First Solar's CdTe module technology – performance, life cycle, health and safety impact assessment

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Brief project description	The objective is to provide First Solar with an independent review for using thin film cadmium telluride (CdTe) photovoltaic (PV) technology in the installation of future power plants in South Africa, based on scientific studies, the result of which is presented in this report.		
Key findings	First Solar's CdTe thin film technology photovoltaic modules are a technically feasible, environmentally friendly and safe way to produce electricity in South Africa.		
Keywords	First Solar, thin film, solar PV, photovoltaic, cadmium telluride		
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EXECUTIVE SUMMARY

Until 2011, the solar photovoltaic (PV) industry in South Africa consisted of small-scale installations, predominantly off-grid and in rural areas. In 2013, construction began on utility scale PV projects with a combined capacity of 632 MW and since then, a further 1 267 MW of utility scale PV projects have been awarded, with an approximate total of 1 000 MW of these utility scale PV that is already connected to the national grid. These projects were the result of the Department of Energy's Renewable Energy Independent Power Producers Procurement Programme (REIPPPP). When compared to the well-developed solar PV market in Europe, South Africa is still at a very early stage with the prediction that the PV market is expected to grow rapidly over the next years.

The electricity supplied to the South African grid is predominantly (90%) generated from coal. With this source of power well established in South Africa, the life cycle cost of established coal-fire generated electricity is low. However in 2013 the utility scale PV market reached grid parity with new-build coal power generation options, and in 2014 the 1 000 MW of connected utility scale PV power plants resulted in a nett benefit of R 800 million to the South African economy.

South Africa has an excellent solar energy resource with the warmest days from December to February when temperatures can exceed 40°C in some parts of the country. The First Solar CdTe modules are less affected by high temperatures than the average crystalline-Si module and this characteristic has recently been proven for locations in South Africa by the ARUP consulting engineer group (ARUP, 2015).

Today, First Solar is producing CdTe modules with 16% efficiency and a manufacturing cost below USD $0.46/Watt. Furthermore, First Solar recently announced that they have produced a thin film PV module with full area efficiency of 18.2%. First Solar has test programmes and quality management systems in place to ensure their modules comply with the required qualification standards.

During a site visit to First Solar's Perrysburg (USA) facility, the safety, industrial hygiene and occupational health procedures that are in place throughout the facility were witnessed and discussed. First Solar has proven that their workplace is safe, even to workers with a high risk of potential exposure to cadmium compounds.

Independent toxicity studies by (Zayed & Philippe, 2009) indicate that cadmium is more toxic in the elemental form compared to the relatively stable CdTe compound and that the acute inhalation and oral toxicities of CdTe in rats are found to be at least 8.9 times lower than that of elemental cadmium.

Raw material, manufacturing, operation and decommissioning stages of CdTe cells typically produce two orders of magnitude less cadmium emissions to the environment compared to coal-burning power plants. The solid semiconductor compound CdTe is a crystalline, non-flammable powder, practically insoluble in water and with a melting point above the typical temperature reached in veld fires. (Fthenakis, et al., 2005) has shown that 99.96% of the cadmium is retained in the molten glass when exposed to extreme temperatures. Other sources that contribute to the exposure of cadmium to humans include coal-burning power plants that emit significant amounts of cadmium into the environment and even more significantly, the use of phosphate fertilisers. Under normal conditions, the CdTe and CdS (cadmium sulphide) compounds are fully encapsulated between two sheets of glass and are, therefore, unlikely to breakdown chemically. Encapsulating cadmium as CdTe in PV modules presents an alternative, safer option for cadmium use when compared to most of its other current uses.

The possible benefits of replacing coal-intensive electricity from South Africa's grid with ground-mounted CdTe and roof-mounted Si PV systems was investigated and the results showed that such a replacement would yield a reduction in the various life cycle impact categories. CdTe modules have the least amount of harmful air emissions and have the lowest carbon footprint compared to CIGS and cost-competitive multi-Si systems. No literature was found indicating that CdTe modules pose a significant environmental and/or health threat due to cadmium emissions or exposure.

Another concern associated with thin-film PV modules is the availability of materials used in the semiconductor layer. Efficiency improvements of CdTe technology, that result in using less CdTe material, may have such a great impact that the 'primary' demand for tellurium could decline after 2020 regardless of increased CdTe market growth.

The life cycle land transformation of ground-mounted PV technologies in general is comparable to that of coal and natural gas cycles. As solar power plants do not require mining for fuel during their lifespan, the land occupation impact of solar power plants decreases as the power plant lifespan increases. PV systems have the potential to be constructed, operated and decommissioned in ways that avoid excessive impact on land and habitats.

Recycling is the most sustainable manner in which modules can be handled at the end of their useful life, not only from an environmental impact perspective but also in terms of resource efficiency. Literature recommends that the use of cadmium as a toxic element is recycled, despite cost implications, and that tellurium recovery is seen as an additional benefit. Environmentally sensitive metals, such as Pb, Cd, In, Ga, Se, Te, Cu and Ag, are common in the industry and therefore recycling is important for all PV technologies. With currently over 177 GW of PV installed worldwide, recycling is crucial to managing large, future PV waste volumes and to reclaiming valuable materials.

Following the visit to the recycling plant at the Perrysburg site and the related discussions, it is clear that the recyclability is fully integrated in the module design. In terms of the current process recycling technology, over 90% of the semiconductor and 90% of the glass material is recycled for beneficial reuse. Looking to the future, regulatory frameworks, greater experience and rising disposal costs will likely lead to smaller and more mobile recycling facilities, with the operational costs of such facilities expected to fall below hazardous waste disposal costs.

Water consumption for the full life cycle of thermoelectric (e.g. coal and nuclear) power plants is substantial. This is especially relevant in water scarce countries like South Africa, where dry cooling has become mandatory and has the potential to reduce the amount of water withdrawn for this purpose to some extent. In this regard, total life cycle water withdrawal per MWh is third lowest for PV (wind power and hydropower are lower). Silicon-based PV has a higher life cycle water consumption level than CdTe due to the water needed for high-purity silicon production. In terms of waste treatment, only the water used in the manufacturing process contains trace amounts of cadmium and all First Solar factories are equipped with state-of-art waste water treatment and analytical capabilities for 24/7 in-house water testing to inform operators if a batch of waste water can be discharged after treatment.

First Solar's CdTe thin film technology modules are a technically feasible, environmentally friendly and safe way to produce electricity in South Africa.

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LIST OF ABBREVIATIONS

BOS	Balance of System
CdTe	Cadmium Telluride
CMS	Change Management System
CRSES	Centre for Renewable and Sustainable Energy Studies
CSIR	Council for Scientific and Industrial Research
CSP	Concentrated Solar Power
DRAS	Delisting Risk Assessment Software
ECHA	European Chemicals Agency
EOL	End of Life
EPA	Environmental Protection Agency
EPBT	Energy Payback Time
EU	European Union
EVA	Ethylene-Vinyl Acetate
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
IEEE	Institute of Electrical and Electronics Engineers
LCA	Life Cycle Assessment
PERC	Passivated Emitter Rear Cell
PID	Potential Induced Degradation
PV	Photovoltaic
REIPPPP	Renewable Energy Independent Power Producers Procurement Programme
R&D	Research and Development
SHE	Safety, Health and Environment
TCLP	Toxicity Characteristic Leachate Procedure
USA	United States of America
USM	Unrefined Semiconductor Material
WEEE	Waste Electrical & Electronic Equipment

Introduction

Purpose and scope

Since 2003, First Solar has invited specialists from various countries and regions to carry out 13 literature reviews on their cadmium telluride (CdTe) module technology. The specialists who participated in these reviews were from the USA, the European Union (EU), France , Spain , Japan , Germany, Italy, India, Thailand, the Middle East, China, Chile and Brazil.

In 2015, First Solar approached the Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University to conduct a similar peer review based on thin film photovoltaic (PV) literature and to visit one of First Solar’s manufacturing facilities. The proposed peer review would include a South African based assessment of specific performance, health and safety throughout the product life and the life cycle impacts that large-scale deployment of CdTe PV systems would have on the environment.

This report focuses on the South African utility scale PV market and describes First Solar’s CdTe PV module technology comparing it to other commercially available PV technologies. The literature review provides comment on the chemistry and toxicology, raw material sourcing, manufacturing, product use, end-of-life disposal, as well as the overall life cycle impacts on the environment, public health and public safety, and considers other energy alternatives.

The South African utility scale PV market

Until 2011, the solar photovoltaic (PV) industry in South Africa consisted of small-scale installations, predominantly off-grid and in rural areas. In 2013, construction began on the first utility scale PV projects with a combined capacity of 632 MW. These projects were the result of the Department of Energy’s Renewable Energy Independent Power Producers Procurement Programme (REIPPPP). A further 1 267 MW of utility scale PV projects have since been awarded through the REIPPPP, on which construction has started with an approximate total of 1 000 MW already connected to the national grid. Compared to the well-developed solar PV market in Europe, South Africa is still at a very early stage but the PV market is expected to grow rapidly over the next year as can be seen in Figure 1, courtesy of the Council for Scientific and Industrial Research (CSIR) (Bischof-Niemz, 2015).

