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PV Module Recycling: Mining Australian Rooftops

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Abstract

The disposal of photovoltaic waste will be a major concern in the future due to the rapid growth of Australia's photovoltaic installations in the past decade. Assuming the nominal power of each solar panel is 200 W and the solar panels are retired after 20 years, more than one million used solar panels will need to be disposed from 2030 to 2034. This report studies the economic feasibility of recycling crystalline silicon based modules in Australia. The results from the proposed model indicate that economic profit up to \$0.12/W, but as low as \$0.036/W, can be expected from the recycling program based on current PV recycling technology and material market. However, the economic benefit from module recycling is sensitive to many factors, for example processing cost and value of polysilicon. The report also presents a prediction of Australia's PV recycling market in the following 20 years in terms of capacity and future potential revenue. Our model predicts that approximately 3 GW of end of life solar panels will need to be disposed after 2030. Given the potential profits and volume of material to be recycled, we predict in 2032 that module recycling will be an industry valued in the order of \$100M.

1. Introduction

Because of the negative environmental impacts of increasing use of fossil fuels, renewable energy technologies such as solar photovoltaic (PV) have emerged and been developed. PV manufacturers generally guarantee at least 80% output after 20-30 years of operation (Vazquez and Rey-Stolle, 2008). Worldwide installations of PV have been in excess of 1 GWp since approximately the year 2000. This means that by around 2020 there could be 1 GWp or 100,000 tons of PV waste to be recycled, which is growing year on year at 30 to 40%. Solar PV technologies have exponentially increasing production suggesting an equally growing future waste stream. In Australia, installations of PV modules started in the 1990s, significant expansions began from 2010 and the growth is continuing. By the end of 2014, a total Australian installed PV capacity of 4042 MW was reported (APVI, n.d.). Regarding this rapid development of the Australian PV market, it is anticipated that there will be a remarkably large amount of PV-related solid waste after 10 to 15 years, and the end-of-life management will become increasingly important. However, no policy currently exists in Australia for end-of-life management, collection, or recycling.

PV recycling is favourable because the benefits of substituting primary materials can significantly outweigh the impacts caused by processing spent modules. Recycling 1 ton of silicon-based PV modules saves up to 1.2 ton of CO_2 equivalent where the module is 100% manufactured from primary materials (Fraunhofer IBP and GaBi, 2012). In addition, production from recycled wafers saves enormous amounts of energy compared with the manufacture of modules from new wafers (BINE Information Service, 2010). Nowadays, the vast majority of PV modules (85–90% of the global annual market) are crystalline silicon (c-Si) and the c-Si PV modules are expected to remain a dominant PV technology until at least 2020 (Radziemska et al., 2010). Greater attention has been paid to recycling c-Si based PV modules due to the abundant recyclable materials contained in the modules.

This study explores the evaluation of PV recycling for c-Si modules in economic aspect regarding Australia's market. The potential economic benefit from c-Si-based PV module recycling has been estimated and sensitive parameters have been discussed - to provide local governments, potential PV recyclers and module owners a guideline. The treatment costs and recycling processes have been analysed based on current PV recycling operations in Europe, and then the potential financial return has been estimated using the proposed mathematical model. The potential economic benefit from PV recycling in the following 20 years has been estimated using Australia's PV installation data.

2. Background

2.1. Module materials

In regards to the investigation of the profit from recycling a PV module, a very important issue is the correct identification of the materials used in module production. Most PV modules in c-Si solar cells consist of the following elements: a transparent top surface, an encapsulant, a rear layer, junction box, metal electrode, copper wires, assembly bolts and a frame around the outer edge. The structure of a conventional bulk silicon module is shown in Figure 1. The top surface is mostly commonly made from tempered, low iron-content tempered glass due to its properties including low cost, strength, stability, transparency and resistance to water and gases. Ethylene vinyl acetate (EVA) is mostly used make an encapsulant to provide adhesion between solar cells, top surface and back surface of PV modules. This sandwich structured layers are then heated to 150 °C to polymerize the EVA and bond the module together (Honsberg and Bowden, n.d.). A thin Tedlar polymer sheet is commonly used as the protective rear surface, and a screen printed silver paste is applied as electrodes for current carrying on the front of solar cells. In regards to the process of manufacturing PV modules, single solar cells are laminated once the n-p connector layer is formed. This implies that recycling process requires thermal treatment to disassemble solar panels. In the final step of PV module production, modules are mounted in aluminium frames and junction and a junction box is installed on each module. In some solar panels manufactured in earlier years, lead soldering was used in the assembly of solar cells; however, lead-free soldering has been applied in recent years.

