Product Group Report: photovoltaics

The potential for remanufacturing of photovoltaic solar cells

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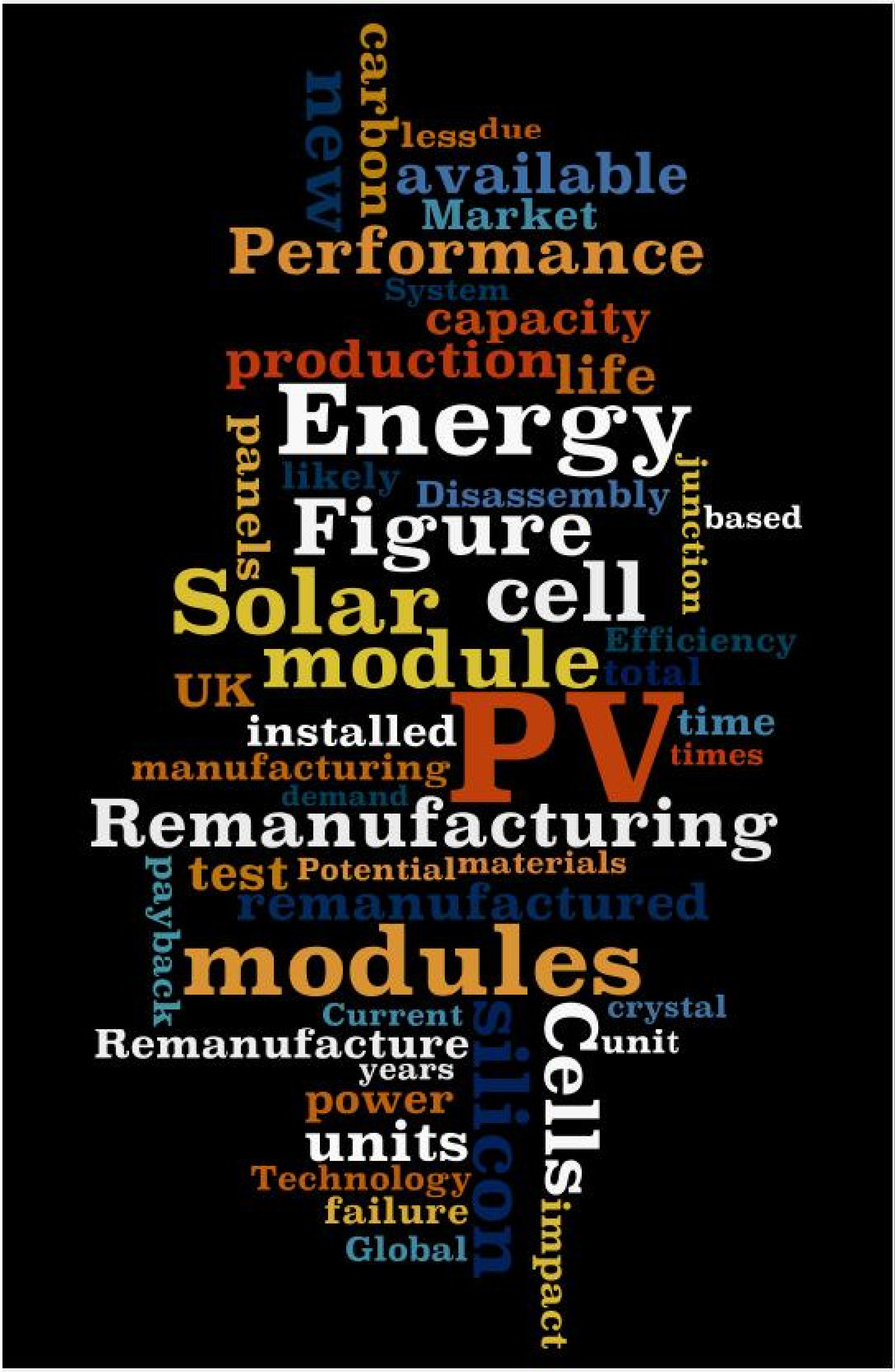
www.remanufacturing.org.uk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Glossary

CO_{2e}	The net emissions of the life-cycle expressed as the equivalent amount of carbon dioxide.
Ecoinvent	Industry-recognised database containing life-cycle phase impacts for numerous materials and products.
IPCC	Inter-governmental Panel on Climate Change, the international forum defining the global scientific position on global warming.
LCA	A technique whereby the various effects of manufacturing, using and disposing of an item or service are evaluated according to a methodology for a stated set of parameters.
OEM	Original Equipment Manufacturer; the first manufacturer of a new item, holding design specifications and possibly copyright.
PV	Photo-voltaics; a class of semiconductor technologies that convert light energy into electricity.
SimaPro	Industry-recognised tool providing an interface to the Ecoinvent database for easier assembly of lifecycles including reuse loops, sensitivity analyses and presentation of the results,

1 Summary

The purpose of this report is to inform those who are interested in commercial opportunities for life extension activity applied to photovoltaic panels operating within the UK (servicing, refurbishment, remanufacture and reuse). Because the solar cell base is lower than in many other countries, present opportunities for reuse in the UK are limited.

As a result the report concentrates on:

- Drawing parallels with other more established markets.
- Describing factors for and against remanufacturing, technical, political and economic.
- Listing the specific engineering capabilities required.
- Speculating on the sorts of companies that may become players.
- Proposing actions for supporting agents: government, RDAs and trade/skills councils.

2 Market Overview

2.1 Global trends

The global power industry is the largest single source of emissions accounting for 38% of CO_2 and 25% of overall emissions. Contribution of CO_2 emissions to climate change is a key motivator for the change in primary energy generation sources, but other diverse factors are currently driving an increase in the global uptake of renewables including solar energy:

- The depletion of fossil fuel reserves.
- National energy security considerations.
- A rise in the price of conventional forms of power generation.
- An overall increasing demand for energy.

Solar power is attractive because of its super-abundance, and higher resilience to climate than, say, wind power. The proportion of the sun's rays that reaches the earth's surface can satisfy global energy consumption 10,000 times over.

As a result of the confluence of drivers indicated, global PV installed capacity has grown in excess of 35% per annum since 1998. Installed global solar capacity increased by 27% in 2007 taking capacity in excess of 9 GW (Figure 1) and representing an investment of about €25 Billion.