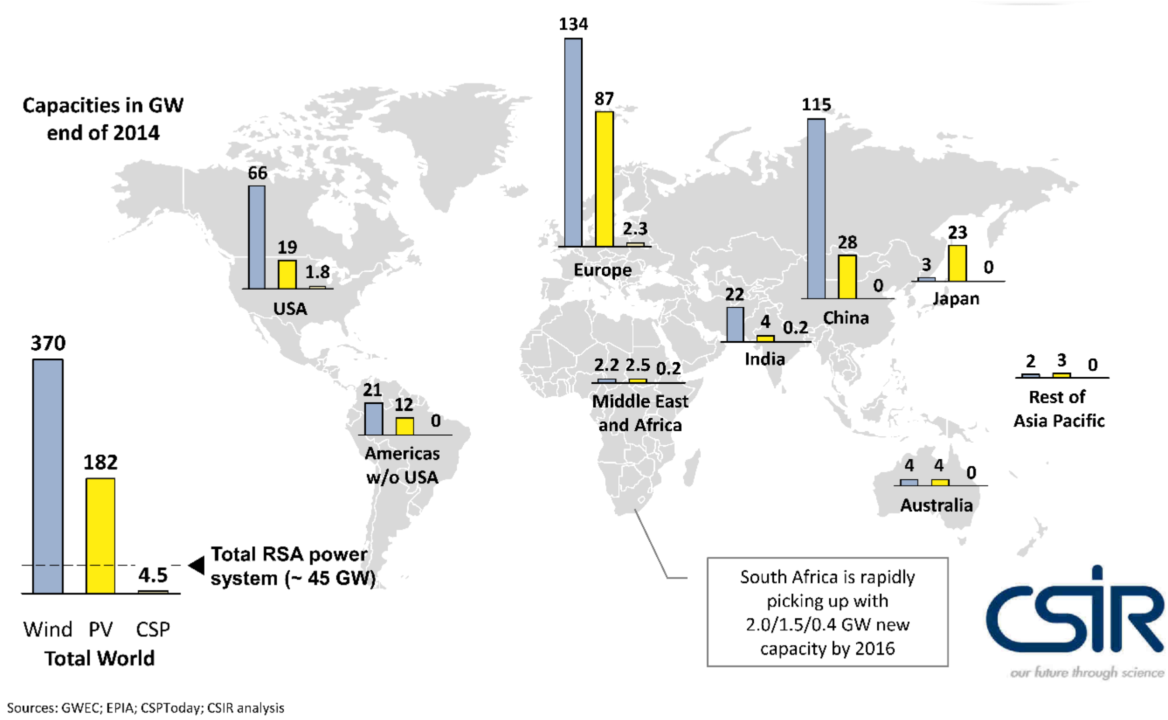

Figure 1. Renewable energy capacity at the end of 2014 (Bischof-Niemz, 2015)

South Africa is supplied with electricity generated mainly from coal, due to the abundant availability of the resource locally and the low cost of generation from older, existing coal-fired power plants, but in 2013, the utility scale PV market reached pricing that makes this a cost competitive power generator, because of the competitive tender REIPPPP. The resulting cost for wind, PV and concentrated solar power (CSP) of the four bid windows in the REIPPPP is shown in Figure 2 (Bischof-Niemz, 2015) where the cost of utility scale wind and PV is now below the cost of new-build coal or gas options. In 2014, the approximate 1 000 MW of utility scale PV power plants connected to the South African grid produced 1.12 TWh of the approximately 250 TWh required, and according to a recent study done by the CSIR, renewables resulted in a nett benefit of R 800 million to the South African economy (Bischof-Niemz, 2015).

On 16 April 2015, South Africa's Minister of Energy announced the expansion and acceleration of the REIPPPP wherein a further 1 800 MW of renewable energy, which includes PV, will be procured, and the minister will submit a new determination for an additional 6 300 MW of renewable energy for the approval of the energy regulator.

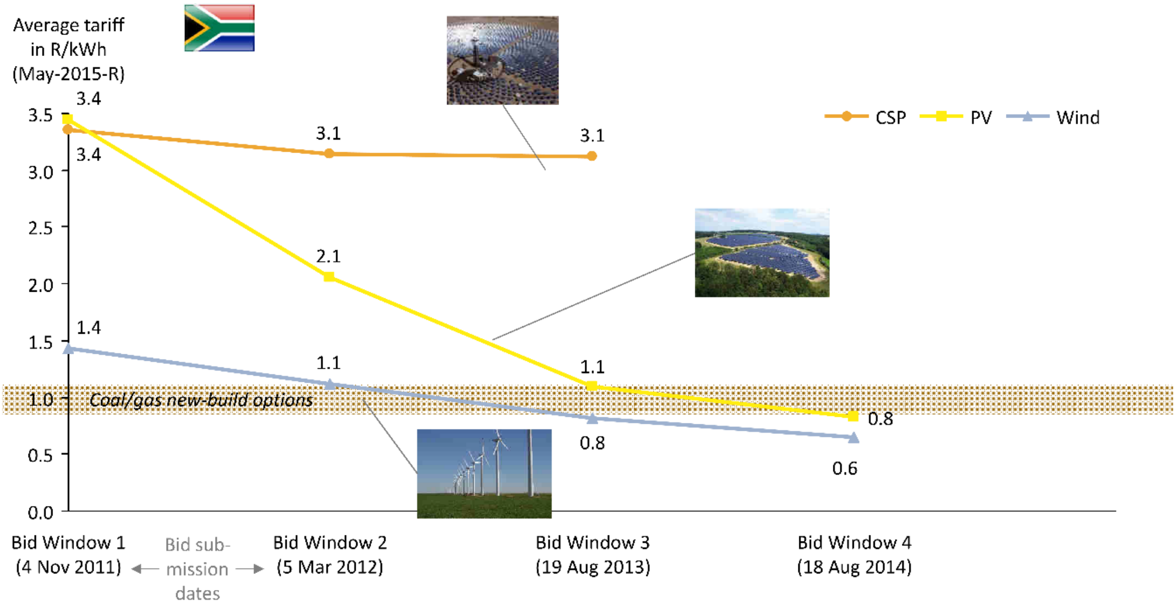

Figure 2. Four bid windows' results of Department of Energy's REIPPPP (Bischof-Niemz, 2015)

The small-scale PV market in South Africa is growing, although at an unknown rate. The known installations amount to approximately 44 MW as of 21 June 2015 (Anon., n.d.) and it is likely that there are an unknown number of small-scale installations that are, therefore, not represented in the 44 MW.

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1: Region-specific performance aspects

The aim of this section is to evaluate the region-specific performance aspects of First Solar's thin film CdTe technology and specifically, the technology roadmap, the influence of climate, reliability testing, grid integration and the field performance data of modules.

1.1: First Solar's CdTe thin-film PV technology

First Solar, founded in 1999, is the first company to break through the $1/watt manufacturing cost barrier and implement a global PV module-recycling program. According to First Solar's manufacturing cost forecast of 2013 for CdTe PV modules (de Jong, 2013), First Solar is aiming to produce modules for less than $0.40/watt in 2017. At the 2015 IEEE PVSC conference, (Garabedian, 2015) from First Solar indicated that their actual 2015 manufacturing cost is below the 2013 forecast of $0.43-0.46/watt for 2015.

First Solar held various world records regarding the best research-cell efficiencies for thin-film technology (Figure 3 shows the CdTe cell records in green circles with yellow centres (NREL, n.d.)). The R&D efforts of First Solar have been paying off since 2013, with cell efficiencies of up to 21.5%, surpassing the Trina Solar multi-crystalline-Si cell record of 20.8%. At the 2015 Institute of Electrical and Electronics Engineers (IEEE) PV specialist conference in New Orleans, First Solar announced that they have produced a prototype thin film PV module with full area efficiency of 18.2%, thereby also surpassing the 17.7% full area efficiency of the Trina Solar 324.5 W multi-crystalline passivated emitter rear cell (PERC) module (Garabedian, 2015).