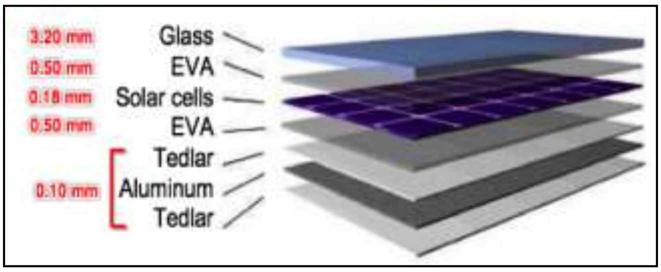

Figure 1 Typical crystalline silicon module structure (*Paggi et al., 2013*)

2.2. PV module recycling technology

The recycling process of c-Si modules offered by PV CYCLE, a European based recycling company, consists of five major stages: separation of frames and junction boxes, shredding panels, high-temperature treatment, automatic separation and chemical bath (PV CYCLE, n.d.), as shown in Figure 2. An automatic conveyor system is utilized in the recycling process to transport materials. Firstly, junction boxes, cables and aluminium frames are manually removed. The second process carried out in the recycling is crushing and shredding the modules. The module pieces and removed junction boxes and cables on the conveyor belt are then manually sorted to ensure appropriate separation. A thermal process is applied to separate laminated silicon cells from EVA encapsulation and Tedlar layer. The Tedlar and EVA layers can be burned off, and glass cullet and pure ferrous metals from metal electrodes and copper cables are obtained from the automatic sorting process. The plastics can be also thermally recovered with appropriate temperature control but this may increase the cost. The high recovery rate is achieved by using efficient refining and sorting systems, such as light sensitive sorting technique. The final stage in PV module recycling is the chemical treatment of the solar cell. In order to recover the silicon powder or pieces for reproduction of new solar cells, the following operations in a specific order are required: removal of front and bottom metal coating, and etching off antireflective coating and n–p junction (Radziemska and Ostrowski, 2010). The recovery of silicon is operated in acidic or alkaline solutions. The researchers have found that a nitric acid treatment combined with immersion in caustic soda could produce silicon with a purity of 99.98% (Yi et al., 2014). The results from current research have shown that the recovery rate of chemically treated silicon cells is approximately 80% in average and up to around 90% (Radziemska and Ostrowski, 2010). The metals contained in solar cells are dissolved in the acid solution, and silver can be recovered by electrolysis from the waste acids (Radziemska and Ostrowski, 2009). The recovered valuable materials, like glass cullet, aluminium frames, copper wires and silicon flux can be sent to secondary processers for new products or for the production of new solar panels. However, the environmental issues caused by the emissions from burning plastics and the chemical solutions should be considered.

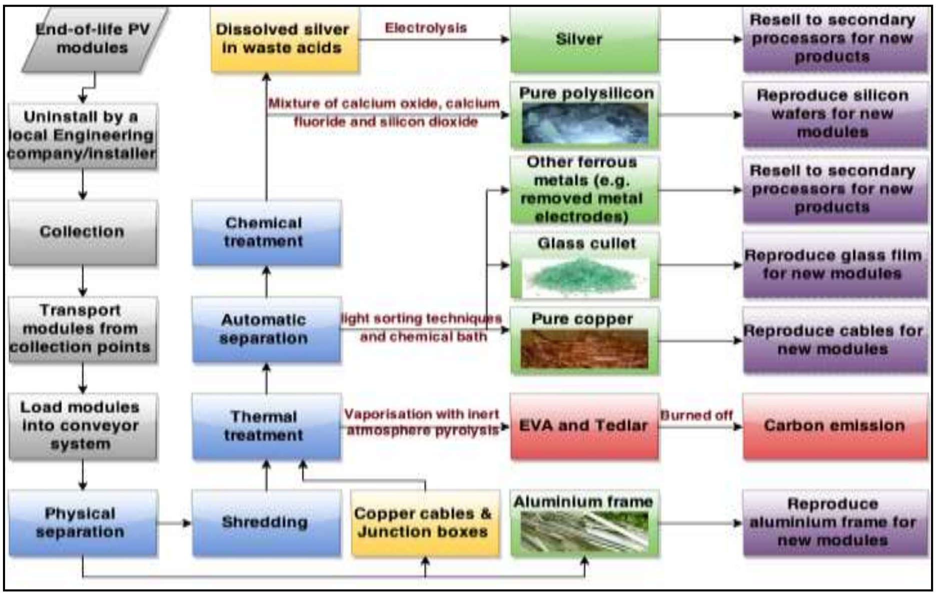

Figure 2 Crystalline PV module recycling process

3. Methodology

Commercial viability is the economic motivation of potential PV recyclers. A model has been proposed in order to investigate the net profit from recycling c-Si PV modules in Australia in two separate aspects: the net profit of recycling each solar panel for the current Australian market, and the potential financial return in the future. Detailed revenue calculations and input parameters can be separately found in Appendix 1 and 2.

