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BINE Informationsdienst

Recycling photovoltaic modules

- Module recycling rate of over 95 percent achievable
- Reprocessing more cost-efficient than purchasing new wafers
- New possibilities for using silicon of previously unusable quality in the solar industry
- High-quality recycling system reinforces the image of the solar sector

Fig. 1

Old modules are prepared for the recycling process in the pilot system in Freiberg.

The solar industry is growing. The installed capacity is set to increase continually. In Germany, new photovoltaic modules with a capacity of around three gigawatts were installed in 2009, while the amount of electricity generated by PV systems rose from 4.4 TWh (2008) to 6.2 TWh. New large-scale projects all over the world, as well as the growing presence on house roofs in Germany, are causing demand for raw materials to rise further. All of this, as well as the valuable materials used in PV systems, means that recycling makes economic sense.
What was previously an irrelevant issue for the solar industry, due to photovoltaic modules' long service lives of 25 years or more, will present it with new challenges in the future. In recent years, the first photovoltaic systems have reached the end of their days and been recycled in a Deutsche Solar AG pilot system. By 2015, a considerable number of PV modules will have fallen into disuse and the resulting amount of waste is expected to rise sharply. By means of recycling, valuable raw materials can be recovered from the generators, thus reducing the demand for primary raw materials.
Since 2002, in a joint project funded by the German Federal Ministry for the Environment, researchers from Deutsche Solar AG and TU Bergakademie Freiberg have been working on making module recycling more environmentally friendly and efficient. State-of-the-art technology now enables recycling of production waste, completely worn-out modules and broken modules, achieving recycling rates of over 95%.
In order to prepare the old modules optimally, a high-quality comprehensive recycling system is needed along the entire solar value-creation chain. The solar industry has founded the association PV CYCLE as a joint initiative, so as to develop such a system at EU level.

▶ Recycling is vital for sustainable photovoltaics

Fig. 2: Estimated amount of material generated according to module technology

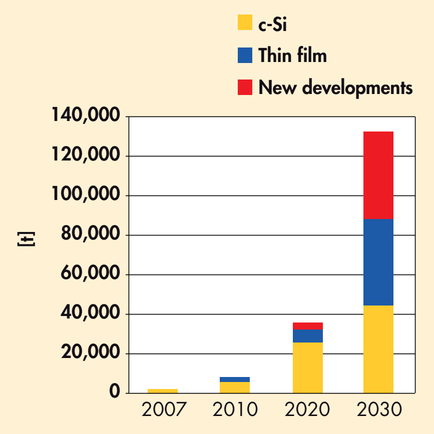


Fig. 3: Composition of c-Si and thin-film modules (corresponding to the respective technology)

	c-Si (crystalline silicon cells)	a-Si (amorphous silicon cells)	CIS (copper indium diselenide cells)	CdTe (cadmium telluride cells)
Proportion in %				
Glass	74	90	85	95
Aluminium	10	10	12	< 0.01
Silicon	approx. 3	< 0.1		
Polymers	approx. 6.5	10	6	3.5
Zinc	0.12	< 0.1	0.12	0.01
Lead	< 0.1	< 0.1	< 0.1	< 0.01
Copper (cables)	0.6		0.85	1.0
Indium			0.02	
Selenium			0.03	
Tellurium				0.07
Cadmium				0.07
Silver	< 0.006			< 0.01

Source: Recycling of solar modules – potential and requirements of a future material flow / PV CYCLE study 2007

Not even "green technology" lasts forever. With the rapid expansion of photovoltaics, the amount of waste to be generated by PV products in the future is also increasing and it is becoming essential to set up recycling management for this waste. This is also due to the fact that strong growth and high price pressure in the industry are necessitating new, low-cost sources of solar silicon.

Recycling also reduces environmental impact. Naturally, alongside saving energy and resources, it is also important to prevent the loss or release of scarce or poisonous elements and compounds.