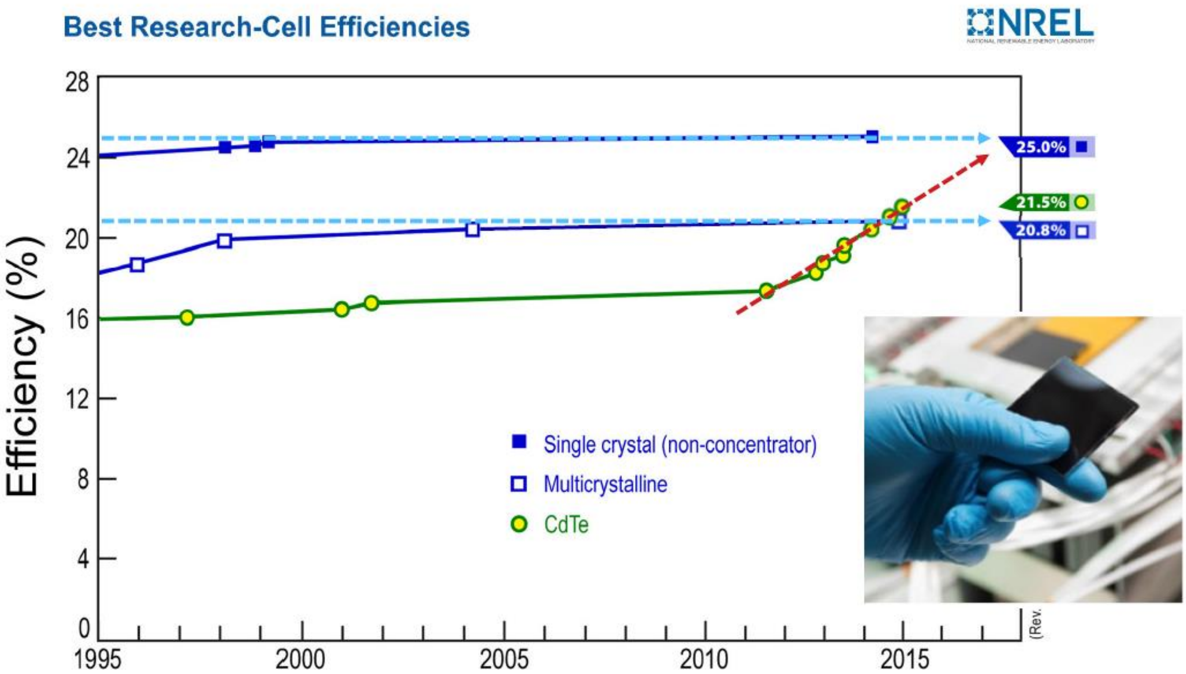

Figure 3. The National Renewable Energy Laboratory's solar cell efficiency chart showing the evolution of the single crystal, multi-crystalline and CdTe technologies

First Solar has a long-term goal to reach 24.8% research cell efficiency by increasing the open circuit voltage, the fill factor, and the current density of their cells, thereby moving towards the 25% efficiency of the record-holding mono-crystalline cells produced by SunPower (NREL, n.d.). The 2017 goal for First Solar is to commercially manufacture a module with an efficiency of 19.5% (Garabedian, 2014).

The First Solar series 4 PV module has a 25-year warranty and is compatible with 1 500 V plant architectures whilst remaining potential induced degradation (PID)-free. The modules have received various IEC certifications, comply with ISO 9001 and ISO 14001 and have a class B fire rating (Class A Spread of Flame) according to UL and ULC 1703 standards.

1.2: Factors influencing PV module performance

Many factors influence the performance of PV systems, with those most often considered being the global horizontal irradiance (GHI) and the ambient temperature of a site. South Africa has an excellent solar resource, as shown in Figure 4 and a wide variety of climates. The coldest days are from June to August and the warmest days from December to February, when temperatures can exceed 40 °C in some regions.

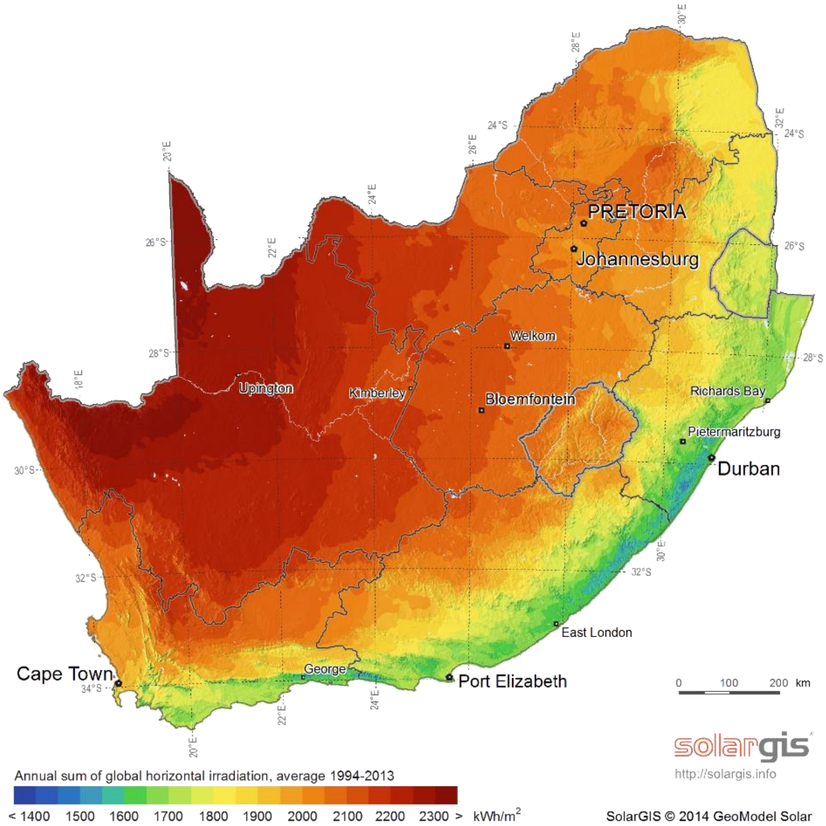

Figure 4. GHI map for South Africa (GeoSun, n.d.)

High temperatures negatively influence the power generation capability of PV modules including First Solar CdTe modules. The First Solar CdTe modules are, however, less affected by high temperature than the average multi-crystalline-Si module, as shown in Figure 5 (Strevel, et al., 2012). In the regions in South Africa that experience the warmest climates, the thin film modules would yield more energy than multi-crystalline modules.

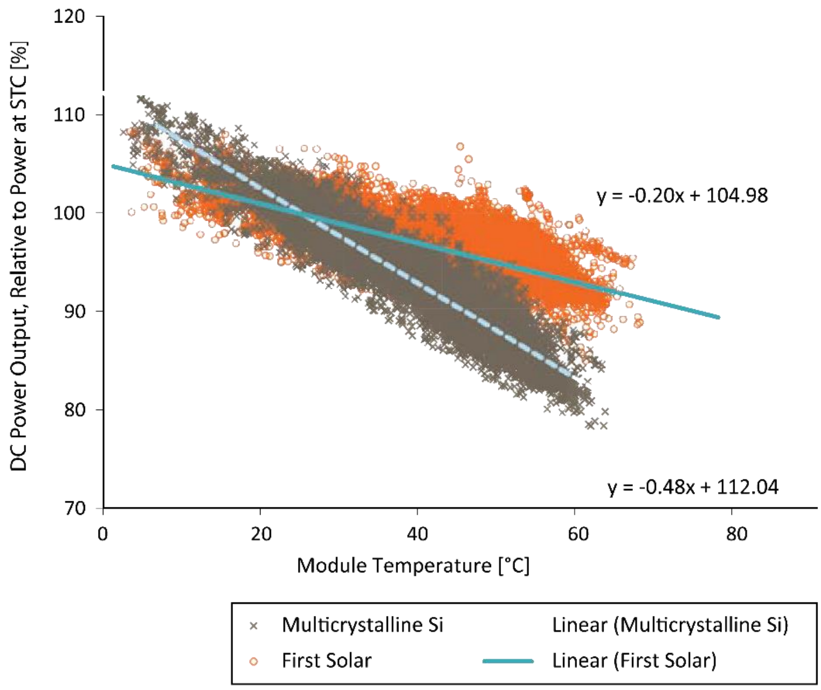

Figure 5. First Solar and multi-crystalline DC power output vs temperature (Strevel, et al., 2012)

The solar spectral irradiance distribution describes light intensity as a function of wavelength. The reference spectral irradiance distribution under which PV module nameplate ratings are defined is given by ASTM G173 and shown in Figure 6. A PV cell can only use a certain portion of the light spectrum as shown by the quantum efficiency curve for a CdTe cell, in Figure 6 (Lee, et al., 2015; Nelson & Panchula, 2013). Because the First Solar cells have a narrow wavelength band that exhibits high efficiency and this band excludes the 950 nm wavelength affected by the amount of water vapour in atmosphere, the energy available to a First Solar PV cell would thus be less affected by high humidity conditions. Figure 7 shows the spectral response characteristics of different PV technologies and here, the effect of humidity can be seen at around 950 nm where the CdTe technology has a low spectral efficiency and the c-Si module has a high spectral efficiency (AUO, n.d.). Thus, if you compare the performance of a First Solar CdTe module with a c-Si model in very humid conditions (such as in the city of Durban), the CdTe module would have a higher output power.

First Solar appointed ARUP consulting engineers to conduct an independent module comparison, by simulation, for First Solar’s CdTe modules with single- and multi-crystalline modules at Vryburg, Upington and Bloemfontein in South Africa. The report revealed that for a plant with the same nameplate capacity, the CdTe modules produce a higher annual yield (ARUP, 2015). The ARUP report also shows the effect on the annual yield due to the influence of humidity or spectral shift and that the modules can have an increased output when true-tracking is employed instead of backtracking[1].