The profit of recycling PV modules is mainly from the refined materials, including metals, glass and polysilicon. The total material profit (P_m) can be calculated using the following equation:

$$P_m = P_{Si} + P_{Cu} + P_{Al} + P_{Ag} + P_{Glass}$$

where P_{Si}, P_{Cu}, P_{Al}, P_{Ag} and P_{Glass} are the profits from recycled silicon, copper, aluminium, silver and glass, respectively. It is notable that the silver usage in c-Si solar cells has been significantly decreased in recent years. To estimate the average mass of silver per module in current PV installations, an average mass over the last five years has been calculated taking into account both the reduced silver consumption, and the changing installations with time. The economic benefit from recycling typical 250W and 150W solar panels (specifications are shown in Appendix 2) are separately estimated using the model to minimise the errors due to different material contents in various solar panels categorised by nominal power, and the panels are assumed having the same structure as shown in Figure 1. Previous study by European researchers has shown that a 22 kg c-Si module contains approximately 12.7 g lead (BIS, 2011). Thus, it can be assumed that the 150W (12kg) and 250W (21.2kg) solar panels contain 6.4g and 12.7g lead, separately.

The other potential economic benefit from diverting modules from landfills is also considered. The total avoided extra landfill charge (C_{ext}) can be found as:

$$C_{ext} = C_{ext\_landfill} + C_{ext\_lead}$$

where $C_{ext\_landfill}$ and C_{ext_lead} are the disposal cost of landfill and lead leaching. The landfill levies are different throughout Australia and the rates in Victoria, South Australia (SA) and Western Australia (WA) are less (ABS, 2006). Australia's maximum landfill levy rate of \$133.8/ton in Australia Capital Territory (ACT Government, n.d.) and minimum rate of \$23.5/ton in SA regional areas (RICARDO-AEA, 2013) are utilised for the calculation of maximum and minimum NP, respectively. The cost of landfills is an external cost saving if the PV modules are recycled instead of landfilled only when the local government bans modules from landfill. In regards to lead disposal, although there is no levy rate of lead leaching and carbon tax set by the Australian Government, the financial analysis here is intending to price the pollution from released lead and carbon emission. The cost of lead releasing, 1.174 Euros per gram, was found from the analysis for the European recycling market (BIS, 2011). In addition, the currency exchange rates 1 EURO = 1.45 AUD and 1 USD = 1.37 AUD are applied to unify currency of the prices found from different resources. It has been found that 13% to 90% of the lead can be released to the environment (BIS, 2011) and a lead leaching rate of 90% has been applied in calculations. Thus, the expenses on disposal of lead leaching (C_{ext_lead}) can be calculated using given lead consumption in kg for each solar panel and the levy rate in \$/kg.

The treatment costs ($C_{treatment}$) of recycling PV modules used for the Australian market are the data transferred from the current recycling costs under European background given by PV CYCLE's financial report in the time period between 2011 and 2013, shown in Appendix 2.

Any expenses on labour, establishment of recycling centres, processing old PV modules, and etc. during the entire recycling process have been taken into account. The model assumes that all of the EVA encapsulant, Tedlar layer and any other plastic components are burned off during the recycling procedure and the only output is carbon dioxide, the cost of disposing carbon emissions is hence moreover regarded in this model. Thus, the total costs (C_{total}) can be known as:

$$C_{total} = C_{treatment} + C_{carbon}$$

In summary, the net profit (NP) can be calculated using the following equation:

$$NP = P_m + C_{ext} - C_{total}$$

$$= P_{Si} + P_{Cu} + P_{Al} + P_{Ag} + P_{Glass} + C_{ext\_landfill} + C_{ext\_lead} - C_{treatment} - C_{carbon}$$

4. Economic evaluation

4.1. Cost-profit analysis

Table 1 outlines the potential costs and profits of recycling a 150W and a 250W PV module under the best and worst scenarios. The average net profit is approximately \$0.12/W for the best scenario and approximately \$0.04/W for the worst scenario. The best scenario gives the maximum potential net profit due to the economic profit from higher extra cost saving and zero cost of carbon emission. The extra costs include the maximum landfill levy and lead disposal cost in the best scenario, whereas the minimum landfill levy is assumed to be the only extra cost saving in the worst scenario. However, the net profit given by the worst scenario may be closer to the actual profit that can be obtained from recycling a module for an Australian recycler, as the lead disposal is not charged in Australia and the recyclers cannot save the cost by recycling modules. Although the involved parameter, carbon tax, has been cancelled by the Australian Government, the estimated cost of carbon disposal, less than ¢10/module, has been neglected.