Old modules and production waste alike are available for disposal. It is difficult to determine the exact amount, because of the many factors of uncertainty. Due to the long service lives of solar modules, this technology, which is still young, has generated little waste so far. In 2008, the amount of waste which it generated in the EU was around 3,800 tonnes (corresponding to 51 MWp). By 2030, this is expected to rise to 130,000 tonnes (see Fig. 2).

PV scrap – what does it contain?

Today, around 90% of PV waste consists of crystalline silicon (c-Si) and the other 10% is accounted for by thin-film cells, which to date include CIS (Cu, In, Se), CdTe, amorphous and microcrystalline technologies. However, the proportion of thin-film cells will rise to around 20% by the year 2020 (see Fig. 2). Until then, the amount of waste generated by new developments will remain negligible. New technologies of the future could, for example, include modules with new substrate materials or organic cells – everything which to date is either still in the infancy of development, or nothing more than a concept. By 2030, the proportions of the different technologies could more or less balance out. Figure 3 shows the composition of various PV module types.

Upcycling rather than downcycling

To date, PV companies have largely failed to achieve satisfactorily pure material fractions when recycling old solar modules. This is referred to as "downcycling", which only yields low sales returns. It entails significant costs, which go beyond those of dumping and have to be covered by acceptance fees.

The cost-efficiency of module recycling depends greatly on whether high-quality recovery is achieved ("upcycling"). Recycling at product level is advantageous with regard to the energy balance and therefore should always be striven towards. Even if it were technically possible to separate all components into pure raw materials, compromises would have to be made in order to keep the costs in check.

However, higher take-back costs and recycling costs must be reckoned with for thin-film solar cells, due to the low amounts of semiconductor materials which they contain.

Recycling initiative in the industry

In order to establish a voluntary industry-wide take-back and recycling programme for old modules in Europe, eight companies in the PV industry founded the association PV CYCLE in July 2007. Now with over five dozen members, it represents around 85% of the European PV market. This industry association undertakes to take back and dispose of PV waste, free of charge.

PV modules should deliver clean energy for at least 25 years. As the first larger photovoltaic systems were installed in the early 1990s, a significant number of PV modules will reach the end of their life cycles from 2015 onwards. By then, a programme for take-back and recycling of old modules, production waste and damaged modules should be in place. The target is to collect at least 65% of all old modules which are dismantled and to recover 85% or more of their valuable materials such as glass, aluminium and semiconductor materials.

Recycling reduces the production of primary materials (which requires more energy and entails more emissions) and thus im-

Sustainability of recycling processes

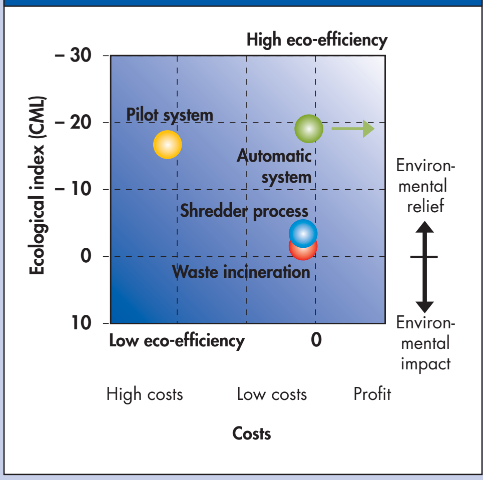
The ecological efficiency of different recycling processes varies greatly (see Fig. 4).

With shredders and waste incineration, the recycling rate for Al, Cu and glass is low, the end products are low-quality and cost reduction is unrealistic.

With manual separation, the pilot system achieves a satisfactory recycling rate with low throughput. The automated system delivers high-quality end products with high throughput, thus achieving a high recycling rate in an energy-efficient and cost-efficient manner.

The concept of eco-efficiency takes a product's entire life cycle into account. Energy consumption, resource consumption, environmental impact and recyclability are compared with the economic value of the product, with the aim of combining environmental relief with cost reduction.

