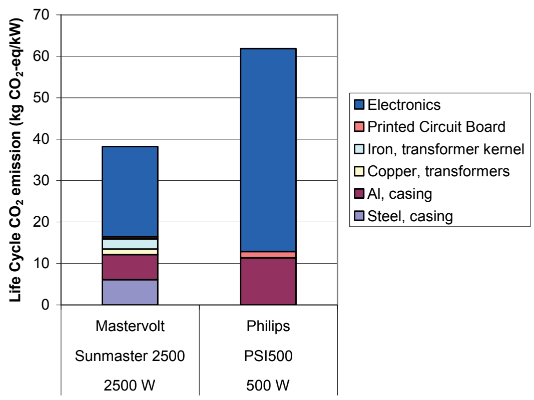

Figure 3: Breakdown of green house gas emissions (in g CO_2-eq/kW) of the inverters Sunmaster 2500 and PSI 500.

4.3 Mounting system

See table I for the inventory of materials used in the various mounting systems.

The different mounting systems investigated may have different static bearing strength for loads like snow/ice and wind (DIN1055).

In figure 4 global warming potential, as expressed by green house gas emissions, is shown. Note that module frames have been included in this figure although these are usually not considered as a BOS component. The reason is that mounting structure design is obviously influenced by the choice for either framed of frameless modules, especially for on-roof or ground-based arrays. Further remark that for those mounting structures that can allow the use of unframed modules, we omitted the frame in our analysis. The impact of the frame alone is often as high as that of the mounting structure. The somewhat heavier design of the frameless-capable mounting structures is more than compensated by the reduction of aluminium use for the module frames. Thus the use of frameless instead of framed modules reduces the global warming potential significantly. One can wonder if a similar advantage could be realized in cost terms.

Also it is interesting to see that the avoidance of ceramic roof tiles in the in-roof systems results in net negative impact scores for the mounting structure, meaning that the global warming effect is decreased. Of the two ground-based mounting structures, although they have comparable weights, the Springerville has lower global warming impact than the Phönix system. The concrete foundations used in Springerville have very little impact, and also less steel and aluminium is used.

Not surprisingly, the roof-top structures have a lower impact than the ground-based ones.

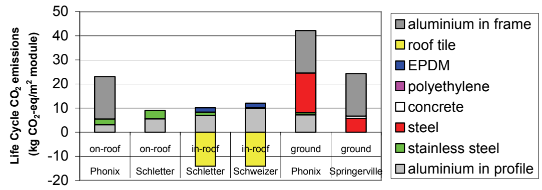

Figure 4: Breakdown of green house gas emissions (g CO_2-eq/m^2 module) for mounting systems including module frame. The "aluminium in profile" is part of the mounting structure, while "aluminium in frame" is the impact of the module frame.

4.4 Cabling and connectors

Cabling and connectors are increasingly being made of halogen free materials and compliant with ROHS [13].

The material composition of the cable used in this LCA are presented in Table II.. Amounts of materials in connectors are not available and therefore are not included in the analysis. The contact materials in the connectors is copper or brass (alloy of copper and zinc) with coating of tin. For the housing of the connectors various plastics are used: polyamide, polycarbonate, polyphenylene oxide, polypropylene, thermoplastic elastomer or thermoplastic polyurethane.

4.5 Total Balance-of-System

See table III for primary energy use of different components of the PV system. The primary energy use is the energy used over the total life cycle of the PV system.

Energy payback times for the different Balance-of-System components are calculated and presented in figure 5 using the following assumptions:

- irradiance of 1700 kWh/m^2/yr (South Europe)
- multicrystalline module efficiency of 13.2%
- performance ratio = 0.75 (http://www.iea-pvps-task2.org/).

The actual performance ratio of PV systems can vary considerably with system design, shading and ventilation. In-roof systems installed in high-temperature areas, may suffer from extra temperature loss, but this depends a lot on the actual roof and mounting design. Because of lacking information on typical loss factors for in-roof systems, we used the same conservative performance ratio of 0.75 for all system designs.

Based on these assumptions, green house gas emissions are calculated and presented in figure 6 using the following additional assumptions:

- life time of PV system is 30 years
- life time of the inverter is 15 years

A breakdown of the global warming potential of the Balance-of-System components is given in figure 6, again showing that by eliminating the module frame a large reduction of the environmental impact can be obtained. Furthermore ground-based systems generally have a higher impact than in-roof systems, and even if possible extra temperature losses for in-roof systems were taken into account, it seems improbable that this effect would negate the observed advantage.