Table 1 Costs and profits of recycling 150W and 250W PV modules

	150W		250W	
	Best	Worst	Best	Worst
P_{Al} (+)	\$3.6/module		\$5.4/module	
P_{glass} (+)	\$1/module		\$1.9/module	
P_{cu} (+)	\$1.5/module		\$1.8/module	
P_{Ag} (+)	\$4.4/module		\$7.4/module	
P_{si} (+)	\$8.1/module		\$13.5/module	
P_m (+)	**\$18.6/module**		**\$30/module**	
$C_{treatment}$ (-)	\$12.7/module		\$22.5/module	
C_{carbon} (-)	0	\$0.04/module	0	\$0.1/module
C_{ext_lead} (+)	\$9.7/module	0	\$19.4/module	0
$C_{ext\_landfill}$ (+)	\$1.6/module	\$0.3/module	\$2.8/module	\$0.5/module
NP	**\$17.2/module (\$0.115/W)**	**\$6.1/module (\$0.041/W)**	**\$29.7/module (\$0.119/W)**	**\$7.9/module (\$0.032/W)**
Average NP	**Best \$0.117/W, Worst \$0.036/W**			

4.2. Sensitivity analysis

The selling price of each material contained in a PV module and the processing costs were found from various sources and given for different time periods. The inconsistent data source may result in inaccurate calculation results. The sensitivity analysis shown in Figure 3 performs the variation of the average net profit with the price fluctuation of input parameters under the best scenario, where the baselines are the calculated average net profit in Table 1. Besides the input parameters of the calculation, the influence of wafer thickness, silver content and lead content on the average profit is also investigated. The red and green colours separately represent the increase and decrease of input data and each layer indicates a fixed scaling factor. The darker the colour, the scale is larger. The darkest green indicates the scenario that the input value of the parameter is zero. The height of columns represents the sensitivity of each parameter. Higher columns mean more sensitive parameters to the net profit. The blue lines represent the range of prices from the 20-year historical data. It can be observed that treatment cost is the most sensitive parameter. The negative trend means the net profit drops as the treatment cost rises. Lead disposal cost, treatment cost and lead content are very sensitive to the net profit, while the value of refined glass and copper and the landfill levy are the least sensitive parameters. Moreover, it can be observed that profit scales equally with variations in either value of material content or price.

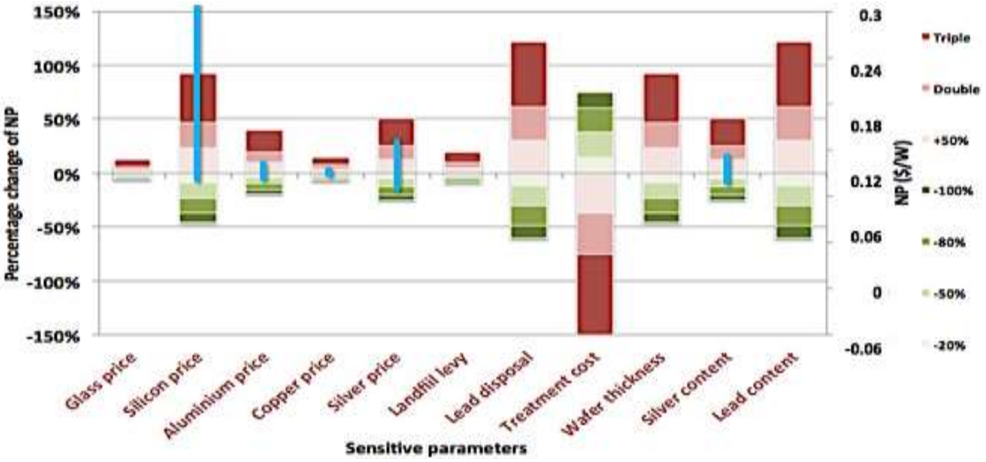

Figure 3 Sensitivity analysis for the best scenario

4.3. Comparative analysis

This section is to compare the proposed model with the models provided by McDonald et al. and BIS. Table 2 presents a comparative analysis for three calculation methods: Method 1 is the model given by McDonald and Pearce (2010), Method 2 is the model designed by BIS for the European market (BIS, 2011), and Method 3 is the model proposed for the Australian market in this report. The results shown in the table are calculated using the three models with updated Australian data, which means the values of input parameters involved in the three methods, such as material values, landfill levies, treatment cost and specifications of the module, are consistent. However, it can be observed that the results given by the three models are very different due to dissimilar assumptions.

Regarding Method 1, it was assumed that 100% of the glass and 60% of the silicon in the frameless PV modules can be recovered and the profits from the other recycled materials are neglected, which explains the reason that the estimated material profit using Method 1 is lower compared with the values from the other two methods. Although fewer types of materials were assumed recycled in Method 2 compared with in Method 3, the material profit given by Method 3 is lower. This is because Method 2 assumed a silver content of 0.3g/W contained in solar cells, which is much higher than the assumed value of 0.19g/cell (approximately 0.05g/W) in Method 3. The assumed thickness of silicon wafer (0.02cm) and glass layer (0.64cm) is larger in Method 1 compared with the values (0.018cm silicon wafer and 0.32cm glass layer) in Method 2 and 3, which results in a higher module mass and hence more costs of module treatment. The avoided cost in Method 1 and 2 included the cost of landfill disposal and the treatment of soil pollution caused by lead release, respectively. In Australia, landfills are charged for the land occupancy and carbon emission rather than soil pollution. Thus, the cost of lead disposal is considered for Australian market in Method 3 in order to price the potential soil pollution. In Method 2, the cost of landfill disposal is not considered and hence there is only one scenario involved. The values of net profit calculated from the three methods are hence different due to the difference of profits and costs in calculations. The consolidated result given by Method 2, a positive economic profit of $0.21/W, is much higher than the net profits calculated from Method 1 and Method 3. It is clear that the profit from recovered metals is significant for a PV recycling program.