Figure 1: Global installed solar capacity

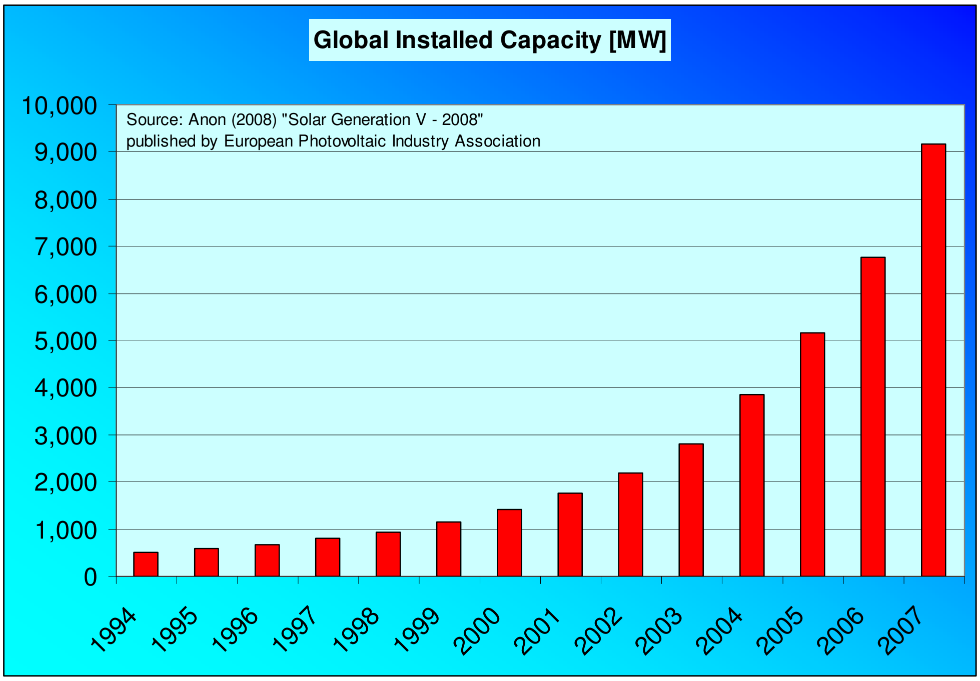
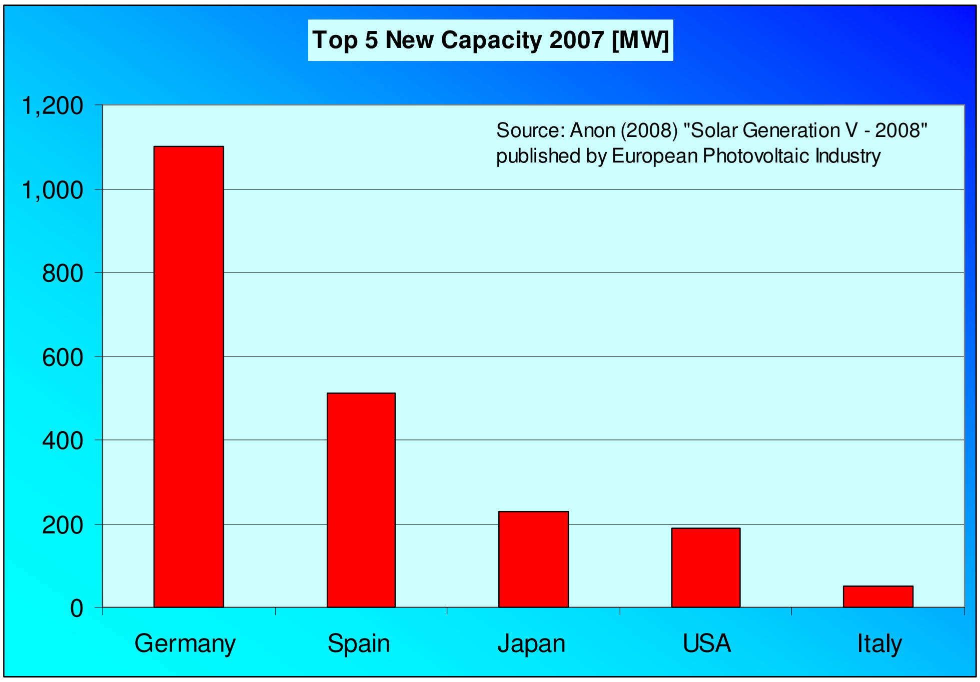


Figure 2 shows how particularly countries are currently adopting solar power.

Figure 2: Top countries for new capacity, 2007



Worldwide, China, Japan and Germany are leading the way in manufacturing capacity (Figure 3) but particularly in the USA, China and Japan, the industry is investing heavily in new production facilities and technologies, as is reflected in Figure 4.

Figure 3: Production of PV by country

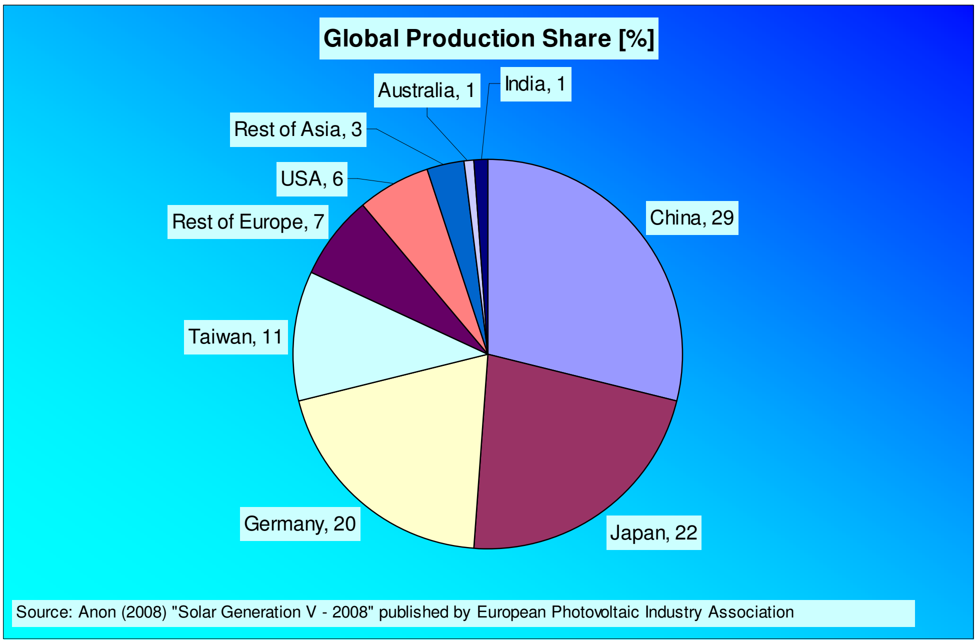
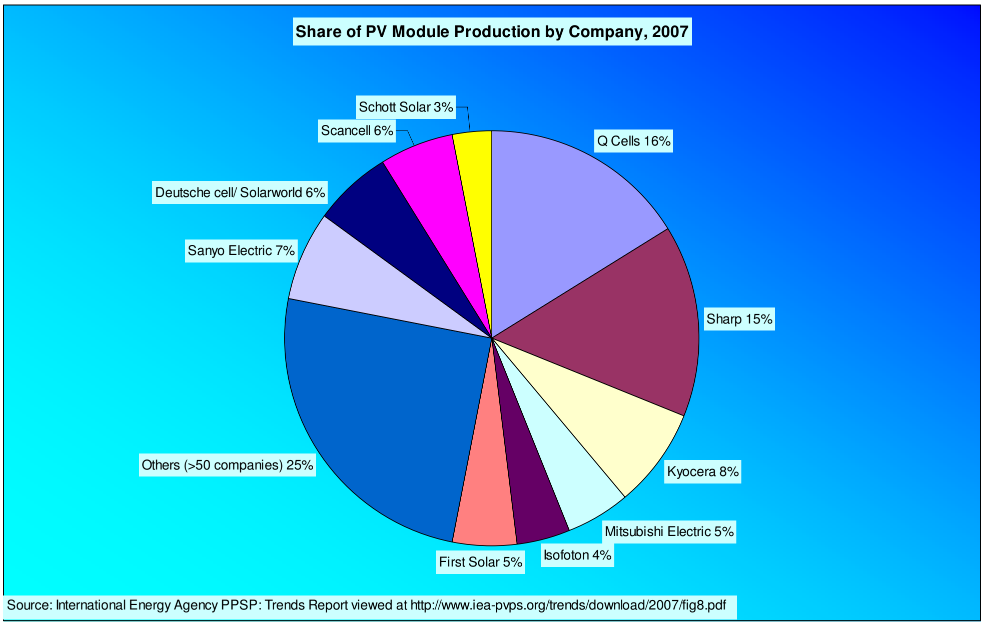


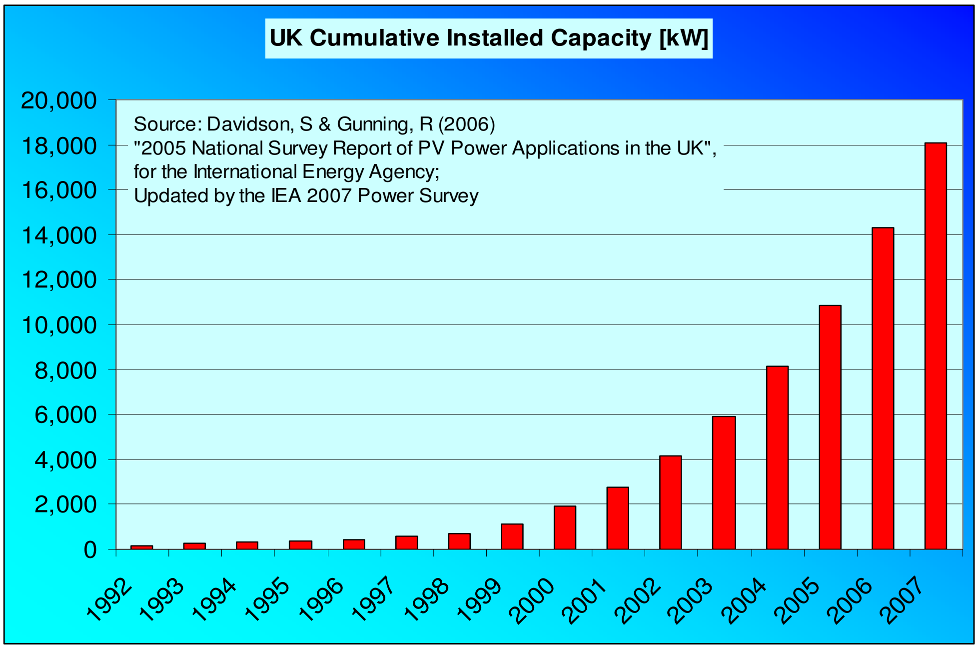
Figure 4: PV production companies' market share, 2007



2.2 UK market

Compared to other similarly advanced countries the uptake in the UK has been relatively modest in absolute terms as reflected in Figure 5.