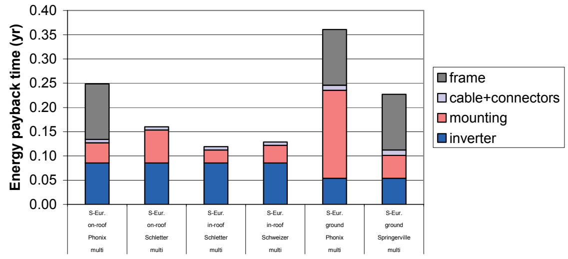

Figure 5: Energy pay back times of Balance-of-System components and module frame of PV systems located in South Europe

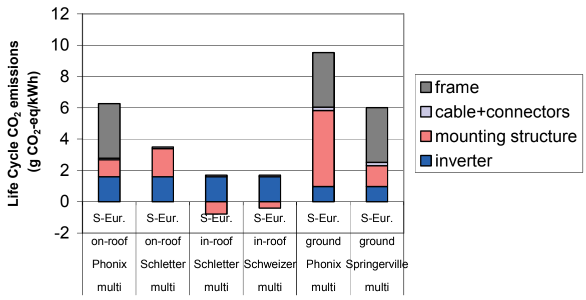

Figure 6: Green house gas emissions (in g CO_2-eq/kWh) of Balance-of-System components and module frames of PV systems located in South Europe

4.6 Total PV system

Figure 7 shows that the global warming potential of the total PV system is still dominated by the module.

For future crystalline silicon technology, where the impact of laminates may be reduced by 50% or more [17], the BOS contribution may increase up to 25% and almost 50% if we consider the frame as well (see figure 8). In this situation an optimized design of the BOS, reducing overall environmental impacts, becomes even more relevant than it is now.

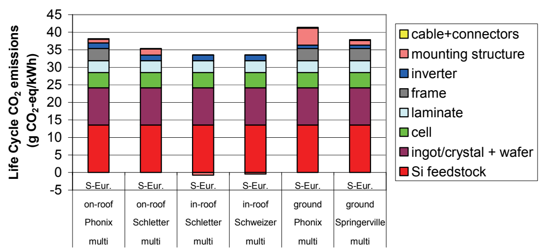

Figure 7: Breakdown of green house gas emissions (in g CO_2-eq/kWh) of PV systems located in South Europe

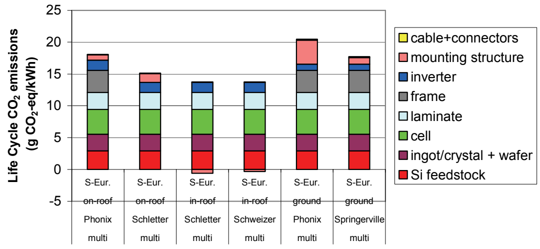

Figure 8: Breakdown of green house gas emissions (in g CO_2-eq/kWh) of future PV systems located in South Europe (17% module efficiency, 150 µm cell thickness, silicon feedstock produced with fluidized-bed-reactor technology)

5 PRICE

All prices mentioned are excluding VAT.

5.1 Modules

Prices of modules [14] are presented in figure 9. For the breakdown of PV system price we assumed a module price of 4 €/Wp (excl. VAT) for small-scale systems and 3 €/Wp (excl. VAT) for large-scale systems.

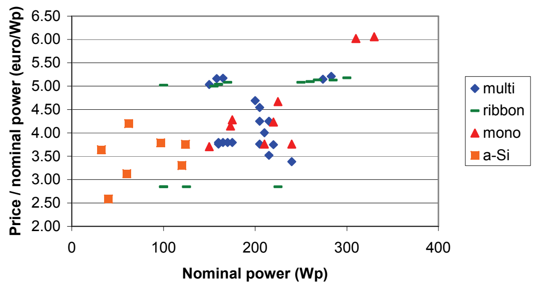

Figure 9: Prices of modules excluding VAT [14]

5.2 Inverters

In figures 10 and 11 it can be seen that the price/kW decreases with nominal AC power of the inverter with the lowest value approaching 0.2 euro/kW.