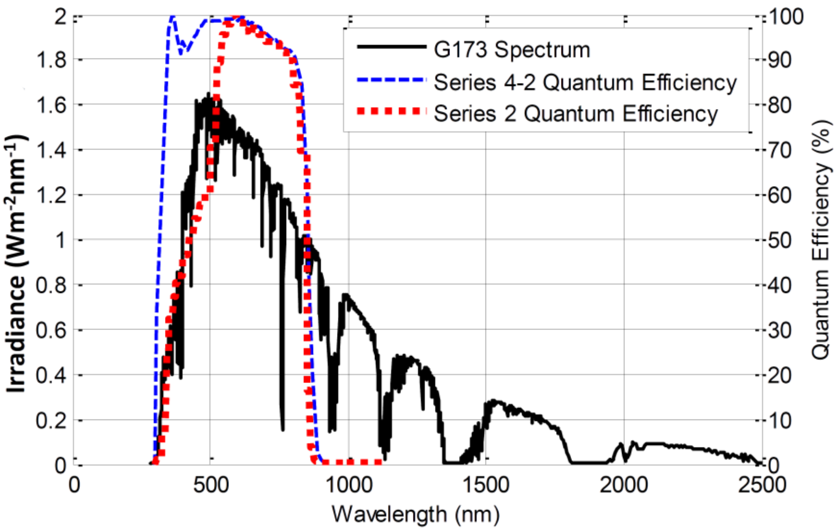

Figure 6. QE curves for First Solar Series 2 and Series 4-2 modules and spectrum as defined by G173 standard (Nelson & Panchula, 2013)

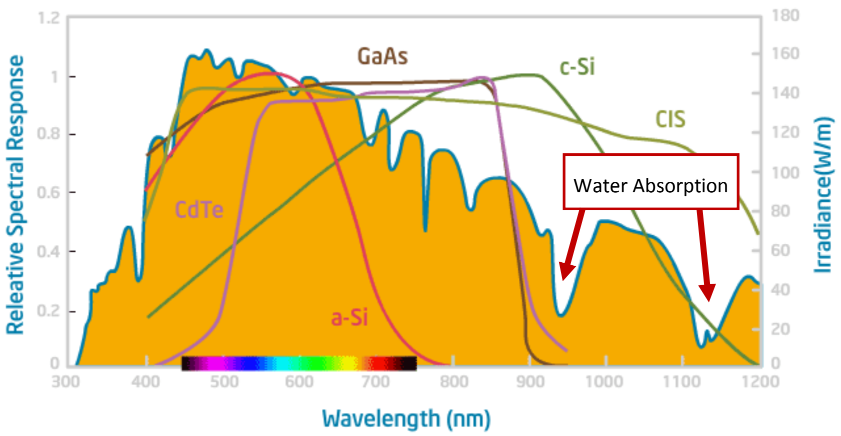

Figure 7. Spectral response characteristics of different solar module technologies and the irradiance from the sun (AUO, n.d.)

[1] True-tracking is when solar modules are tilted to follow the sun regardless of inter-row shading. Backtracking is when the inter-row shading begin and the tracking angle stop following the sun but returns to a zero shading position in order to reduce near shading caused by adjacent PV modules.

Apart from temperature and precipitable water, soiling can also influence a PV power plant's performance. In South Africa, the majority of utility scale power plants are installed in more arid regions where dust may negatively influence the power generation capabilities of these plants. A recommendation is that soiling measurement equipment is installed as a standard to monitor the performance of a plant. First Solar has done extensive soiling tests and confirms that when their modules are used for soiling measurements the short circuit currents can be used, which serve as a proxy for the effective irradiance received by the soiled versus the clean module (Gostein, et al., 2014).

1.3: Reliability, grid integration and filed performance

First Solar has a test programme and quality management system to make sure their modules comply with the required qualification standards. Modules are sampled from the production line and approximately 80 000 modules per annum (roughly 8.0 MW) undergo various tests at the First Solar indoor reliability labs (Experts, 2015; First Solar (P. Buehler), 2015). Apart from the indoor testing, First Solar also carries out outdoor testing at various tests sites to verify and validate the indoor laboratory results. Through the development process, First Solar improved their modules by changing the edge sealant to the proprietary 'Black' edge sealant that enhances the long-term durability and extended test performance of the modules. In the series 3 Black plus modules, the back contact composition was also changed to minimise long-term degradation (Strevel, et al., 2013). According to observations during the site visit to the Perrysburg manufacturing facility, and the quality and reliability presentation at the recent 42nd IEEE PV Specialist Conference, the most recent First Solar series 4 version 2 modules have passed various long-term durability tests including the Thresher, Long Term Sequential, and Atlas 25+ tests (First Solar (P. Buehler), 2015).

Photovoltaic power plants are expected to operate for at least a 20-year period in South Africa and although long-term reliability is important, the integration with and the stability of the electrical network, or utility grid, is even more important. PV power plants operating in South Africa need to comply with the South African Grid Code. Grid integration is possible with the use of a plant controller that can control the behaviour of the plant accordingly to satisfy the specified requirement, standard or regulation (Morjaria, et al., 2014).

The field performance of the First Solar CdTe modules are being documented (Strevel, et al., 2012; Strevel, et al., 2013; Panchula, et al., 2011) and this also assists plant operators to improve their yield forecasting capabilities for CdTe modules, which is shown in (Strevel, et al., 2012; Strevel, et al., 2013) and here the measured plant performance is close to 100% of the P50 prediction.

2: Health and safety impacts of the CdTe

The aim of this section is to evaluate the safety, health and environmental (SHE) aspects associated with the production, testing and on-site implementation/operation of the First Solar CdTe modules. This evaluation was done over the life cycle of the module and is based on existing literature and site visit. During a site visit to First Solar's Perrysburg facility, the existing safety, industrial hygiene and occupational health procedures were observed and discussed (Experts, 2015). First Solar is OHSAS 18001 compliant with a safety first policy and implements industrial hygiene procedures that, through medical monitoring, have proven that the workplace is safe, even to workers with a potential high exposure risk to cadmium compounds.

2.1: CdTe stability and toxicity (catastrophic events)

In accordance with the classification from the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), adopted in 2015 by the European Chemicals Agency (no classification for CdTe in South Africa could be found), CdTe is classified as

i) harmful if inhaled;

ii) harmful to aquatic life with long lasting effects.

However, even in a worst-case rooftop fire scenario where there are 1 000 m^2 of CdTe modules with an average Cd content of 66 g/m^2 and a heat source of 60 MW, potential Cd emissions are still substantially below human health evaluation levels (Beckmann & Mennenga, 2011), actual Cd content in First Solar PV modules (Sinha, et al., 2012) is lower by an order of magnitude than that assumed by (Beckmann & Mennenga, 2011).

Independent toxicity studies indicate that Cd is more toxic in the elemental form compared to the relatively stable CdTe compound. For example, (Zayed & Philippe, 2009) studied the acute inhalation and oral toxicities of CdTe in rats and found the median lethal concentration and dose to be at least 8.9 times higher than that of elemental Cd. The CdTe compound also exhibits low aquatic toxicity (Agh, 2011; Kaczmar, 2011), no mutagenicity in bacteria (Agh, 2010; Kaczmar, 2011) and no acute adverse reproductive effects in rats (Kaczmar, 2011; Chapin, et al., 1994).

CdTe modules do not generate any toxic gases during normal operation. This is because the energy absorbed from the high frequency photons of the electromagnetic spectrum is not enough to break the bonding electrons in the solid lattice structure. The energy of any photon in the solar spectrum is therefore lower than the chemical bonding energy in the CdTe or CdS layers of a PV cell; this is the intrinsic feature that stabilises the Cd-containing compounds (Bonnet & Meyers, 1998).

2.2: Raw material sourcing

It is important to note that conventional silicon PV cells, as well as the coal used in coal burning power plants contain Cd. In fact, as highlighted in the life cycle study of (Fthenakis, 2004), raw material, manufacturing, operation, and decommissioning stages of CdTe cells typically produce two orders of magnitude less Cd emissions to the environment compared to coal burning power plants. That is to say, air emissions of 0.02 g Cd/GWh from CdTe PV cells, compared to 2 g Cd/GWh produced from coal burning power plants.

The main potential for harm to animals, humans or the environment relates to toxic gas emissions during catastrophic events, such as fires. Telluride is a rare metal, whilst Cd is a heavy metal and studies on the toxicity of Te in its elemental form show that it appears to be only mildly toxic and not carcinogenic (Raugei, et al., 2012).

The solid semiconductor compound CdTe is a crystalline non-flammable powder, practically insoluble in water and has a high melting point of 1 041°C. This melting point is above the typical temperature (800-1 000°C) reached in a veld fire (Martell, 2009), as opposed to the melting point of Cd metal of only 321°C (Lide, 2004). Testing has shown that 99.96% of the Cd is retained in the molten glass during fire testing up to 1 100°C (Fthenakis, et al., 2005).