Figure 5: Installed power in the UK



However, the increase in uptake is not untypical of global trends and reflects a modification of the environment as indicated in the next section.

2.3 Policy drivers for market growth

Current UK Government targets call for a 60% reduction in carbon emissions by 2050. Furthermore, the European 'Renewables Obligation' (January 2008) requires Britain to source 15% of energy from renewables by 2015. As this 15% includes all energy use (e.g. including heat and transport) it equates to 37% of the nation's electricity consumption.

The following policies are supportive of renewables:

- Climate Change Bill
- Micro-generation Strategy & the UK Micro-generation Certification Scheme
- Code for Sustainable Homes
- UK Energy Technology Marketing Strategy
- Stamp duty reduction on carbon-neutral new homes.
- Energy Efficiency Commitment (EEC) by utilities.
- National planning policy integrating climate change into LA policy.

2.4 Summary

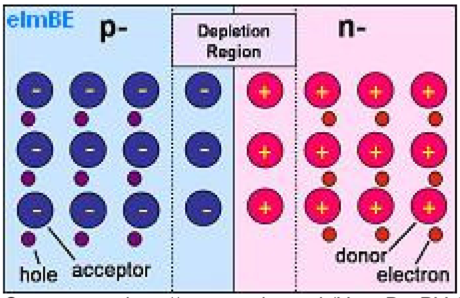
The historic installed capacity of PV in the UK is relatively low reflecting an absence of policies to stimulate uptake. However, recent growth rates are typical of the rest of the world and policies are in place to support this trend. As it is firmly in the micro-generation bracket, there are likely to be significant numbers of domestic installations in the future, with a corresponding potential for end-of-life redeployment.

3 Technical Overview

3.1 Development

PV (photovoltaic) solar panels generate electricity by the Photovoltaic Effect. Discovered in 1839 by Becquerel, the photovoltaic effect is the phenomenon by which certain materials produce electric current when they are exposed to light. For traditional PV solar panels a semiconductor p-n junction (Figure 6) is manufactured in which two halves of one pure silicon crystal are doped with two different dopants (e.g. arsenic, gallium, aluminium, phosphorus). One half of the crystal is left electron deficient (the p-type layer), and one half is left with an excess of electrons (the n-type layer). The dopants in the semiconductor lead to an electric field across the junction between the two halves of the crystal with electrons able to travel in one direction only – from the electron rich half to the electron poor half.

Figure 6: Schematic p-n junction



Source: http://www.reuk.co.uk/How-Do-PV-Solar-Panels-Work.htm

Where the two halves of the crystal meet, there is a so-called depletion region, which is depleted of charge carriers (electrons and holes). Electrons move from the n-type (negative) side to the p-type (positive) side of the crystal recombining with holes. Likewise holes move from the p-type side to the n-type side. As the silicon atoms themselves do not move, any holes which remain uncovered by electrons in the n-type side are left positively charged, and any electrons without holes to cover in the p-type side remain negatively charged. This leaves positive material close to the junction in the n-type side, and negative material close to the junction in the p-type side with a potential between the two sides of around 0.6-0.7 volts in a silicon p-n junction. This potential barrier between the p and n-type sides of the crystal prevents further electrons and holes from travelling across the junction until sunlight hits the solar cell and releases electrons with enough energy to overcome the barrier.

This understanding of the function was not achieved until the 1950s when the “silicon revolution” and a determined exploitation of semi-conductor properties began. With large scale silicon production the use of the silicon cell as a source of electrical energy became a practical possibility. Energy efficiency has risen from 8% in the 1980s to between 11 and 17% at present[a].

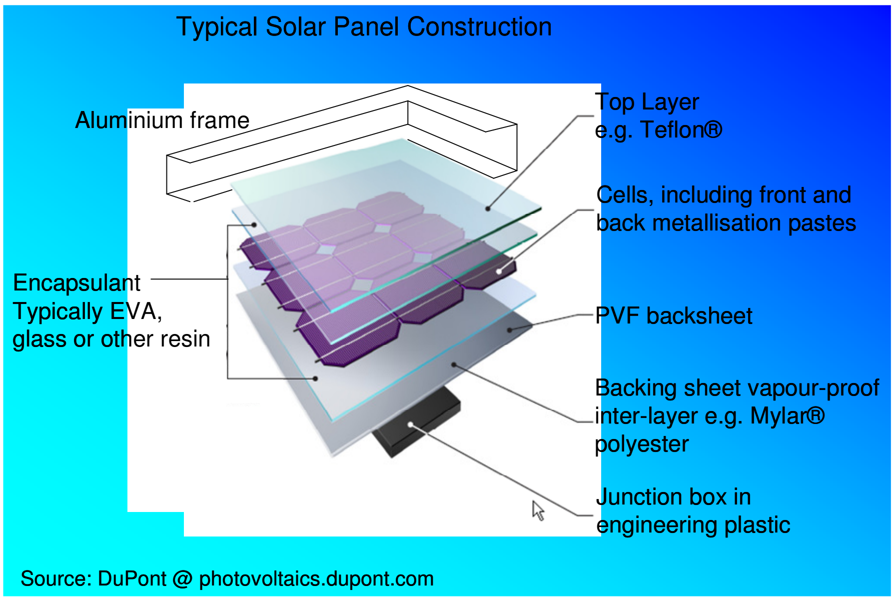
[a] Lefèvre, M-F (2008) “Photovoltmania”, in Research EU, April 2008 pp23

3.2 Systems

Fully assembled PV systems comprise the following major components:

- Front sheet – glass (annealed); the front plate imbues the assembly with an element of its mechanical strength. It must be strong and rigid, weather resistant and must transmit a high proportion of light.
- Frame – aluminium (anodised) clamping units, providing first-line edge protection and attachment.
- Cells – silicon-based photo-electric devices.
- Contacts and interconnects – silver paste (printed onto wafers).
- Encapsulant – EVA, a polymer used to coat and seal the cells and the edge connections.
- Back sheet – weather protection foil comprising PVF sheets at very small thickness. Requirements are for weather sealing over long periods in harsh environments and to act as a weather/vapour barrier, physical protection, electrical isolation and the reduction of cell operating temperatures. Two layers of PVF at approximately 30 microns a re used to sandwich a thin layer of polyester film between two layers of PVF in a tri-laminate.

Figure 7: Typical solar panel construction



An exploded view of a typical installation is provided in the Figure 7, courtesy of DuPont photovoltaics.

3.3 Variants

Three distinct types of silicon photovoltaic cells exist and are characterized by the type of silicon crystal from which they are manufactured: mono- and poly-crystalline and amorphous.

Mono-crystallines

The production of mono crystalline silicon involves the use of absolutely pure material which is cast as a single crystal and sawed into thin plates.

Poly-crystalline

The production of polycrystalline cells involves the same sawing process carried out on cast ingots of polycrystalline material. By obviating the single crystal casting phase the production of polycrystalline cells is less energy and time consuming but, as non productive defects are included at crystal junctions, results in a less efficient product.

Amorphous

Amorphous cells are produced when a thin silicon film is deposited onto a substrate. The layer thickness may be of the order of 1 micron and as a result significant materials cost savings can be made. The architecture and flexible nature of thin film cells also lend suitability to higher speed and continuous production techniques such as reel to reel laminating.

Thin films are significantly less efficient at solar energy conversion and there are question marks remaining concerning their stability to aging.

Cell Efficiency

The efficiency of a solar cell is defined as the percentage proportion of light energy impinging on the surface of a cell which is converted to electrical energy.

Material	Efficiency in Laboratory [%]	Efficiency at Production [%]
Monocrystalline	24	14-17
Polycrystalline	18	13-15
Amorphous	13	5-7

Table 1: Efficiencies of various silicon cells.

below compares the efficiencies obtained for the various silicon based cells produced under laboratory and standard production conditions.