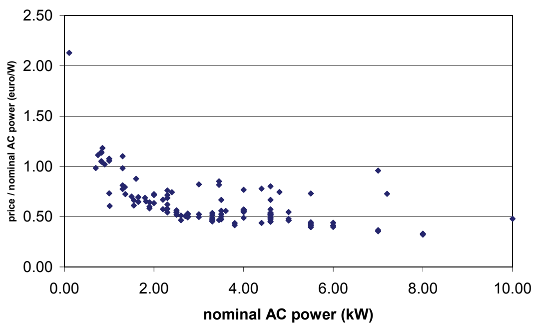

Figure 10: Prices of small inverters excluding VAT

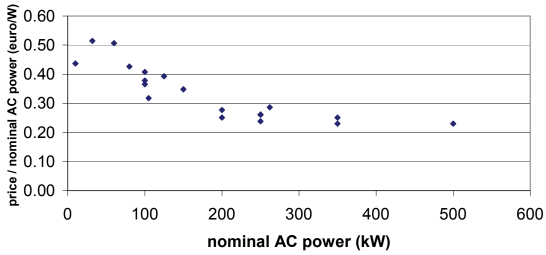

Figure 11: Prices of large inverters excluding VAT

5.3 PV system

Figure 12 shows prices of small-scale PV systems [15]. Figure 13 shows investments of large-scale PV systems [16].

A breakdown of the prices of PV systems is presented in figure 14 using data from [2], [3] and [4] for large-scale PV systems and own estimates for the roof-top systems.

The total Balance-of-System prices of roof-top and ground-based systems are comparable. Although the weight of the mounting structure of the ground-based systems is much larger than the weight of the roof-top systems, the prices are comparable because the components used in ground-based system are made of less expensive materials and can be designed/installed more efficiently. The large-scale ground based systems furthermore have the advantage of bulk purchasing compared to the small-scale roof top systems.

The PV system prices are still dominated by the module price.

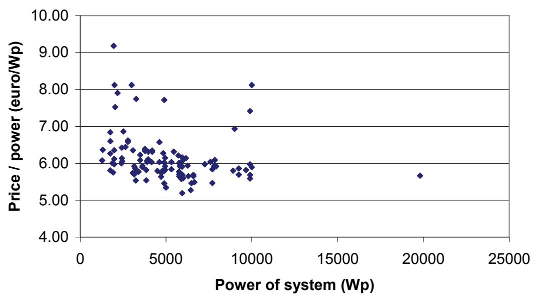

Figure 12: Prices of small-scale PV systems excluding VAT

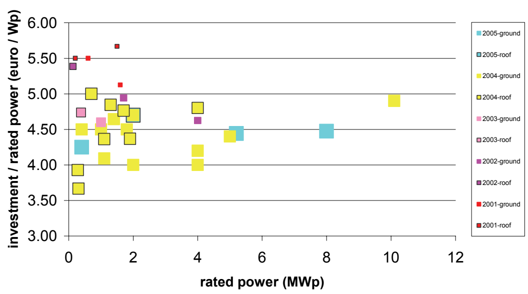

Figure 13: Investments of large scale PV systems

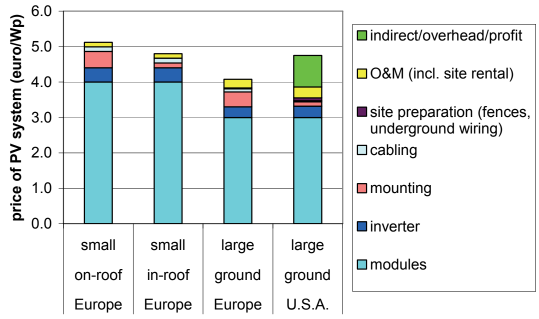

Figure 14: Breakdown of prices of PV systems excluding VAT

6 CONCLUSIONS

The environmental impact and total system costs have been investigated for roof-top and ground-based crystalline silicon PV systems by using environmental and cost life cycle assessment.

Greenhouse gas emissions and other environmental impacts from Balance-Of-System components are relatively small, in comparison with present-day modules.

Frameless laminates are largely preferred from an environmental point of view; the extra impacts from a somewhat heavier mounting structure are more than compensated by the avoided impacts of the frames.