Table 2 Comparative analysis of the three mathematical models with updated Australian data

	Method 1 [min, max]	Method 2	Method 3 (This work) [min, max]
P_m (+)	Glass, silicon	Glass, aluminium, silver	Glass, aluminium, silver, copper, silicon
	$0.07/W	$0.23/W	$0.12/W
C_{total} (-)	Recycling + Logistics	Recycling + Logistics	Recycling + Logistics + Carbon emission
	$0.1/W	$0.087/W	$0.088/W, $0.087/W
C_{ext} (+)	Landfills	Soil pollution	Soil pollution, landfills
	$0.003/W, $0.015/W	$0.07/W	$0.002/W, $0.082/W
NP	**-$0.04/W, -$0.05/W**	**$0.21/W**	**$0.04/W, $0.12/W**

4.4. Prediction of future PV recycling profit

Figure 4 represents the forecast of potential profit under the best and worst scenario from PV recycling in the time period of 2021 and 2034. The data has been predicted based on the estimated recycling capacity, the calculated average net profit values, as well as an assumption of 20-year lifespan. In 2032, when the peak recycling capacity will appear, a profit of approximately $30 million will be obtained under the worst scenario and about $100 million under the best scenario. However, the uncertainties are significant in the prediction. The applied net profits were calculated based on the historical silver consumption data from 2010 to 2014. The higher silver content for the earlier solar cell production will lead to and underestimation potential profits in 2021-2029, as modules from 2010 to 2014 are due to be recycled in 2030-2034.

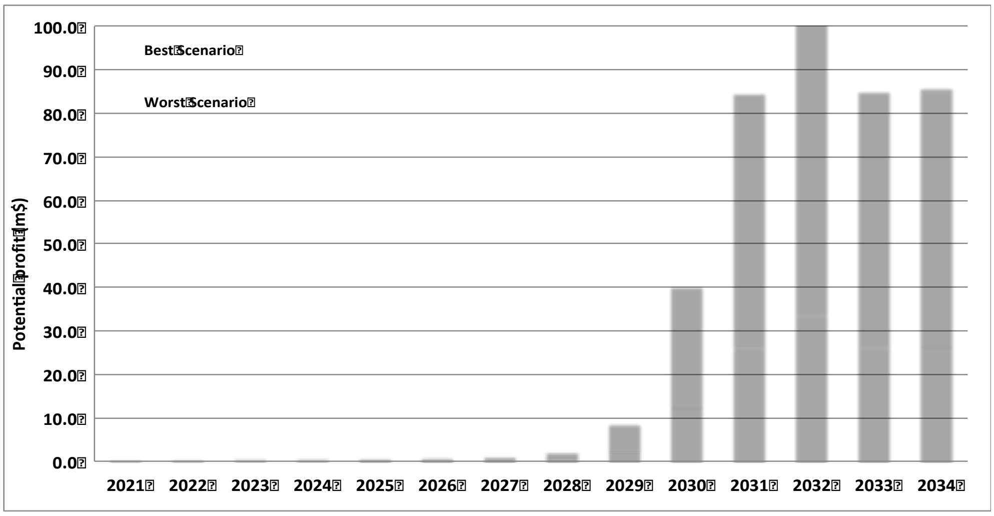

Figure 4 Market potential profit from PV recycling in the 2021-2034 time horizon

4.5. Discussion

The treatment cost of PV recycling utilised in calculations was assumed to be the average cost coming from PV CYCLE's financial reports for the three financial years from 2011 to 2013. The costs included the processing fees, the expense of collection services, labour costs and assets, as well as the investment for building collection centres. However, it might be inaccurate to directly transfer the costs in European market to Australian market. Since Australia has a large land area and small populations, fewer recycling centres and collection points may be needed in Australia but the logistics cost may be higher.