To date, most cell production has been concentrated on mono and polycrystalline forms (90% in 2007) although flexibility of application and to high speed production routines promise a greater share for thin film in the future. The EPIA expects "a growth in the thin film market share to reach about 20% of the total production of PV modules by 2010".

Material	Efficiency in Laboratory [%]	Efficiency at Production [%]
Monocrystalline	24	14-17
Polycrystalline	18	13-15
Amorphous	13	5-7

Alternative materials

Although the vast majority of PV cell production to date has been based on the use of silicon in its various forms, alternative semiconducting materials can be used. The leading contender in conventional semiconductors is Cadmium Telluride. However, there is an emergent technology based on plastic semiconductors. Although currently showing lower conversion efficiencies[b] and long term concerns over performance and physical stability, these hold out the prospect of both cheaper installation in $ per watt, and the ability to mount onto a variety of substrates including flexible elements.

3.4 The materials and manufacturing processes.

In order to make the appropriate voltages and outputs available for different applications, single solar cells are interconnected to form larger units. Cells connected in series have a higher voltage, while those connected in parallel produce more electric current. The interconnected solar cells are usually embedded in transparent Ethyl-Vinyl-Acetate, fitted with an aluminium or stainless steel frame and covered with transparent glass on the front side.

[b] Currently around 5%.

Case Study 1: Sharp NT series 175W mono-crystalline photovoltaic module.

72 off 125 x 125 cells in series

Dimensions-	1575 x 826 x 46 mm
Weight-	17.3 kg
Efficiency-	13.5%
Module max power Voltage	35.4 V
Module max power Current	4.95 A

Sharp offer a 2 year product guarantee along with a 10 year performance guarantee for 90% power output and a minimum 20 year performance guarantee of 80%.

Data from NT-175U1 www.sharpusa.com

Single solar cells are mounted and interconnected to form modules. These modules are typically sized to create a power rating of somewhere between 10 and 100 watts. Characteristic data is obtained under the standard test conditions of 1000W/m² solar radiation at 25° C. Typical modern nominal power outputs for crystalline silicon cells are of the order of 150 W per m² [c].

The current cost of silicon is US$ 200 per kg.

The following Table 2 summarise the mass of the main constituent materials in the panel.

Table 2: Component masses

Component	Material	Weight (kg)
Silicon cell	mono- crystalline silicon	1.7
Glass front plate	annealed glass	9.8
Encapsulant	ethyl-vinyl-acetate film	2.5
Frame	Aluminium (anodised) ext.	3.2
Back sheet	PVF weather protection foil	0.1
Total		17.3

Manufacturing cost, and hence price, has been dominated by the production of silicon. The cost of crystalline silicon has fluctuated widely over recent years, largely because of the inability of established manufacturing facilities to meet the

[c] Ref: http://www.renewableenergyworld.com/rea/news/story?id=51442, read September 2008.

increase of demand from both the wafer fab and PV markets. This is because supply to the cell market has been through reject from the chip wafer fab plants. Fab-grade silicon quality exceeds that of solar grade.

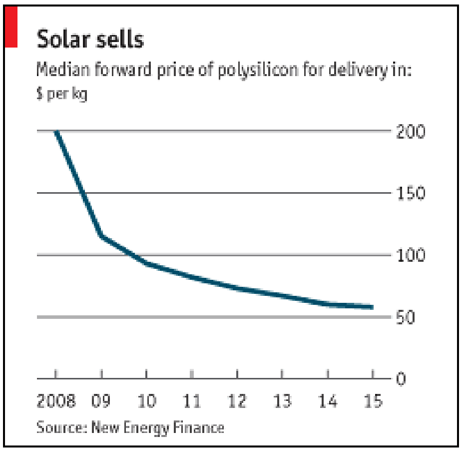
Figure 8: Predicted price of polysilicon

The long-term fall in the price of PV systems as a whole was interrupted when the increase in demand for silicon pushed prices from $25 US/kg in 2003 to up to $250 US/kg in 2008. This was driven by the recent resurgence in IT markets. More recently and into the foreseeable future, new capacity which specifically addresses the lower quality demands of solar grade with its now sustainable demand growth, suggests a trend to lower manufacturing costs. The Economist predicts that prices will fall rapidly (Figure 8) in the near future to stabilise around the $50 US mark by 2015[d].

This would indicate that the supply chain for the PV industry will become commoditised and somewhat more stable provided production can meet demand. This sets a background against which to benchmark the competitive market for remanufactured panels.

3.5 Performance, failure modes / life expectancy

The solid state heart of PV systems has no moving parts and is therefore not subject to mechanical wear. Although there is a mechanism for the degradation of individual cell performance through metal migration across the pn junction, this is usually fairly limited and the life expectancy of cells is largely currently dictated by the aging stability and corrosion resistance of associated component parts.



A typical manufacturer's quoted life expectancy for a modern unit is in the region of 20 years and guarantees the "performance over that period in terms of the original conversion efficiency retained. Units are rated by nominal capacity which is a measure of the output of a module under standard test conditions, although performance tests by independent bodies have shown that modules often fail to conform to the manufacturer's rating.

[d] Anon (2008) "Silicon Rally" in The Economist, Aug 30 2008 pp.71

Case Study 2: SCUPSI reliability data

Although the larger scale uptake of solar cells has occurred over the last decade or so, some substantial arrays have been continuously operating over a significant period of time. Reports detailing the ongoing performance and condition of these units provide an indication of the life expectancy, maintenance effort and failure modes associated with their extended operation. One such study has involved an analysis of the "mean time before failure" of a photovoltaic array located at the Scuola Universitaria Professionale della Svizzera Italiana (Lugano).

A 10kW array was originally installed on to the roof of the building in 1982. As such it represented the first grid connected PV system in Europe. Its performance and operating characteristics have been monitored over time to culminate in a report by Antonella Realini published in 2003. The report drew conclusions from data sourced through visual and infra red inspection and performance measurement over an extended period of time.

Accelerated lifetime testing was also carried out. In order to determine the effects of the individual failure modes, a comparison was drawn between individual cell defects and operating efficiencies. It was found that the cells themselves are stable over long periods of time. The most common and damaging failures were associated with the failure of some of the ancillary systems – wiring junction boxes and energy conditioning devices used to link with the local grid (inverters). The most significant forms of degradation occurred as a result of aging and weathering of the systems leading to delamination and corrosion.

The cells were largely found to retain their original performance characteristics and a substantial remaining useful life.

Source: Realini, A. (2003) "MTBF – PVm: Mean Time Between Failure of Photovoltaic Modules", report 99.0579 June 93 published by SUPSI

Alongside the physical failure of components, poor systems build and installation have been shown to make a significant contribution to lower than expected performance. Location and orientation are critical: For example, units which do not actively track the direction of the incoming light, the choice of attitude will always be a compromise aimed at making the best of the available resource. But module areas which are shaded for extended durations will not only restrict power output but may also suffer damage through the presence of hot spots, as noted below. There are indications that manufacturers and operators alike are learning and adapting their designs as experience accumulates.

Most failure modes are related to water ingress or thermal stresses which in turn are associated with exposure to a wide variety of environmental conditions. Degradation can be characterised by a gradual reduction in performance over time or a more serious sudden breakdown or loss of performance. A selection of irreversible failures is given below[e]:

- Increase of resistance of electrical contacts due to peeling or corrosion.
- Oxidation of contact surfaces.
- Metal migration through the p-n junction.
- Cell short circuits: Short circuiting can occur at cell interconnections. This is also a common failure mode for thin-film cells since top and rear contacts are much closer together and stand more chance of being

[e] Abridged from "Failure and Degradation Modes for Solar Cells" at http://pvcdrom.pveducation.org/ viewed in October 2008.

shorted together by pin-holes or regions of corroded or damaged cell material.

- Cell open circuits: This is a common failure mode, although redundant contact points plus "interconnect-busbars" allow the cell to continue functioning. Cell cracking can be caused by: Thermal stress; hail; or damage during processing and assembly, resulting in "latent cracks", which are not detectable on manufacturing inspection, but appear some time later.

- Module open-circuits: These occur in the module structure, typically in the bus wiring or junction box.

- Module short-circuits: Although each module is tested before sale, module short circuits are often the result of manufacturing defects. They occur due to insulation degradation with weathering, resulting in delamination, cracking or electrochemical corrosion.

- Thermal cyclic loading leading to fatigue of components: Fatigue due to cyclic thermal stress and wind loading leads to interconnect open circuit failures.