In-roof systems clearly have a lower environmental impact of the Balance-of-System components in comparison to on-roof and ground-based systems. This advantage is due to the credit from avoided ceramic roof tiles. For an in-roof system the greenhouse gas emissions of the balance-of-system components can be as low as 3% of the emission of the total PV system, while the BOS (including frames) of an on-roof system is responsible for about 18% of the emissions of the total PV system..

The BOS (including frames) of ground-based systems are responsible for 16 to 23% of emissions of the total PV system. With frameless modules and a proper design of the mounting structure, ground-based systems will have comparable impacts as *on*-roof systems, but still higher than for in-roof systems. The BOS then produces about 7% of emissions of the total PV system.

If in future the impact of PV laminates will be 1/2 of today's impact, then the relative impact for BOS will be about 8% for in-roof PV and 15% for optimized ground based PV respectively, compared with the emissions of the total PV system.

Among BOS components the inverter seems to cause a relatively large impact, especially in smaller PV systems. Better LCA data on the electronic parts of an inverter would be helpful to reduce uncertainties for this component.

Although large ground-based systems use larger weights of mounting structures than small roof-top systems and occupy land, they have considerably lower prices than small-scale roof-top systems due to efficient installation and bulk purchasing. This effect will be in future lower as it scales mainly with the (falling) module prices.

On the other hand ground costs (which were taken into account) can be higher in more densely populated areas, thus reducing the cost advantage.

Future PV roof-top systems should try to reduce further on costs and materials for mounting structure, roof tiles and on installation work because the relative impact of BOS will rise with falling module prices.

The environmental life cycle inventory data are available at the ECN website as Excel file [18].

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Table I: LCI of mounting systems.

kg / m²	on-roof Phönix TectoSun	on-roof Schletter Eco05 + EcoG[1]	in-roof Schletter Plandach 5[1]	in-roof Schweizer Solrif	ground Phönix	ground Springerville
module size (mm x mm):	1675x1001	1675x1001	1675x1001	1675x1001	1318x994[2]	1892x1283[3]
framed (f) or unframed (u) modules	f	f+u	f+u	u[4]	f	f
Steel	0.00	0.00	0	0.00	11.50	4.01
Stainless steel	0.49	0.72	0.28	0.08	0.17	0.00
Aluminium	0.54	0.97	1.21	1.71	1.26	0.00
Concrete	0.00	0.00	0.00	0.00	0.00	8.03
TOTAL	**1.03**	**1.69**	**1.49**	**1.79**	**12.93**	**12.04**
frame of module	3.04	0.00	0.00	0.00	3.04	3.04
EPDM under-roof	0.00	0.00	1.41	1.41	0.00	0.00
Avoided roof-tiles	0.00	0.00	-40.00	-40.00	0.00	0.00

[1] For the Schletter mounting systems the Excel tool Autokalkulator version 8.22 is used to calculate the amounts of materials.
[2] Phönix ground-based PV system uses Sharp 162 Wp multicrystalline silicon modules.
[3] Springerville ground-based PV system uses ASE 300DG/50 300 Wp multicrystalline framed modules.
[4] The Solrif profiles are fixed to the frameless module (=laminate) in the factory.

Table II: Material composition of cabling

kg / m	Helukabel Solarflex 101 4 mm² DC	Helukabel NYM-J 6 mm² AC
Copper	38.4	173
TPE Thermoplastic Elastomer	29.6	0
PVC	0	147

Table III: Primary energy use of the PV systems

MJ / kWp	Phönix TectoSun on-roof	Schletter Eco05 + EcoG on-roof	Schletter Plandach 5 in-roof	Schweizer Solrif in-roof	Phönix ground	Springerville ground
module size (mm x mm):	1675x1001	1675x1001	1675x1001	1675x1001	1318x994	1892x1283
Si feedstock	13319	13319	13319	13319	13319	13319
ingot/crystal + wafer	9204	9204	9204	9204	9204	9204
cell	3368	3368	3368	3368	3368	3368
laminate	3201	3201	3201	3201	3201	3201
frame	1697	0	0	0	1697	1697
inverters	1267	1267	1267	1267	795	795
mounting system	612	1000	393	534	2682	701
cabling	99	99	99	99	159	163
total	**32766**	**31457**	**30850**	**30991**	**34424**	**32447**