2.3: Cadmium exposure during manufacturing

First Solar enforces proactive cadmium-containing material management practices that prevent the environmental exposure and human health risks associated with cadmium materials processing during module manufacturing. First Solar has an active medical monitoring programme for their employees to ensure that their industrial hygiene practices are effective. Medical monitoring results compare recently hired to long-term employees and smokers (cadmium is a constituent of cigarette smoke) showing that cadmium levels in workers are well below the threshold level and do not rise due to working in the manufacturing plant (Bohland & Smigielski, 2000). Table 1 lists other sources that can result in cadmium exposure (Van Assche, 1998).

Table 1. Sources and relative contributions of Cd exposure to humans (in Europe) (Van Assche, 1998)

Cd source	Relative exposure contribution
Phosphate fertilisers	41.3%
Fossil fuel combustion	22.0%
Iron and steel production	16.7%
Natural sources	8.0%
Non-ferrous metals	6.3%
Cement production	2.5%
Cd products	2.5%
Incineration	1.0%

2.4: Impact of CdTe PV on human, animal and plant life during operation

A typical Life Cycle Assessment (LCA) analyses the impact of material and energy flows in and out of a product. In evaluating the potential risk to the environment and the potential impact on human, animal and plant life, the CdTe PV manufacturing process and its commercial deployment should be viewed in the context of the Cd emission contributions from other industries. Vast quantities of Cd are released into the environment via primary fossil fuels industries (Fthenakis, 2004), whereas the CdTe PV industry utilises the by- or waste-products from essentially two base metal industries, i.e. Te from the copper (Cu) and Cd from the zinc (Zn) refiners. Neither Te nor Cd are found alone in commercial deposits.

Cd is generated primarily as a residue during electrolytic (hydrometallurgical) Zn production and as fumes and dust collected from emissions during pyro metallurgical processing. It is used primarily in NiCd rechargeable batteries, within paint pigments, plastic stabilisers and other uses making up the difference. Owing to the very large quantities of Zn metal produced, there are substantial amounts of Cd generated as by-product. If the market does not absorb the Cd generated, it is stored or disposed of as hazardous waste. Therefore, in light of the discussions in the previous section, encapsulating Cd as CdTe in PV modules presents an alternative and safer usage of the mineral compared to most of its current uses (Fthenakis, 2004).

2.5: Release of Cd from CdTe PV modules to the environment

Unless a strong oxidant such as hydrogen peroxide (H_2O_2) solution, used for leaching semiconductor material from PV modules during recycling, finds its way through cracks in a broken glass panel, no Cd (or Te) will be released into the environment because under normal conditions, the CdTe and CdS compounds are fully encapsulated between two sheets of glass.

An unlikely, albeit necessary, scenario to consider is the potential chemical release to an aquatic environment after decommissioning, i.e. if the PV modules end up in a landfill and toxic elements leach from the CdTe/CdS compound layers. Therefore, the aspect dealt with here relates to the disposal of large volumes of CdTe PV modules dumped in unlined landfills instead of being recycled or sent to an appropriate sanitary landfill. The standard Toxicity Characteristic Leachate Procedure (TCLP) is utilised by the U.S. Environmental Protection Agency (EPA) Delisting Risk Assessment Software (DRAS) risk assessment model to evaluate potential leaching risks using waste fragments less than 1 cm (Sinha, et al., 2014). Although end of life (EOL) module recycling and responsible disposal are important for all PV technologies, (Monier & Hestin, 2011) considered six different commonly used multi-crystalline silicon (c-Si) PV modules and found that the leachability of toxic lead (Pb) is significantly greater than that of Cd from CdTe PV modules. In fact, the potential negative impacts of improper disposal of c-Si PV modules have been found to be higher than for the CdTe PV module. Modelling that has been carried out by (Sinha, et al., 2012) shows that potential exposure to Cd, from rainwater leaching of broken modules, is highly unlikely to pose a potential health risk to humans.

The important question remains: what happens if large volumes of CdTe PV modules are sent to unlined landfills, e.g. if the unlikely scenario develops, where a large installation reaches an instantaneous EOL state and no recycling is enforced? The US EPA DRAS risk assessment model is utilised by (Sinha, et al., 2014) and concluded that such a scenario is unlikely to result in significant risk to human health and the environment. Furthermore, since the US EPA DRAS risk assessment model evaluates potential leaching risks using TCLP data for waste fragments less than 1 cm, it tends to overestimate the leaching potential of PV modules crushed by a landfill compactor, with 75% of the crushed module fragments typically larger than 1 cm and with some large pieces remaining intact (Sinha & Wade, 2015).

Besides using sanitary landfills, high value recycling will have the lowest environmental impact and will benefit resource recovery, provided this recycling is also conducted in an environmentally responsible manner.

3: Life cycle impacts of the large-scale deployment of CdTe PV systems

The overall life cycle impacts of large-scale CdTe deployment covers a broad spectrum and the following discussion includes comparisons with other technologies by using different life cycle analysis methods, the carbon footprint, metal depletion, land transformation, water usage and life cycle emissions of CdTe.

3.1: Carbon footprint, energy payback time and heavy metal emissions

By means of a hybrid life cycle assessment, (Bergesen, et al., 2014) investigates how the two most common thin film technologies (CdTe and CIGS) offer long term environmental benefits and how impacts from the technologies will potentially change between 2010 and 2030.

The review found that the life cycle impacts of thin-film PV technologies were at least 90% lower than other technologies in the U.S. generation grid mix across more than half of the impact categories in 2010. The life cycle greenhouse gas (GHG) emissions of CdTe and CIGS were estimated at 20 and 22 gCO_2eq/kWh respectively, with much lower water depletion impacts and carcinogenic emissions than the U.S. grid. The metal depletion potential of thin-film technologies are regularly questioned and it was found that the metal depletion was estimated at 2.8 and 3.3 times higher than the U.S. electricity generation grid mix for CdTe and CIGS respectively in 2010, the metal depletion potential is not unique to only thin film but PV in general. However, by assuming that technology design and efficiency improvements will take place by 2030, stress on metal resources will be somewhat reduced, but other balance-of-system (BOS) components also need to be recycled to reduce this impact further. The suggestion to include BOS components in recycling comes from the finding that although most studies focus on the metals used in semi-conductive layers, as copper is used in inverters, transformers, wiring and other BOS components, it had the greatest contribution to the metal depletion potential. It is estimated that if PV generates 2.7 per cent of the U.S.'s electricity in 2030 as predicted in the IEA Blue Map scenario, the amount of copper needed would be greater than half of the total refined copper within the U.S. in 2013. Recycling of BOS components is thus expected to result in major reduction of future copper depletion.

All other life cycle impacts are expected to be reduced by 2030 for both thin-film technologies, but the two most significant reductions are a 69% reduction in life cycle gCO_2eq/kWh emissions, and an expected 50% reduction in carcinogenic human health impacts with carcinogenic impacts primarily attributed to emissions from production of copper used for transformers, inverters, and wiring (Bergesen, et al., 2014).

Using methods developed by the Joint Research Center of the European Commission through the International Reference Life Cycle Data System, (Sinha, et al., 2014) investigated the possible benefits of replacing coal-intensive electricity from South Africa’s grid with ground-mounted CdTe- and roof-mounted Si PV systems. The results showed that such a replacement would yield a reduction of more than 66% in various impact categories such as ecosystems, human health and natural resources. Furthermore, this reduction holds strong even with local content requirements such as in the Renewable Energy Independent Power Producers Procurement Programme where the balance-of-system would make up the bulk of this local content in CdTe systems. The only category without any perceived benefit was the mineral, fossil and renewable resource depletion category, within which recycling of all materials offers great potential for mitigation.

In an earlier study by (Fthenakis, et al., 2008), it was also found that although there are differences between the emissions per PV technology, these amounts are still much lower than that of conventional energy technologies, as shown in Figure 8. The same study confirmed that CdTe had the lowest amount of harmful air emissions because of the lower energy-intensive production processes required. Furthermore, if electricity generated from central PV systems could replace conventional grid electricity used to produce CdTe modules, harmful cadmium and other GHG emissions could be reduced by a minimum of 89%. The concept of increasing the ‘quality’ of energy used for PV production by using electricity produced by PV systems is termed a ‘PV breeder’.