- De-lamination caused by reductions in inter-laminate bond strength can be accelerated by moisture ingress, photo-thermal aging and stress. This can be induced by differential thermal and humidity expansion rates of the cell components.

- Individual damaged or underperforming cells can act as high resistance joints within the overall circuit leading to elevated local temperatures (hot spots). A gradual degradation in module performance can be caused by: Increases in R_S due to decreased adherence of contacts or corrosion (usually caused by water vapour); decreases in R_{SH} due to metal migration through the p-n junction; or antireflection coating deterioration.

- By pass diodes, used to overcome cell mismatching problems, can themselves fail, usually due to overheating, often due to undersizing[f]. The problem is minimised if junction temperatures are kept below 128°C.

- The encapsulant for the devices is often protected by UV absorbers and stabilisers. Concentration of these elements may be reduced over time by the processes of leaching and diffusion. This can lead to the degradation of the encapsulant materials (E.g. browning and embrittlement).

- Module Glass Breakage: Shattering of the top glass surface can occur due to vandalism, thermal stress, handling, wind or hail.

Many producers give performance warranties of 20-25 years for their modules. At the EC Joint Research Centre in Ispra (Italy), crystalline modules have been operating in a field test, with excellent performance results, for more than 20 years. The majority of the modules continue to exceed 92% of their nominal power output as recorded at the beginning of the testing period.

[f] Durand, S. (1994), "Attaining Thirty-Year Photovoltaic System Lifetime", Progress in Photovoltaics, April issue.

Case Study 3: “1000 Roofs Programme”

A survey was conducted within the framework of the International Energy Agency Photovoltaic Power Systems Task7 to collect data on the operation of PV plants situated in a number of countries including the UK, Germany, Spain, Japan, US and Canada. The report largely focussed on small residential systems with peak power ratings of typically 1-5 kW.

The failure statistics output by the report (Table 3) showed decreasing failure rates as operators became more accustomed to their systems.

As with the previous study the modules themselves were largely found to be reliable with the majority of failures being attributed to the break down of ancillary systems such as inverters.

The report concluded that the quality of units had significantly improved over the last 20 years and stated that modern units, properly run and maintained could exhibit failure rates as low as 0.01% per annum (based on the consideration of 50W units).

The report suggests that further research and development of some of the associated electronic components and conductor connection/protection is required in order to imbue future units with longer trouble free life expectancy. It recommends regular inspections, cleaning and performance checks should be carried out by operators.

Table 3: defects and deficiencies found by inspections of 200 “1000 Roofs Programme” PV systems

Problems in Operation	% systems affected
Corrosion and defects in mounting structure	19 %
Moderate to strong soiling of modules	12 %
Defect string fuses	4 %
Faulty modules (broken glass, open circuits, discoloration)	< 2 %
Defect string diodes	< 2 %
Corroded plug/receptacle connectors	1 %
Defect overvoltage protection devices	< 1%

Source: “Reliability Study of Grid-Connected PV Systems”, IEA, Report IEA-PVPS T7-08: 2002 (March 2002) available at iea.org

3.6 Energy payback times for photovoltaic technologies

A recurrent topic of debate, and one very germane to the issue of whether or not to remanufacture, is the relative energies involved in the manufacture of a PV unit compared to that which can be generated during its productive life (Table 4). If a unit requires a long period to "pay back" the energy investment – the so-called embodied energy – it indicates that a functional unit is worth maintaining, particularly if the remanufacture is a relatively simple step, and life extension is significant.

Table 4: System Energy Payback Times for Several Different Photovoltaic Module Technologies

Cell Technology	Energy Payback Time (EPBT)[1] (yr)	Energy Used to Produce System Compared to Total Generated Energy[2] (%)	Total Energy Generated by System Divided by Amount of Energy Used to Produce System[2]
Single-crystal silicon	2.7	10.0	10
Non-ribbon multi-crystalline silicon	2.2	8.1	12
Ribbon multicrystalline silicon	1.7	6.3	16
Cadmium telluride	1.0	3.7	27

(1) Source: Fthenakis V, & Alsema E, "Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004-early 2005 status", Progress in Photovoltaics, vol. 14, no. 3, pp. 275-280, 2006.

(2) N.B.: Assumes 30-year period of performance and 80% maximum rated power at end of lifetime. (1700 kWh/m²/yr insolation and 75% performance ratio for the system compared to the module.)

The above research suggested that in well insolated locations payback times were relatively modest compared to total life. These comparisons would clearly not look as good in the UK where overall insolation is lower, but this is still likely to be less than 20% of life, and should improve with both technology efficiency and improvements in solar silicon manufacture.

This, of course, should not be confused with the financial payback time, which is significantly longer. However, it does indicate that there is no pressing *a priori* reason to promote remanufacture as an exceptional carbon benefit.

4 Remanufacturing Issues

4.1 Core availability

Given that the manufacturer's quoted life expectancy for modules is of the order of 20 years and that the installed capacity in the UK in 1992 was of the order of just 0.2 MW it can be seen that there is likely to be limited core availability sourced from units which have naturally reached the end of their first life.

If we take the (probably conservative) failure rate figure for 50 Watt modules (as derived from the IEA report[g]) of 0.01% failures per annum and assume that all of these units are suitable and can be made available for refurbishment and that the total nominal installed capacity for the UK stands at 18.1 MW. This represents 362,000 units which, if subject to the 0.01% failure per annum expectancy results in the expected failure of the equivalent of approximately 36 units per year.

Germany currently has 3862 MW installed capacity- the equivalent of 77 million 50 Watt units. If these were to fail at the predicted rate of 0.01% per annum, 7,700 units could become available for reconditioning yearly.

4.2 Specific remanufacturing activities

There is a good deal of consistency between the designs of module offered by the major manufacturers. This continuity allied with the relatively simple make up will allow remanufacturers to apply learnt skills and processes to the refurbishment of end of life modules from a variety of different manufacturers.

Moreover the traditional choice of stable, weatherproof materials for the component parts of modules and arrays means that many of them will be suitable for re-application with little or no remediation – glass, aluminium, stainless steel and crystalline silicon.

Return of core

PV is intended as a mass market technology so by its essence will be highly distributed as are other consumer goods. Recovering end-of-life units will then be subject to similar issues: Knowing the location of units; giving consumers sufficient information to recognise end-of-life value and to contact appropriate recovery agents; local diagnosis and partitioning; disassembling and retrieving installed units without further damage; transport, aggregation and distribution to repair agents.

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[g] "Reliability Study of Grid-Connected PV Systems", IEA, Report IEA-PVPS T7-08: 2002 (March 2002) available at iea.org

Because PV tends to be an inaccessible building element, some skill will be required to diagnose and retrieve it. In the first instance it is likely that repair agents will be aligned with installers and agents of primary manufacturers since this will increase the likelihood of a reusable unit and offer the possibility of new for old swaps, or even repair.

Inspection/testing/balancing

As stated, modules are rated according to their measured output under standard test conditions. We assume that competent operators will have the ability to replicate these conditions in-house and to performance test modules in-bound and out-bound to the highest standards. An underperforming cell can have a disastrous effect on the performance of an array.

Disassembly

To date there appears to have been little consideration by the manufacturers for the end of life treatment of solar modules.

The EPIA claim that one of their most important recent achievements for their members has been the non inclusion of PV technology in the WEEE directive. It seems apparent however, that they are anticipating the possibility of some sort of producer end-of-life responsibility and greater consideration of design for end of life will become a more significant factor in the future.

One of the implications is likely to be the simplification of the process for module disassembly either for recycling or remanufacturing routines.

The current extensive use of PVA as a the cell mounting and encapsulant provides a stable, relatively degradation free basis for module construction to suit extended life expectancy but lends difficulties to disassembly operations and the subsequent separation of component parts. A reliable and repeatable method for the separation of encapsulant from the cells and associated wiring is not clear.

Remediation

The most common failure modes associated with operating modules involves the deterioration of the integrity of component parts through weathering and corrosion. Options for the remediation of elements which has failed in this way are limited. It is better in most cases to replace such items.

It is assumed that the repair of surface interconnects and edge connects is possible. It may even be feasible to replace individual cells if old stock is available or similar units can be cannibalised. Repair or replacement of ancillaries such as inverters is possible. Assuming the unit can be de-encapsulated, a high standard of re-encapsulation akin to new manufacture will be critical. The delamination of modules might be addressed by re-sealing them without having to disassemble.

The anti reflection coating on the front cover might be replaced.