Fig. 4: Comparison of recycling processes



proves the ecological and economic characteristics of PV systems. Its effects on environmental impact and the CO_2 balance can be determined by means of a life-cycle analysis. The so-called "yield factor" describes the ratio of harvested energy to expended energy. With the usual 25-year period of use, the factor is between 5 and 50, depending on acceptance and conditions, and is generally higher for thin-film modules than for crystalline silicon modules.

▶ Reprocessing

From the pilot system...

The researchers developed a sustainable recirculation system for photovoltaic products. After small-scale testing (2002 – 2005), the separation process was transferred to the Freiberg pilot system. In the current project, solar silicon reprocessing methods which are as environmentally friendly as possible are being developed. Here, one aim is to reduce the toxicity and environmental impact of etching solutions, thus also reducing the costs of disposing of the residual solutions. On the other hand, improved etching processes enable a higher light yield and thus higher efficiency for new solar cells.

The original recycling objective of recovering undamaged cells was abandoned because today's low solar cell thicknesses (< 180 µm) and modules' heavy prior damage after dismantling and transport mean that it is no longer profitable. Therefore, broken solar cells are obtained and cleaned, so that pure Si is produced. This is re-melted into polycrystalline ingots, from which new wafers are then produced. This avoids the laborious extraction of Si from high-purity quartz.

This, the world's first pilot system for the recycling of all standard solar modules, has been running since 2002 and processes a diverse range of solar cells which use different technologies and come from different manufacturers. This system has already recycled the oldest German PV system and the oldest Belgian PV system.

The new process is mainly used to recycle standard modules with solar cells made of monocrystalline, polycrystalline or amorphous silicon. Solar cells from different manufacturers require treatments specifically adapted to suit their layer systems.

The system separates the modules' components in two process steps. In the first, thermal step, the module's plastic parts are removed, and glass and frame parts are disassembled, sorted, then recycled (see Fig. 5). At the beginning of the second step, not only broken solar cells, but also whole solar cells are recovered. The solar cell structure is removed for wafer recovery by means of an etching process. Recovering solar silicon from broken solar cells has proven more economical.

Running the pilot system still uses considerable amounts of energy and raw materials. The manual separation and the low throughput also entail relatively high costs.

... to automated recycling

With energy-optimised automated systems, the environmental impact caused by the thermal process and material separation should be reduced to one third. The yield and purity achieved when reprocessing an old Belgian system ("Chevetogne") in the pilot system are shown in Fig. 6. Developers hope to achieve similar yield and purity on a large scale. It is expected that with higher-quality end products, higher throughputs and higher recycling rates, it is possible to operate in such a way as to cover costs, or even to make a profit.

The broken Si obtained in the automatic system is subsequently melted down and made into modern solar cells. Compared to old modules from the 1980s, the efficiency of the new modules can be as much as 50% higher.

In comparison with the manufacture of modules from new wafers, production from recycled wafers saves enormous amounts of energy.

Fig. 5: Module processing procedure in Freiberg

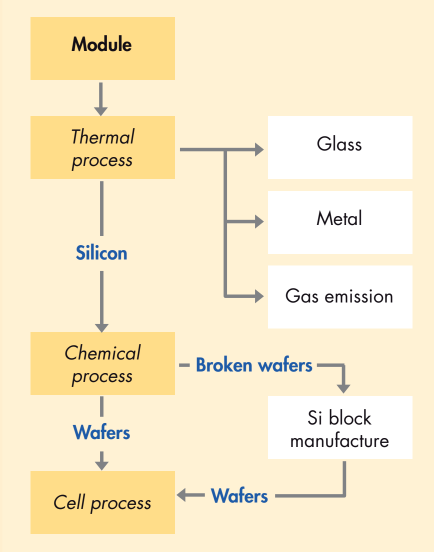


Fig. 6: Yield from the recycling process

Process parameter	Pilot system	Automated system	
Material input requirements	unbroken PV modules	broken and unbroken modules	
Material separation	manual separation	automatic separation	
Process applicability	crystalline modules	all module types	
Capacity	200 t p.a.	20,000 t p.a.	
Results			
	"Chevetogne" generator yield [%]	**Yield [%]**	**Purity [%]**
Glass	96	94.3*	99.99975
Si cells and broken cells	84.6	72.8*	41% > 99.995 59% > 99.9999
Films	-	Energy recovery 100%	
Copper	77.78	100	100
Frames	100	100	100
Connection sockets		electronic scrap 100%	
Recycling rate	**84.57**	**95.7****	