In the previous calculations, the wafer thickness of 0.18mm and silver content of 0.19g/cell were assumed based on the data for solar cell design from 2010 to 2014. The International Technology Roadmap for PV (ITRPV, 2012; ITRPV, 2014; ITRPV, 2015) shows that the wafer thickness and the amount of silver consumption decrease with the development of PV technology, which means recycling the PV modules produced before 2010 may obtain more silicon and silver. As the useful life of solar panels is 20-30 years, the results calculated based on 2010-2014 data may be more accurate for the prediction of the recycling profit in the 2030-2044 horizon. In Australia, much less quantity of waste may be processed before 2030 but with higher financial return for recycling per unit c-Si PV. The situation may be opposite after 2030 because of the growth of PV installation in recent years as well as the reduction in material usage, for example thinner silicon wafers and less silver consumption in current c-Si solar cell production. Also, lead-free solar panels have been considered in many PV industries due to the concerns of environmental issues caused by lead release. Once lead-free solar cells are broadly applied, landfilling PV waste may be economically comparable if the cost of landfill disposal is lower than recycling expense. However, Australia's landfill levies tend to increase in the future. The Western Australian Government announced a plan to raise the landfill levy from $28/ton for putrescible waste and $8/ton for inert waste in 2014 to a putrescible and inert rate of $70/ton until 2019 (WA Government - DER, n.d.).

Moreover, the economic profit from PV recycling is strongly sensitive to the market value of materials as mentioned in the sensitivity analysis. As the actual economic benefit from PV recycling is dependent on various parameters including material values, design of solar cells and local regulations for waste management, the potential profit is difficult to predict. It is also notable that the annual potential revenue in this time period would be varied with the assumption of solar modules’ life expectancy. In order to improve the economic efficiency, the lifespan of modules may be enhanced to 30 to 40 years in the future with the staggering development of PV technologies. Although this would lead to a delay of solar panels in reaching the EoL stage, the total amount of waste and recycling revenue may not be affected.

5. Conclusions and future work

This report studied the feasibility of c-Si PV recycling by estimating the potential economic profit from the recycled PV modules based on Australian data and legislations. It can be found from the results that recycling solar panels in Australia may be economically feasible with the support of appropriately settled regulations and legislations. Nevertheless, the financial return cannot be precisely predicted for the future recycling market due to the unpredictable materials’ market price and unknown material contents for producing solar cells in the earlier years before 2010. Significantly reduced expense for the recycling of EoL modules and higher extra cost savings from increased landfill levies can be expected in the future. This primarily depends on the development of recycling technology at certified waste disposal companies, and furthermore on the political support by local councils and governments. The analysis showed that mentionable quantities of PV-related waste would occur from around 2029. Therefore, the Australian Government will have sufficient time to prepare for the management of EoL PV disposal.

The future work, such as investigating the management of chemicals, analysing the possibilities of shipping treated module pieces overseas, and studying the disposal of non-silicon based solar panels, should be also implemented. The current technology requires substantial amount of acid and alkaline liquid to recover silicon and to extract silver. Thus, appropriate management of waste chemicals needs to be considered. Shipping module pieces to developing countries may be another disposal option. A financial analysis is needed to compare PV recycling and sending modules overseas. Moreover, the application of thin-film PV technology has been broader in recent years, which means larger quantities of non-silicon PV modules will need to be disposed in the future. A feasibility study of recycling non-silicon based solar panels is hence desired. The study may also involve the difference of disposal requirement for silicon and non-silicon based modules in order to investigate an approach which can recycle old modules composed of both silicon and non-silicon solar cells.

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Appendix 1—Revenue calculations

Step 1. Material Profit

Material profit (Pm) is determined by adding up the value of each material that can be recovered from the recycling processes. The parameters involved in the estimation of the profit from recycled materials include mass, unit price of raw materials as well as recycling rate.

Aluminium Frame

The mass of aluminium fame is given by

$$P_{Al}\ (\$/module) = T_{Al} \times A_{Al} \times \rho_{Al} \times V_{Al}$$

where T_{Al} is the thickness of aluminium frame, A_{Al} is the total cross-section area of frames, ρ_{Al} is the density of 6063 aluminium alloy, and V_{Al} is the recent value of aluminium in international metal market.

Glass Film

The area of glass cover can be calculated using geometric method as follows

$$A_{glass} = (L_{module} - 2 \times T_{Al}) \times (W_{module} - 2 \times T_{Al})$$

where L_{module} is the length of module and W_{module} is the width of module.

Therefore, the profit is found to be

$$P_{glass} = T_{glass} \times A_{glass} \times \rho_{glass} \times V_{glass}$$

where T_{glass} is the thickness of glass layer, A_{glass} is the area of front glass, ρ_{glass} is the density of solar glass and V_{glass} is the value of refined glass in Australia.

Copper Cables

The profit from recycling copper cables can be calculated using

$$P_{cu}\ (\$/module) = \pi \times r^2 \times L_{cu} \times \rho_{cu} \times N_{cu} \times V_{cu}$$

where r is the radius of copper cables, L_{cu} is the length of copper cables, ρ_{cu} is the density of copper, N_{cu} is the number of copper cables, and V_{cu} is the value of copper in international metal market.

Silicon Wafers

The profit of recovered solar cells can be given by

$$P_{si}\ (\$/module) = A_{si} \times N_{si} \times T_{si} \times \rho_{si} \times R_{si} \times V_{si}$$

where A_{si} is the area of each solar cell, N_{si} is the number of solar cells in a module, T_{si} is the thickness of solar cells, ρ_{si} is the density of silicon, R_{si} is the recovery rate of silicon cells, and V_{si} is the value of raw crystalline silicon.