Frames are predominantly manufactured from anodised aluminium or stainless steels and are likely to be re-applied without any significant refurbishment.

Reassembly

This is assumed to be the similar to new part assembly.

Redistribution – warranty

It is not clear whether remarketing will be as an independent retailer or as a contracted agent of the primary manufacturer. To some extent this may depend on whether demand outstrips supply in a growing market, and on the perceived quality and guarantees offered.

At this stage, it is probably safe to assume that remarketing will be an independent venture, possibly removing original branding, and into secondary markets looking for a budget unit of less than as-new life expectancy.

4.3 Key competences

Sourcing of devices of varying provenance, design and construction and in diverse locations but retrieved in a good condition is likely to require the cooperation of established supply chains as a back-haul route.

Potential remanufacturers will be conversant with previous generation, new-build technologies[h] as well as the latest developments in power management and grid connectivity.

[h] Given the expected life in service of devices, at the time of failure, the device is likely to be of a vintage state of technology.

4.4 Summary of remanufacturing feasibility

Modular construction does, in theory, lend itself to remanufacture. However, the joining technologies employed, created specifically to promote impregnability and longevity, act in opposition.

It is therefore by no means certain that a PV panel can, under current design limitations, be deconstructed and reconstructed without further and excessive damage to the unit.

If deconstruction is possible, then remediation will be limited to certain classes of failure:

- Repair or replacement of structural components such as the frame or front sheet;
- Repair or replacement of peripheral ancillaries such as inverters, controllers and by-pass units; this also includes upgrade for improved performance.
- Repair of non-embedded components and linkages such as edge connectors and soldered inter-connects;
- Deactivation of short-circuit elements to return unit to use perhaps with reduced performance;
- Potentially, the replacement of individual cell elements, where compatible spares exist.

These capabilities will need to be placed within a system that can retrieve, test units to a suitable performance standard, market, install and warrant. This might best be achieved with the cooperation of the original manufacturers and installers.

5 Remanufacturing: a carbon impact

In the previous section we established the likely bounds of the scope for remanufacture. Before that, we also established that newly manufactured units were likely to pay back their "carbon investment" between 1½ and 4 years according to climate and specific technology, and this is likely to fall. We therefore need to judge the relative impacts of remanufacturing over new build, and to these ends we have completed a rough carbon impact assessment taking the scenario outlined below.

The methodology outlined for this is necessarily short-cut, but is based on standard LCA modelling techniques and tools: the SimaPro, an LCA tool by Pré Consultants[i] and the Ecoinvent[j] database. Tools are only as good as the system definitions and data employed and so key assumptions have been highlighted. This analysis is not intended to be precise, but to be accurate enough to indicate broad benefits or otherwise of remanufacture with an assessment of key sensitivities.

5.1 Base System

The based system chosen for the carbon impact study was a commercial module, Sharp NT 175W, manufactured by Sharp UK. This unit has 72 cells in series which is composed of 125.5mm x 125.5mm monocrystalline solar cells. The dimensions of the PV module are 1575mm x 826mm x 46mm (1.3 m^2). The total weight of the system is 17.3kg (Table 2).

5.2 Scope of Remanufacture

Decision for remanufacture of PV modules will be underpinned by:

- the availability of the cores
- ease of disassembly
- speed of technology evolution
- credible business case

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[i] http://www.pre.nl/

[j] http://www.ecoinvent.ch/

In this analysis we assumed that the cores will be available and credible business case exists. Even if the speed of technology evolution is fast there will be demand for old module to replace the failed ones due perhaps favourable costs. Currently, as highlighted earlier in the report, PV modules are not manufactured in a way disassembly in mind. Given the long life time expectancy of the PV units, robust encapsulation and insulation requirements undermines the disassembly. However, if there is a business case, there will be technology development for a reasonable disassembly of these units. There it is reasonable to assume that individual PV cells can be removed along with aluminium frame and solar glass. All of these parts can be remanufactured and reused at variable efficiency rates.

5.3 Key Assumptions

The following assumptions are made for the carbon impact comparison of new and remanufactured PV modules:

- Only materials and processes are included, i.e. no transport and use phases

- Installation and disassembly was included involving transport to the point of use from the local provider, electric installation and slanted roof construction.

- Waste scenario for the new PV modules is based on the data available in Ecoinvent Database for England. This has set recovery rates for each material type, paper, metals, plastics etc. and the remaining waste is sent to landfill and incineration (83 and 17%, respectively). This however can be updated when new data is available.

- For remanufactured PV panels, various efficiencies of remanufacturing for all parts are assumed. Any waste arising from remanufacturing was sent to the above waste scenario. The parts and efficiency rates are shown in Table 5.

- Assembly and disassembly processes are assumed to be same and there are no losses during the disassembly for remanufacturing.

- Majority of the data used in this study was obtained from Ecoinvent database version 2. Arguably, this is the most comprehensive database for such data but the quality of each data set might affect the outcome.

Table 5: Remanufactured parts and remanufacturing efficiencies assumed in the analysis

Component	Remanufacture (%)	Waste (%)
PV cells	90	10
Aluminium frame	80	20
Solar glass	75	25
Inverter	90	10

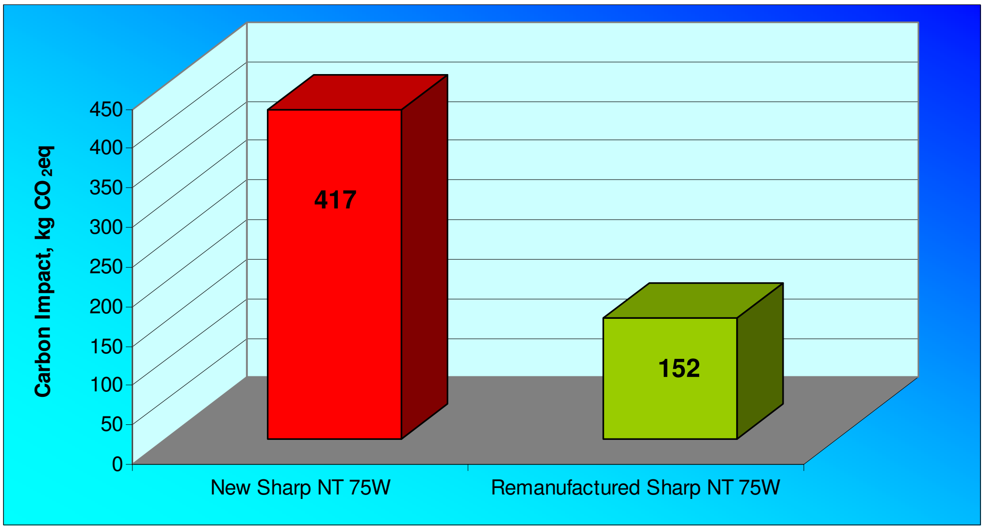
5.4 Results

Carbon impact of the remanufactured and new PV panels was assessed using the methodology developed by the Inter-governmental Panel on Climate Change (IPCC). This methodology looks at the global warming potential of a product or service over a 100 years (GWP_{100}) timescale and is defined as CO_2 equivalent. This methodology is available in the SimaPro software tool.

Process tree of the new and remanufactured PV modules are shown in detail in Appendix C and D, respectively.

Using the methodology on the life cycle analysis it was found that new PV modules have a carbon impact of 417kg CO_2eq compared to 152kg CO_2eq that of remanufactured ones (Figure 9). Carbon impact of remanufacturing is 64% less than that of new PV modules.

Figure 9: Carbon impact of new and remanufactured PV panels



Both wafer manufacturing and cell production processes are the major contributors to the overall carbon impact of new PV panels, 146kg CO_2eq and 183kg CO_2eq, respectively (Figure 10). In contrast, slanted roof installation was the major contributor to total carbon impact for remanufactured PV panels (Figure 11).