* *The heavy prior damage of modules (breakage of glass and cells) decreases the yield in comparison to the "Chevetogne" generator*

** *Poor mix fraction 4.3% (broken glass and broken cells)*

Another method for the recycling of thin-film modules

Another method, specifically for the recycling of CdTe thin-film solar modules, has been used by the US photovoltaic company First Solar since the end of the 1990s. Here, whole and broken modules and production waste are all processed in a single procedure. This results in recovery of 90% of the glass and 95% of the semiconductor material. This method is used at various locations in the USA, as well as in Frankfurt an der Oder, Germany.

The modules are roughly broken down in a shredder, then ground in a hammer mill to form pieces which are 4 – 5 mm in size. In this process, the lamination seal is broken. In a stainless-steel drum, the semiconductor layers are removed with acid. Subsequently, solid materials (glass and larger pieces of lamination film) are separated off. The metal-bearing liquid is purified and concentrated in a three-stage precipitation process with increasing pH values. Semiconductor material for new modules can be obtained from the resulting filter cake.

▶ Conclusion, outlook

Taking back and recycling PV waste free of charge makes sense ecologically and economically. In the future, automated recycling processes will make it possible to achieve recycling rates of over 95% and to recover raw materials without cost, or even at a profit. Recycling has positive effects on the entire energy balance and ecological balance of PV technology. Modules with solar cells made solely from newly produced silicon need three times as long to generate the energy required for their manufacture as modules of equal capacity with solar cells made using recycled material. Wafers for which a proportion of recycled material is used in their manufacture are also significantly more cost-effective than new ones.
The joint project is conducting important preliminary work for the development of a more environmentally friendly and effective recycling process on an industrial scale. The enhanced pilot recycling method can process new cell and module technologies, heavily damaged modules and thin-film modules into higher-quality products. The method has also been successfully developed further for etching back solar cells and broken solar cells to yield new products, such as fine-grained silicon.
Standardised and automated workflows enable an economically and ecologically optimal recycling result. The researchers are constantly enhancing and optimising the reprocessing procedures. The results which can be achieved in this way improve if the processing methods can be adapted to suit the respective cell technology and module technology more specifically.
As yet, only two processes are being implemented on a large scale: Deutsche Solar's treatment process, mainly for crystalline silicon modules, and First Solar's process for CdTe modules. Processes for other module types still require development expenditure. A Europe-wide efficient recycling system which can process future waste volumes must be developed, both for the image of a sustainable photovoltaic industry and in order for a sustainable photovoltaic industry to function. Thus, the industry's recycling association has a demanding task to perform.
The materials and compounds used in products greatly influence the subsequent recycling possibilities and process costs. Therefore, already when developing new technologies, it is important to consider how these materials and compounds can be dismantled and recycled in a correct and environmentally compatible way at the end of their usage periods. In this regard, appropriate selection of materials and precise documentation of their constituents is helpful.

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▸ ADDITIONAL INFORMATION

Literature (in German)

- Schlenker, S. u. a.: Entwicklung eines nachhaltigen Kreislaufsystems für photovoltaische Produkte „SOMOZELL II". Schlussbericht. Deutsche Solar AG, Freiberg (Hrsg.). 2009. FKZ 0327566A,B

Internet
- www.deutschesolar.de
- www.chemie.tu-freiberg.de
- www.solarworld.de
- www.sunicon.de
- www.pvcycle.org

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