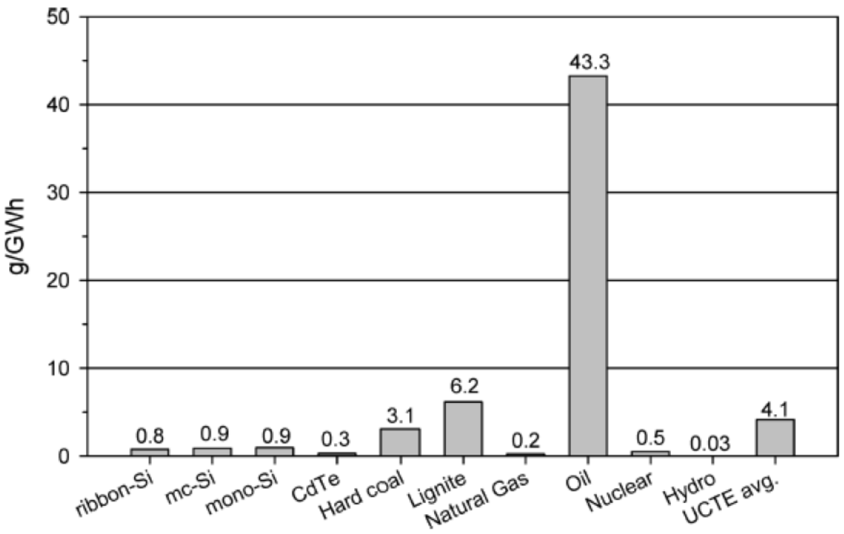

Figure 8. Life cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption, normalised for a Southern Europe average insolation of 1 700 kWh/m^2/yr, performance ratio of 0.8, and lifetime of 30 yrs (Fthenakis, et al., 2008).

To determine the 'eco-efficiency' of different electricity generation technologies, seven potential impacts on the environment were combined into an 'eco-index'. In a report investigating this parameter, it was also found that differences between PV technologies are very small and on average have an environmental impact 10 to 20 times less than that of fossil electricity sources. The environmental impact of the BOS of different PV technologies was investigated and for ground-mounted systems, the BOS contributed 86% (CdTe) and 68% (silicon) of the environmental impact (Seitz, et al., 2013).

When investigating the GHG emissions of various commercial PV systems, CdTe production was found to have the lowest carbon footprint, at 15.83 gCO_2eq/kWh compared to 21.44 gCO_2eq/kWh for CIGS and 27.20 gCO_2eq/kWh for cost-competitive multi-Si systems. In addition to life cycle gCO_2eq/kWh emissions, energy payback time (EPBT) is another widely used concept to investigate the environmental performance of a technology or product. The associated energy payback times of the various PV technologies were also estimated at 0.68, 1.01 and 1.23 years for CdTe, CIGS and Multi-Si systems respectively. All values were estimated based on an annual irradiance of 1 700 kWh/m^2. The energy intensive nature of silicon purification and ingot growing is the primary reason for the higher carbon footprint and energy payback period associated with crystalline silicon PV technologies as shown in Figure 9 (de Wild-Scholten, 2013). In South Africa the annual irradiance is higher than 1 700 kWh/m2 and therefore the energy payback period will be shorter for the different PV technologies.

The results above are comparable to the results of another study that compared sustainability of the five most common PV systems (i.e. Mono-SI, multi-Si, a-Si, CdTe and CIGS). Here, CdTe was also found to have the lowest life cycle GHG emissions and EPBT. The combined emissions for the CdTe and CIGS thin-film technologies are in the range of 10.5-50 gCO_2eq/kWh and the combined EPBT was slightly higher than that of (de Wild-Scholten, 2013) ranging from 0.75-3.5 years. Mono-Si systems were found to have to highest energy requirements because of the energy intensive process of silicon purification and crystal growing (Peng, et al., 2013).

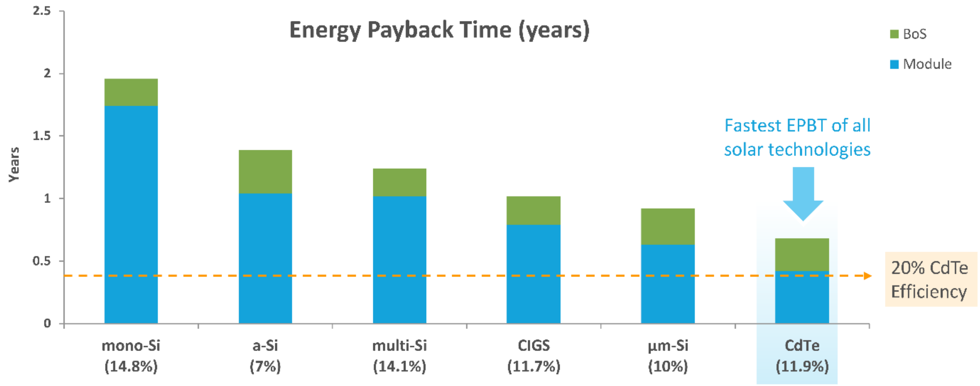

Figure 9. Energy payback time for different PV technologies and their balance of system component (de Wild-Scholten, 2013)

Taking into consideration other carbon sinks that are affected when land is cleared for the installation of a PV power plant such as carbon stocks and sequestration rates in various natural environments, carbon emission avoidance rates for solar and life cycle carbon emissions, (Turney & Fthenakis, 2011) found that solar power still has a net benefit in terms of life cycle emissions.

Cadmium release into the environment from CdTe modules is one of the main concerns related to the technology, however, several experiments have been performed by various authors where extremely conservative cadmium levels are regarded as threshold values, but no literature was found where it was shown that CdTe modules pose a significant environmental and/or health threat due to cadmium emissions or exposure. In a study where the impact of fire on encapsulated cadmium was tested, it was demonstrated that 99.5-99.96% of cadmium diffuse within the molten glass (Fthenakis, 2004). In terms of life cycle cadmium emissions, a typical U.S. coal-fired plant, with necessary cadmium removal filters, emits 2 g cadmium per GWh, whereas U.S. produced, CdTe modules emit 0.016 g cadmium per GWh, largely attributed to electricity use during PV module manufacturing. The results of the comparative benefits of thin-film PV technologies are well documented, but end-of-life risks associated with the modules remain a concern as policies and systems with regard to disposal or recycling appear to be inadequate in some instances (Fthenakis, 2012). In this regard, PV recycling under the EU WEEE Directive serves as an example of an effective policy instrument covering all PV technology end-of-life risks.

At a higher level, the contribution of CdTe to global cadmium flows, air- and water emissions have also been investigated. It was found that under a large growth scenario where 1 TW of CdTe is installed by 2050, cadmium emissions would still be an estimated two to three orders of magnitude lower than that of the 27 countries of the EU at the time of writing with those emissions largely attributed to electricity use during PV module manufacturing.. Although an increase in the use of cadmium is inevitable at higher installed CdTe capacity, the growth in this sector can very well reduce cadmium emissions and overall environmental pollution related to cadmium, globally (Raugei & Fthenakis, 2010).

3.2: Raw material availability

Another concern associated with thin-film PV modules is the availability of materials used in the semiconductor layer. The limiting element in CdTe modules is tellurium, where current production of this element is predominantly linked to base metal production and more specifically, anode slimes from copper electro-refining. Taking into account the estimated amount of annual tellurium production, cost limitations, tellurium recovery through recycling of CdTe modules and the expected increase in sourcing tellurium from recycled modules after 2045, upper production limits of CdTe modules are projected. The cumulated global production of CdTe from known tellurium resources is estimated at 120 GW by 2020, 0.9-1.8 TW by 2050 and 3.8-10 TW by 2100 (Fthenakis, 2012). These figures are closely related to the demand projections for copper and do not include the possibility of directly mining tellurium from ocean floor reserves where the element is present in ferromanganese nodules.

In another study that investigated three scenarios in terms of technological advancement and increase in recycling, it was found that efficiency improvements may have such a great impact that the 'primary' demand for tellurium could decline after 2020 regardless of increased CdTe market growth. However, estimates are influenced by demand projections for other uses of tellurium, and the current prediction is that the CdTe industry could be fully reliant on tellurium recovered from recycled modules by 2038 (Marwede & Reller, 2012).

(Houari, et al., 2013) uses a systems-dynamic model to determine whether the availability of tellurium will constrain the maximum potential growth of the CdTe market by 2050. The model showed that the most sensitive parameters regarding tellurium supply for reaching the maximum potential CdTe market are the use of tellurium during manufacturing and the increase of the recycling of modules, module lifetime, and the dynamics related to tellurium reserves. The study concluded that even without technology improvements or tellurium supply growth, the potential of the CdTe market is expected to be higher than previously estimated.

Calculating the amount of tellurium needed at different percentage CdTe market share, semiconductor layer thickness, and module efficiencies up until 2030, (Zweibel, 2010) also cannot foresee that tellurium would be a limiting factor within the next 20 years. These prospects excluded the possibility of increasing the tellurium reserve by improving and expanding metal refining processes or exploiting undersea tellurium resources.

From a combination of studies, it becomes evident that increases in CdTe module-efficiency and the reduction in semiconductor layer thickness will result in less CdTe used per module, and that the study of cadmium reserve quantities and the recycling of modules are key to improving the sustainability of the technology.