Figure 10: Process contributions (≥1%) to overall carbon impact of manufacturing new PV module

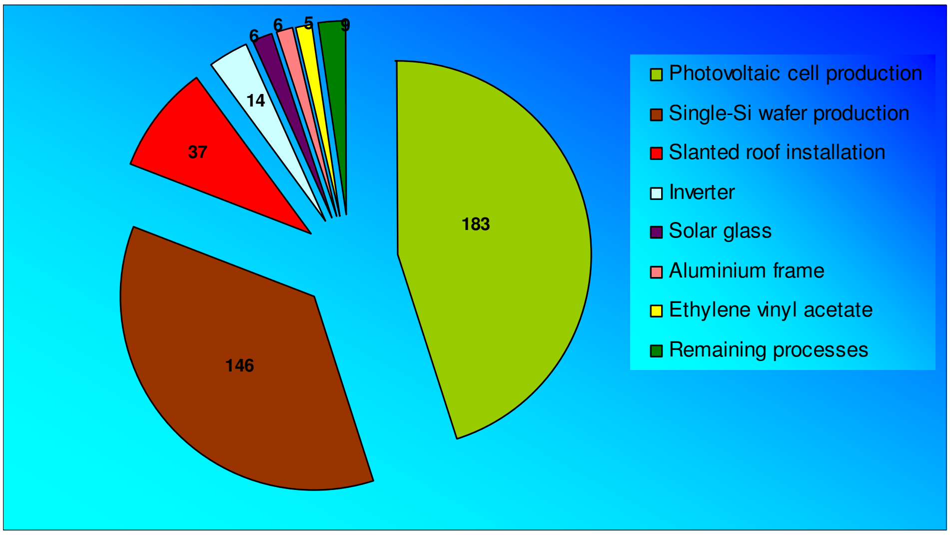
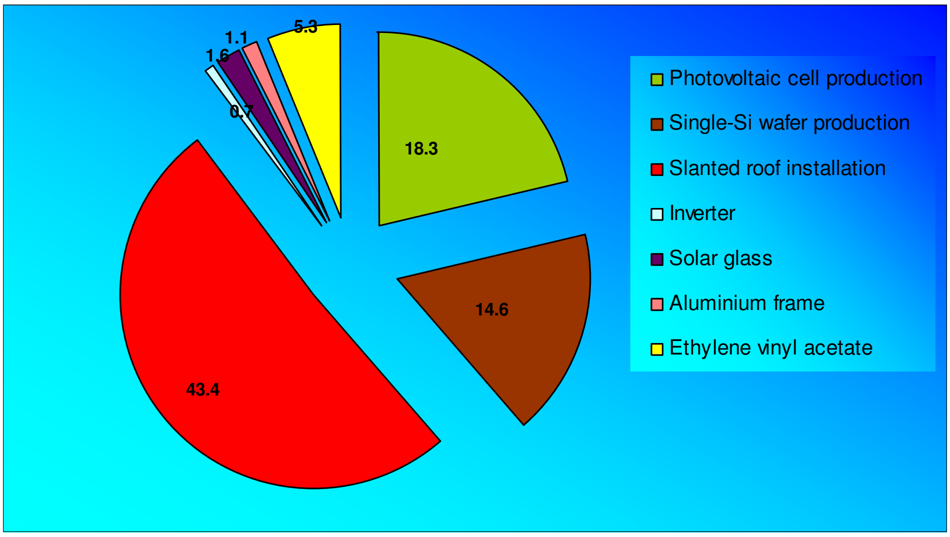
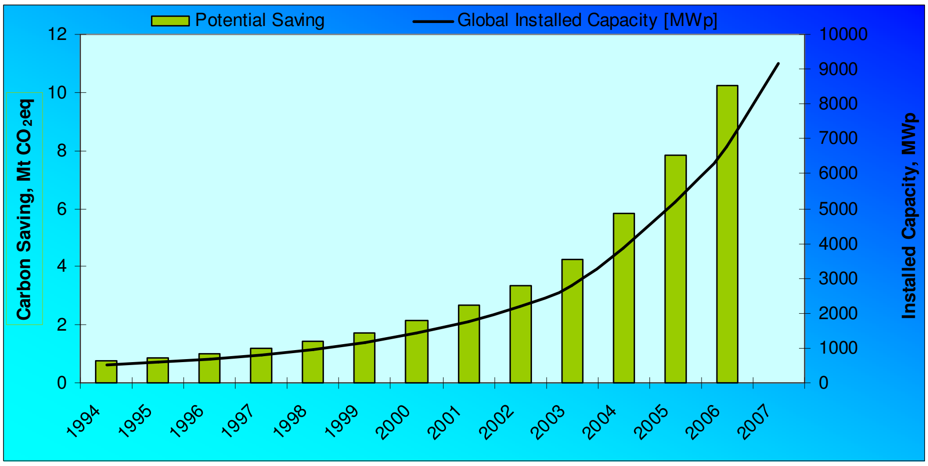


Figure 11: Process contributions (≥1%) to overall carbon impact of remanufactured PV module



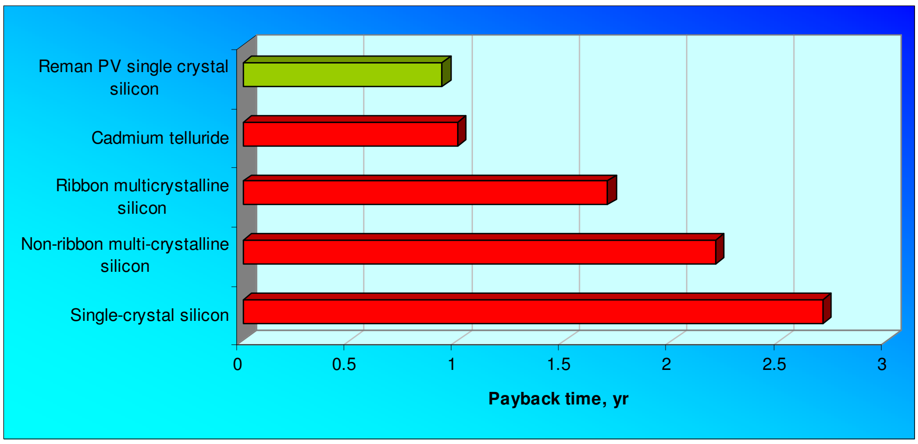
Based on the world installed capacity (Figure 1) carbon saving available through manufacturing PV modules are shown in Figure 12. We assume 20 years of lifetime for a PV module then the first batch of cores will be available for remanufacture by 2014. There will also be availability of failed modules due to various failure modes explained earlier. By then minimum saving is around 760, 171 tCO_2e with a substantial increase each year if these modules are remanufactured.

Figure 12: Available carbon saving worldwide through implementation of remanufacturing



We also calculated the "Cumulative Energy Demand" (CED) using the methodology[k] available within the SimaPro. CED calculates the total (primary) energy use through a life cycle based on lower heating value and is especially suited to determine and compare the energy intensity of processes. The goal of the CED methodology is to calculate the total primary energy input for the generation of a product, taking into account the pertinent front-end process chains. Based on this methodology, cumulative energy demand of manufacturing new PV module was calculated to be 8441MJ eq. compared to 2902MJ eq. for remanufactured one. Energy saving of 64% is available for remanufactured panels over new ones. This would ultimately have a positive effect on the payback times. Based on the payback times of 2.7 years (Table 4) for single crystal silicon PV module, payback time of remanufactured PV panels is less than a year. This makes remanufactured PV panels on par with the Cadmium telluride based panels (Figure 13).

Figure 13: Payback time of remanufactured module



[k] http://www.pre.nl/simapro/impact_assessment_methods.htm#CED

5.5 Discussion

There is a huge materials and energy saving potential of remanufacturing PV panels. To be able to achieve these benefits either disassembly technologies need to be developed or the modules designed in a modular manner. It is thought that the technology will be available if there is commercial viability of remanufacturing PV modules in the future. Design for disassembly will perhaps come at later stage once the sector is very well established.

Wafer and cell productions are the major burdens for both environmental and energy point of view. They also contribute to about 60% of the manufacturing costs[1]. Therefore there is every reason to implement remanufacture/reuse of these components as a better option to recycling. PV OEMs should consider disassembly for these parts to achieve the savings highlighted in this report.

There is about 20 years or so time lag for the availability of cores for remanufacture. Although this time lag seems so long, PV modules produced in the early 1990s will be available soon. Due to very rapid rise of the PV sector the amount of available cores will be higher along with the potential saving available through remanufacturing.

As production of PV modules requires substantial amount energy, payback time becomes important in decision making for a purchase along with the efficiency of the technology. Remanufactured PV panels can be on a par or even lower than Cd-Te PV panels in payback time. This is very important as the PV industry is trying to reduce this by increasing the efficiencies of existing modules or introducing new technologies. Remanufacturing is perhaps the easiest and cost efficient way achieving this and it is available today.