Silver Contact

The profit from recycled silver can be estimated using

$$P_{Ag}\ (\$/module) = R_{Ag} \times M_{Ag} \times N_{cell} \times V_{Ag}$$

where R_{Ag} is the recovery rate of silver, M_{Ag} is the mass of silver consumption to produce one solar cell, and N_{cell} is the number of solar cells in the module, and V_{Ag} is the recent value of silver in international metal market.

Total Profit

The total profit from refined materials can be found using

$$P_m = P_{si} + P_{cu} + P_{Al} + P_{Ag} + P_{glass}$$

Step 2. Avoided Cost

The cost of landfill disposal ($C_{ext\_landfill}$) and lead leaching (C_{ext_lead}) can be avoided by a recycling program. The avoided extra landfill charge can be found as

$$C_{ext\_landfill} = M_{module} \times R_{landfill}$$

where M_{module} is the mass of a PV module, and $R_{landfill}$ is the landfill levy rate.

It has been found that 13% to 90% of the lead can be released to the environment (BIS, 2011) and 90% of the lead is assumed to release to soil. The avoided cost of soil disposal due to lead leaching can be calculated as follows

$$C_{ext\_lead} = 90\% \times M_{lead} \times R_{lead}$$

where M_{lead} is the mass of lead contained in a PV module, and R_{lead} is the levy rate of lead releasing.

Hence, the total avoided cost is

$$C_{ext} = C_{ext\_landfill} + C_{ext\_lead}$$

Step 3. Recycling Cost

Treatment processes of PV modules considered in the model include recycling of PV modules, recovery of silicon cells. The model assumes that all of the EVA encapsulant, Tedlar layer and any other plastic components are burned off during the recycling procedure and the only output is carbon dioxide. The cost of disposing carbon emissions is hence regarded in this model.

Treatment Cost

The cost of module recycling processes can be given as

$$C_{treatment} = M_{module} \times R_{treatment}$$

where $R_{treatment}$ is the rate of treatment cost in dollars per kilogram, and M_{module} is mass of each module.

Cost of Carbon Disposal

Although the carbon tax has been cancelled by the Australian Government, the disposal of carbon emissions is priced in the model in case that the carbon tax is back in the future. It has been found that every 1 kg of plastic burned produced approximately 2 kg of carbon dioxide (Sonnemann et al., 2003). Therefore, the amount of released carbon dioxide can be estimated from the mass of plastic components contained in a PV module. The plastic components considered in the model are the EVA encapsulant and the Tedlar layer. Therefore, the mass of plastics in a solar panel can be calculated using

$$M_{plastic} = T_{eva} \times A_{glass} \times \rho_{eva} \times N_{eva} + T_{tedlar} \times A_{glass} \times \rho_{tedlar}$$

where T_{eva} is the thickness of EVA encapsulant, ρ_{eva} is the density of EVA, N_{eva} is the number of EVA layers, T_{tedlar} is the thickness of backsheet, and ρ_{tedlar} is the density of Tedlar.

The cost of carbon emissions for each module can be known using the following formula

$$C_{carbon} = 2 \times M_{plastic} \times T_{carbon}$$

where T_{carbon} is carbon tax in units of $/kg.