3.3: Land use and biodiversity

As land use intensity is often used as a proxy for various impacts, this aspect remains relevant when quantifying the impact of all electricity generation technologies. Land is becoming scarce in some areas for the specific purpose of solar power installations and competition might exist for other land use options; thus the efficiency of land use is becoming increasingly important (Hernandez, et al., 2014). It is often found that results in literature on the life cycle land use per electricity generation technology are contrasting because of the different approaches used to estimate land use, and whether or not both direct and indirect impacts are included. Direct impacts refer to the land where a power plant is located and indirect impacts refer to the land used for mining fuel for conventional electricity generation technologies. Life cycle land uses are also further grouped as land transformation, in area unit, per energy or land occupation where it is the land transformation, per year.

The life cycle land transformation of ground mounted PV technologies in general is comparable to that of coal and natural gas cycles, where different coal mining methods are applied and these values range between 100 – 500 m^2/GWh (Fthenakis & Kim, 2009). Land occupation is regarded as the more appropriate metric to use for comparison as more information is included in such figures over the lifetime of a power plant/technology. Since solar power plants do not require mining for fuel during their lifespan in the way that coal power plants do, the land occupation impact of solar power plants decreases as the power plant lifespan increases. In studies where the land impacts from mining as well as the recovery rate of mined areas are taken into account, the parity between coal and solar power plant land occupation is reached after 24 years (Turney & Fthenakis, 2011). It can further be argued that land occupation and transformation figures will continuously change as improvements are made with regard to the efficiency of modules.

The World Wide Fund for Nature took into account the energy demand of seven politically and demographically diverse regions with high solar resources and calculated the amount of land needed to supply 100% of each of these regions' electricity needs in 2050. In each of these regions, South Africa included, the amount of land needed for PV installations was less than one per cent of the region's total land area. The specifically required land use to produce 100% of South Africa's electricity in 2050, with solar PV, was calculated to be only 0.09% and equates to 1 130 km^2. Recognizing that 100% of electricity generation by PV is unlikely, this calculation demonstrates that the space needed on rooftops and on land is relatively small and would thus be far lower, at a lower percentage PV penetration (World Wildlife Fund, 2012). The impacts that will be caused by the transformation of this relatively small surface area can arguably also be managed by responsible land management practices such as proper site selection, minimizing soil grading and increased effort and caution concerning project decommissioning and module recycling. All of these recommendations have been made specifically for South Africa by (Sinha, et al., 2014).

Quantitative studies of the impacts of large solar power installations on plant and animal life are still relatively limited, as the technology on such a large scale is new when compared to older impacts such as mining and agriculture. The presence of wildlife is, however, important in determining a site for a solar power installation and certain areas may even be excluded due to the presence of wildlife (Woody, 2009). Impact on wildlife from solar power plants is largely determined by the land use of the installation as habitats are transformed and this is likely to have further impacts on animal movement and feeding. In situations where the ground preparation involves scraping of the soil surface bare earth is exposed, which may include the use of herbicide, bringing changes to the vegetation communities (Turney & Fthenakis, 2011). Another under-studied ecological impact of PV power plants is the microclimate change brought about through shading, and water runoff, from PV modules in the field.

By considering 32 possible impacts that may arise from large-scale solar power plants, (Turney & Fthenakis, 2011) concluded that solar power plants located in true deserts where wildlife is sparse or absent, are likely to have the least negative environmental impacts.

A study on the impact of solar parks on biodiversity in Germany reported that plant and animal life can be increased by following certain best-practice guidelines. These guidelines range from selecting and prioritizing site selection on specific land use types, to avoiding the creation of barriers that prohibit movement across a larger area, to regular maintenance and monitoring. This report did not focus on a specific PV technology, but remains applicable in the effort to reduce the environmental impact and increase the benefits from large CdTe ground-mounted installations.

The integration and management of environmental and energy systems is a field of study in which there is still plenty of room for learning and potential for synergies between these systems as well as that of climate protection and nature conservation (Peschel, 2010).

As the population grows and land becomes degraded and more scarce, it is essential that there must be parallel development between renewable energy and environmental protection. PV systems have the potential to be constructed, operated and decommissioned in ways that avoid excessive land and habitat impacts.

3.4: Recycling

Disposal of modules in landfills is not desired and (Sinha, et al., 2014) performed an aggressive experiment to establish the risk of exceeding toxicity levels in the event that Si or CdTe modules are deposited on an unsanitary landfill site. While within human health and ecological screening limits, their results indicated that all PV technologies need to be responsibly disposed of, as the concentrations of lead (which is toxic to human and plant life) from silicon PV in ground water, surface water, ambient air and soil are comparable to that of cadmium from CdTe. Recycling is the most sustainable manner in which modules can be handled at the end of their useful life, not only from an environmental impact perspective, but also in terms of resource efficiency. In addition, the recycling of CdTe PV offers an opportunity to decrease the primary energy demand of module manufacturing and would consequently reduce the associated energy payback period (Sinha, et al., 2012; Held, 2009).

The scale economy of growing waste streams and the decline of materials used within modules was identified by (Marwede & Reller, 2012) as two important, yet opposing aspects that will have a significant influence on the feasibility and economics of tellurium recovery in the future. Also mentioned is that the use of cadmium, as a toxic element, should require recycling despite the cost implications and that tellurium recovery should be regarded as an additional benefit. This benefit is enhanced by the fact that First Solar has demonstrated that a 99.999% refined product is achievable after recycling of the modules and that they are able to reuse this recycled product (Sinha, et al., 2012).

Environmentally sensitive metals, such as Pb, Cd, In, Ga, Se, Te, Cu and Ag, are common in the industry and therefore recycling is important for all PV technologies. In realising that the recycling of PV modules at the end of their useful 'life' will resolve any environmental concerns, as well as create an alternative Te (and Cd) resource, First Solar established the first global and comprehensive module recycling program in the PV industry in 2005. Recycling facilities are now operational in all First Solar manufacturing plants worldwide, with a total annual recycling capacity of approximately 26 000 tons (Experts, 2015). Besides the fact that recycling maximises resource recovery and increases the sustainability of PV, the socio-economic and environmental benefits of recycling are critical to minimise life cycle impacts. Inclusion of PV in the EU Waste Electrical & Electronic Equipment (WEEE) Directive is expected to yield approximately €16.5 billion in 2050 (Monier & Hestin, 2011), which would obviously create long-term economic benefits, including job creation.

First Solar's recycling process currently results in higher operating costs (compared to obtaining the semiconductor elements from the primary base metals mining industry by-product route), but the CdTe recycling process is continuously improving and the associated operational costs are decreasing. Coupled with this is the decreasing mass of semiconductor material usage per unit module (thinner PV layers), which could elevate recycled material to a primary resource level in the future. With currently over 177 GW, according to the latest Ren21 report (REN21, 2015), PV installed worldwide, recycling is crucial to managing large future PV waste volumes, and to reclaiming valuable and energy intensive materials. The First Solar modular recycle process (described below) is scalable, i.e. there would be no fundamental reason why high volumes of waste material could not be accommodated in localised recycling facilities in the future. The First Solar business objective would be to establish such 'regional / mobile' processing centres rather that to ship waste material around the globe (Experts, 2015).

3.5: Recycling process review

Recycling is the crucial 'cog' that closes the high-level loop between the manufacturing material inflow and the EOL waste material outflow, i.e. only if the recycling loop is functioning efficiently can PV become the true eco-efficient technology over the material life cycle.

After the visit to the recycling plant at the Perrysburg site and the related discussions, it was apparent that recyclability is fully integrated in the module design. The Change Management System (CMS) utilised by the actual high-tech manufacturing process is also used to track the recyclability of the manufacturing change and implement recycling process improvements.

The First Solar recycling process at the Perrysburg site has developed from a 10 t/day Version 1 (V1) batch process in 2006, to a 30 t/day Version 2 (V2) batch process in 2011. Besides the material handling improvements made to reduce erosive wear on the process equipment (by broken glass particles), in 2015 this process has now progressed to a third generation (V3) continuous process. Although still in a pilot phase, this process is more efficient and yields higher quality unrefined semiconductor material (USM) on a continuous basis.

The process consists of a number of unit operations that are relatively common to a typical metallurgical refinery: first, the EOL module scrap is reduced to a fraction of the original size in a shredder, after which the average particle size is reduced further by impact forces in a hammer mill. Although these comminution units operate dry, dust generation in the work environment is controlled by dust extraction / collection ducting to the appropriate dust collectors. The crushed particulates, consisting primarily of glass, laminate material and the semiconductor compounds are then withdrawn from a surge (holding) bin and oxidatively leached using sulphuric acid as the lixiviate and hydrogen peroxide as the oxidant. The semiconductor elements dissolve into the aqueous liquid phase, whilst the glass and laminate materials remain in the solid phase. The solid material is removed from the solution and progresses to a separation step where the encapsulation polymer lamination (film) layer and other plastic components are removed from the glass in a specific gravity float bath. The glass cullet exits through a spiral conveyer, is rinsed and then collected in a clean glass bin. The metals-bearing leaching solution progresses to a pH driven precipitation step where the Cd and Te elements are precipitated, followed by a filtration and washing step to produce the unrefined semiconductor material (USM) cake. This cake is packaged for further refining by a third party recycling partner who will again produce semiconductor grade CdTe for use in new modules. This refining process is discussed in detail in (Sinha, et al., 2012).