[1] http://secondlawoflife.files.wordpress.com/2008/05/breakdown-pv-costs.jpg

6 Market & technical potential

The current installed volumes in the UK coupled with the expected failure rate do not create a valuable opportunity for remanufacture at the current time. If installation volumes were to rise in line with those of comparable countries in the EU such as Germany, significant and attractive volumes of devices would become available. In the intervening years it is likely that efficiency, system resilience and diversity of installation possibilities and features will all improve, and the real-term installed cost will fall by perhaps 50%.

It is likely that remanufacturing of devices would be limited to the repair or replacement of peripherals, connectors, and energy conversion and management devices. The inherent sealed nature of the core solar panel unit may militate against remanufacture, but this has not been absolutely established.

As a result, it is likely that refurbished units would be cascaded into secondary markets in the UK. Given the pace of advancements of grid-enabled solar devices, such refurbishment would either be specifically for stand-alone applications or would be retrofitted with grid-enabling power management facilities.

Given the expected drop in price and increase in performance, prices obtained are unlikely to be greater than 25% of the new price of an equivalent power unit. This price must therefore include any margin for retrieval, de-manufacture, repair, replacement, testing, sales and reinstallation. This may be a tall demand.

Appendix A: Data tables

Top 5 Total installed capacity 2007 [MW]		Top 5 New capacity 2007 [MW]	
Germany	3,800	Germany	1,100
Spain	632	Spain	512
Japan	1,938	Japan	230
USA	814	USA	190
Italy	100	Italy	50

UK Installed Capacity [kWp]	
1992	173
1993	266
1994	338
1995	368
1996	423
1997	589
1998	690
1999	1131
2000	1929
2001	2746
2002	4136
2003	5903
2004	8164
2005	10877
2006	14300
2007	18100

Global Installed Capacity [MWp]	
1994	502
1995	580
1996	669
1997	795
1998	948
1999	1150
2000	1428
2001	1762
2002	2201
2003	2795
2004	3847
2005	5167
2006	6770
2007	9162

Global Production Share %	
China	29
Japan	22
Germany	20
Taiwan	11
Rest of Europe	7
USA	6
Rest of Asia	3
Australia	1
India	1

Appendix B: Panel tests

Summary of test levels according to IEC 61215: 2005

- Visual inspection: Detection of visual defects like broken cells, bubbles, de-laminations, faulty interconnections etc.
- Performance at STC: Cell temperature: 25 °C, irradiance: 1,000 W/m^2 with IEC 904-3 reference solar spectral irradiance distribution.
- Insulation test: Dielectric withstands at 1,000 V_{DC} plus twice the maximum systems voltage for 1 minute. For modules with an area of less than 0.1 m^2 the insulation resistance shall be not less than 400 MΩ. For modules with an area larger than 0.1 m^2 the measured insulation resistance times the area of the module shall be not less than 40 MΩ·m^2 to be measured at 500 V or maximum systems voltage, whichever is greater.
- Measurement of temperature coefficients: Determination of temperature coefficients of current (α) and voltage (β).
- Measurement of NOCT: Total solar irradiance: 800 W/m^2. Ambient temperature: 20 °C. Wind speed: 1 m/s.
- Performance at STC and NOCT: Cell temperature: 25 °C and NOCT. Irradiance: 1000 W/m^2 and 800 W/m^2 with IEC 60904-3 reference solar spectral irradiance distribution.
- Performance at low irradiance: Cell temperature: 25 °C. Irradiance: 200 W/m^2 with IEC 60904-3 reference solar spectral irradiance distribution.
- Outdoor exposure test 60 kWh/m^2 total solar irradiance.
- Hot-spot endurance test: Five-hour exposure to 1,000 W/m^2, irradiance in worst-case hotspot condition.
- UV preconditioning: 15 kWh/m^2 total UV irradiation in the wavelength range from 280 nm to 385 nm with 5 kWh/m^2 UV irradiation in the wavelength range from 280 nm to 320 nm.
- Thermal cycling test 50 and 200 cycles from –40 °C to +85 °C with STC peak power current during 200 cycles.
- Humidity freeze test: 10 cycles from +85 °C, 85 % RH to –40 °C.
- Damp heat test: 1.000 h at +85 °C, 85% RH.
- Robustness of termination test: As in IEC 60068-2-21.
- Wet leakage current test: For modules with an area of less than 0.1 m^2 the insulation resistance shall be not less than 400 MΩ. For modules with an

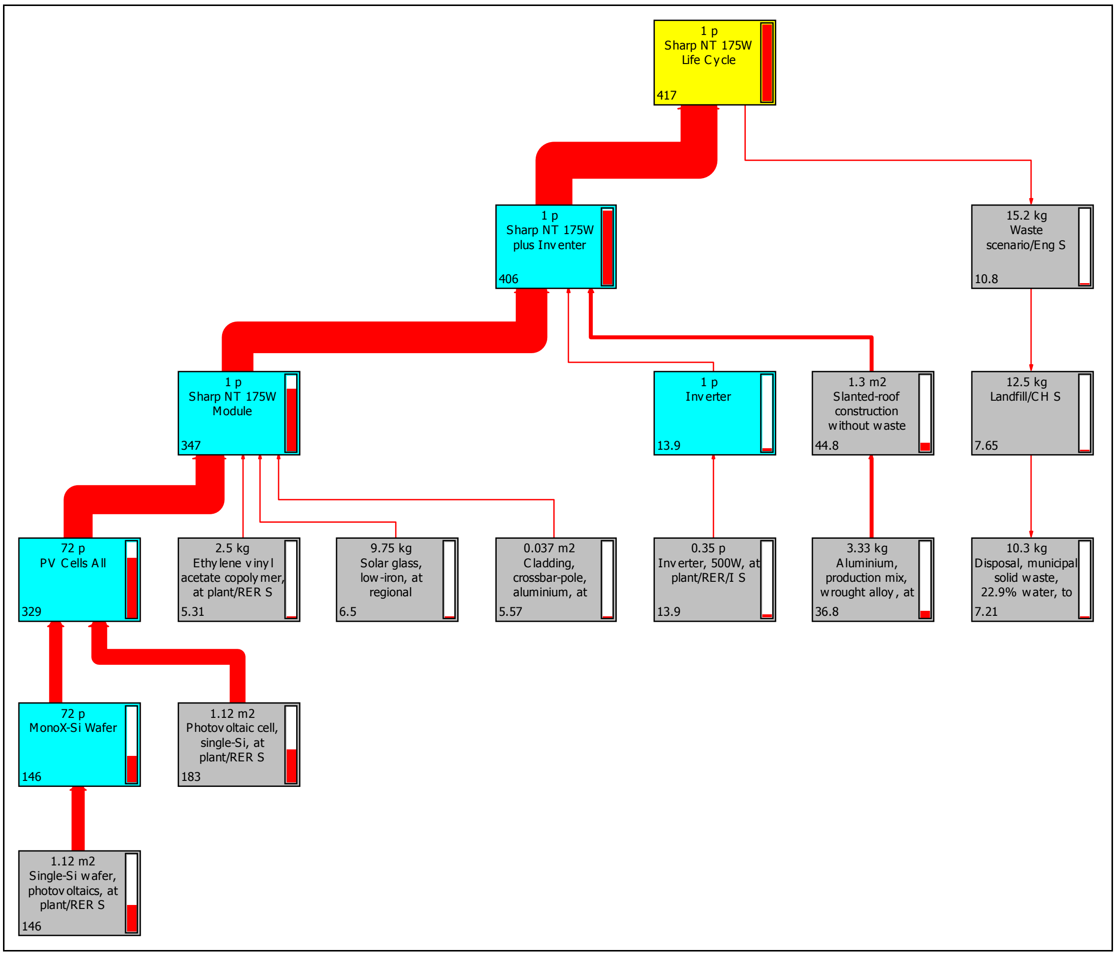
area larger than 0.1 m^2 the measured insulation resistance times the area of the module shall be not less than 40 $M\Omega \cdot m^2$ to be measured at 500 V or maximum systems voltage, whichever is greater.

- Mechanical load test: Three cycles of 2,400 Pa uniform load, applied for 1 h to front and back surfaces in turn. Optional snow load of 5,400 Pa during last front cycle.

- Hail test: 25 mm diameter ice ball at 23.0 $m.s^{-1}$, directed at 11 impact locations.

- Bypass diode thermal test: One hour at I_{SC} and 75 °C. One hour at 1.25 times I_{SC} and 75 °C.

Appendix C: Network diagram of new PV module



Appendix D: Network diagram of reman PV module