In terms of the current process recycling technology (described above), over 90% of the semiconductor and 90% of the glass material is recycled. About 90% of the module weight is recovered, most of it as glass, which will be reused in new glass products. The unrecovered material, i.e. the encapsulation polymer and small waste glass fraction, is handled in accordance with local waste disposal requirements, e.g. the plastics wastes could be disposed of at municipal incineration facilities whilst the inert glass waste could be safely disposed of at inert waste landfill sites. Any spillages (captured in the recycling plant bunted areas) or effluent is treated via the waste water effluent plant (discussed in the next section).

From an overall LCA perspective, the consumption of energy (electricity & transport fuel) and materials would increase the environmental impact of any PV recycling technology. Specifically to First Solar's CdTe recycling technology, recycling of one panel currently consumes around 4.4 kWh per m^2 panel (Sinha, et al., 2012).. Sulphuric acid (lixiviate), hydrogen peroxide (oxidant) and sodium hydroxide (neutralising agent) are the main chemical reagents consumed by the current CdTe recycling technology (Sinha, et al., 2012). On the other hand, environmental credits are gained in the form of the recycled CdTe, glass and Cu, which displace the primary sources of these products. The current recycling and waste water treatment routes limit Cd emissions to air and water to below 6×10^{-9} and 9×10^{-8} kg/m^3 respectively. Furthermore, to mitigate the risks associated with uncontrolled disposal, recycling is a convenient way to meet various regulatory and permit requirements (global regulatory developments will in future continue to limit PV disposal options; (Experts, 2015)).

Looking to the future, greater experience and rising disposal costs will likely result in recycling becoming economically attractive in the future. Smaller and mobile in-country recycling facilities will further reduce recycling costs by minimizing transport requirements and with operational costs expected to fall below hazardous waste disposal costs and high volume, fourth generation (V4) mobile recycling is expected to increase significantly (Experts, 2015). This, coupled with the above-mentioned socio-economic and environmental benefits, could drive the CdTe PV industry to become fully reliant on recycled end-of-life materials in the future, especially for metals like Te (Marwede & Reller, 2012).

First Solar's drive to collaborate with responsible PV EOL management in South Africa was discussed during the visit to the facility in Perrysburg (Experts, 2015) and First Solar stated that they offer recycling services in all regions of the world, including South Africa. The recycling costs will be optimised for the local market conditions but will also cover the logistic costs and the owner will always have the discretion to elect an alternate recycling vendor or responsible disposal method.

3.6: Water management (including waste water treatment)

Water consumption for the full life cycle of thermoelectric (e.g. coal and nuclear) power plants is substantial. This is especially relevant in water-scarce countries like South Africa, where dry cooling has become mandatory and has the potential to reduce the amount of water withdrawn for this purpose to some extent. In this regard, total life cycle water withdrawal per MWh is third lowest for PV (wind power and hydropower is lower; (Meldrum, et al., 2013)). Operational usage of water is related to (panel) cleaning, with relatively little consumption in the manufacturing process (approximately 1.5 litres/W produced in 2013; (First Solar, 2015)). Silicon-based PV has a higher life cycle water consumption level than CdTe due to the water needed for high-purity silicon production. The combined direct and indirect water usage for module production and preparation is 1 470 l/MWh for multi-Si compared to 575 l/MWh for CdTe. Includin power plant operation, these levels are 1 900 l/MWh for multi-Si and 800 l/MWh for CdTe. These values are at least an order of magnitude lower than that of conventional wet cooled fuel cycles such as coal (2 500 – 98 400 l/MWh) and gas fuel cycles (2 300 – 85 900 l/MWh). Of all electricity generation technologies, hydropower has the lowest withdrawal at 80 L/MWh, and that of biomass-to-electricity can be between 2 000 – 438 000 L/MWh depending on the biomass used and the conversion technology (Fthenakis & Kim, 2010).

The water usage of CdTe during the different components and life stages of the technology, i.e. module manufacturing, balance-of-system manufacturing, and maintenance as well as end-of-life activities have been determined by (Sinha, et al., 2013). The module accounted for the largest percentage of water withdrawal and activities related to end-of-life made up a very small portion of the total water withdrawal. The single largest contributor to total water consumption consists of the electricity used from the grid during module manufacturing. The production of steel used in the balance-of-system contributes second most to the total. Although comparable to the results of (Fthenakis & Kim, 2010), results obtained here are lower and estimated at a total life cycle withdrawal of 382 – 425 l/MWh. Another positive aspect of the low water withdrawal of CdTe is attained by calculating how much life cycle water withdrawal can be displaced from conventional grid electricity. This was estimated to be between 1 700 – 5 600 l/MWh (Sinha, et al., 2013). It is, of course, important to note that the location of a power plant would also influence the amount of water used due to the variation in different environmental factors such as dust and soil cover. In the same manner as technology improvements take place in order to minimise the amount of tellurium needed, it would also be valuable to the sustainability of CdTe modules in order to adapt manufacturing processes, operations and maintenance procedures to decrease the amount of water used during the technologies life cycle.

In terms of waste treatment, only the water used in the manufacturing process contains trace amounts of Cd (up to 30 mg/L Cd) prior to treatment. For this reason, no waste water leaves any of the First Solar manufacturing sites until it is treated, tested and verified as safe to discharge. The First Solar waste water process flow diagram begins at the metals water collection tank. The primary metals removal step relies on conventional metal hydrolysis by adding caustic soda, NaOH (neutralising agent), to raise the pH from about 5 to a value of 12. The resulting sodium chloride (NaCl) solution holds no environmental restrictions.

The precipitation of the solid particulates is conducted in the presence of iron(III) chloride (coagulant) and flocculent to improve the settling and filterability of the solids phase. After clarification, the underflow progresses to a filter press where the solid filter cake (containing the metals) is removed for recycling (discharged every 12 hrs). The primary filtrate is recycled to the waste water collection tank. If required, the clarifier overflow is pumped to a polishing filter (which can remove any ultra-fine particles down to 0 – 6 mg/l). First Solar also implemented ion exchange (IX) polishing technology to further reduce Cd levels to less than 0.020 mg/L (typically 0.010 mg/L). The standard metals precipitation technology (without polishing) will remove Cd to approximately 0.1 mg/L, as required by most municipalities. At First Solar's manufacturing plant in Malaysia, the waste water enters at 15 – 80 mg/l Cd and is discharged at levels as low as 0.005 mg/l Cd (Experts, 2015).

In terms of the SHE aspects related to water management, dedicated / monitored chemical storage facilities are employed, storm-water outflow is managed and no chemicals are used outside covered buildings. Bunted secondary containment of containers / vessels is also a standard feature in all the manufacturing and recycling areas. All factories are equipped with state-of-the-art analytical capabilities for 24/7 in-house water testing of Cd, Cu and other parameters such as pH (weekly composite samples are also sent to outside laboratories for analysis). Finally, all waste water systems operate in a batch discharge mode, i.e. after treatment, water is collected in holding tanks and these tanks are sampled and tested to confirm compliance with permitting limits before discharging. If not compliant, the water is sent back for re-treatment internally.

Conclusion

The First Solar thin film CdTe technology is suited for South Africa, with warmer climate areas generating a higher yield with the CdTe modules than for single or multi-crystalline silicon PV modules. Advances in the double glass CdTe module capability is allowing for the use of higher system voltages, thereby increasing the energy density and reducing the size and cost of power inverters.

The active component, CdTe, of the First Solar modules is a solid and stable compound that is insoluble in water and has a high melting point. These factors limit the potential exposure to humans and in the event of potential exposure during extreme events, CdTe is at least 8.9 times safer than Cd with respect to acute exposure via inhalation or ingestion. When considering other sources of cadmium exposure, manufacturing PV modules from CdTe should be regarded as a responsible and safe way to beneficially utilise a by-product of industrial processes. It is important to understand that during normal operation CdTe modules emit no pollutants to the air, water or soil.

CdTe PV modules also have shorter energy payback times and lower life cycle CO_2 emissions than any other PV modules and have comparable or less CO_2 emissions than nuclear and wind technologies. The impact that large-scale PV plants have on land use is better than that for coal power plants over the fuel cycle and improves with the lifetime of the plant. The specific location of a PV plant will determine the actual impact, where desert like locations will show the least amount of impact. To reduce the impact on the environment, First Solar advocates the recycling of solar PV modules.

As part of the First Solar recycling and manufacturing process, the waste water is treated to an acceptable level within their permit specifications and tested before it is released from site. The water consumption during manufacturing and operation compares favourably against other electricity generation technologies, in part because solar PV plants utilise passive cooling and this is very important in a water scarce country like South Africa.

First Solar's CdTe thin film technology modules are a technically feasible, environmentally friendly and safe option to producing electricity in South Africa.

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