The total cost of recycling the module is found as

$$C_{total} = C_{treatment} + C_{carbon}$$

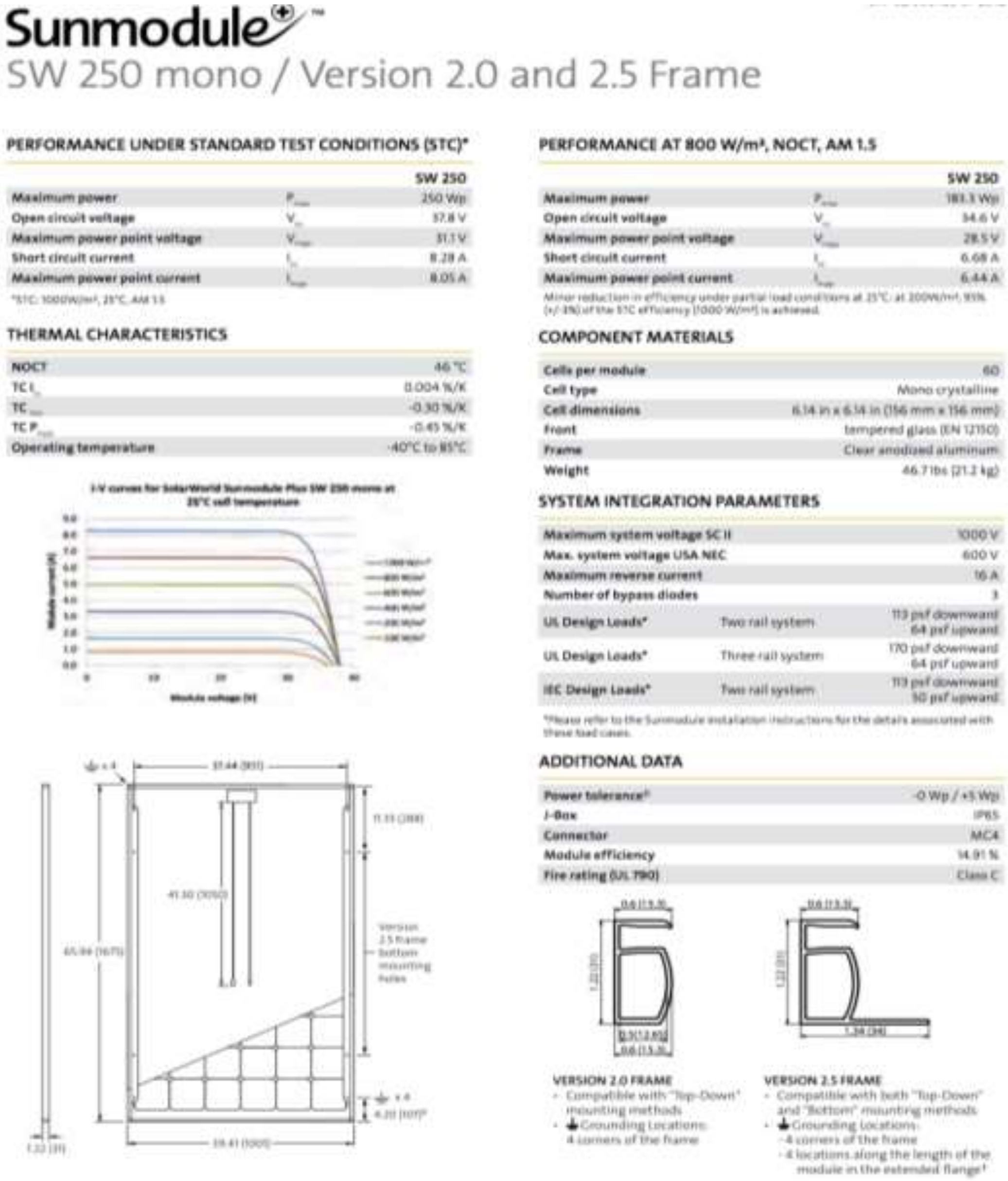
The model assumes the cost of recycling processes in Australia is the same as in Europe.

Step 4. Net Profit

The best and worst scenario of recycling the module can be found as

$$NP = P_m + C_{ext\_landfill} + C_{ext\_lead} - C_{treatment} - C_{carbon}$$

Appendix 2—Revenue calculation inputs



Sunmodule

SW 250 mono / Version 2.0 and 2.5 Frame

PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

		SW 250
Maximum power	P_{max}	250 Wp
Open circuit voltage	V_{oc}	37.8 V
Maximum power point voltage	V_{mpp}	31.1 V
Short circuit current	I_{sc}	8.28 A
Maximum power point current	I_{mpp}	8.05 A

*STC: 1000W/m², 25°C, AM 1.5

THERMAL CHARACTERISTICS

NOCT	46 °C
TC I_{sc}	0.004 %/K
TC V_{oc}	-0.30 %/K
TC P_{mpp}	-0.45 %/K
Operating temperature	-40°C to 85°C

PERFORMANCE AT 800 W/m², NOCT, AM 1.5

		SW 250
Maximum power	P_{max}	183.3 Wp
Open circuit voltage	V_{oc}	34.6 V
Maximum power point voltage	V_{mpp}	28.5 V
Short circuit current	I_{sc}	6.68 A
Maximum power point current	I_{mpp}	6.44 A

Minor reduction in efficiency under partial load conditions at 25°C: at 200W/m², 95% (+/-3%) of the STC efficiency (1000 W/m²) is achieved.

COMPONENT MATERIALS

Cells per module	60
Cell type	Mono crystalline
Cell dimensions	6.14 in x 6.14 in (156 mm x 156 mm)
Front	tempered glass (EN 12150)
Frame	Clear anodized aluminum
Weight	46.7 lbs (21.2 kg)

SYSTEM INTEGRATION PARAMETERS

Maximum system voltage SC II		1000 V
Max. system voltage USA NEC		600 V
Maximum reverse current		16 A
Number of bypass diodes		3
UL Design Loads*	Two rail system	113 psf downward 64 psf upward
UL Design Loads*	Three rail system	170 psf downward 64 psf upward
IEC Design Loads*	Two rail system	113 psf downward 50 psf upward

*Please refer to the Sunmodule installation instructions for the details associated with these load cases.

ADDITIONAL DATA

Power tolerance[2]	-0 Wp / +5 Wp
J-Box	IP65
Connector	MC4
Module efficiency	14.91 %
Fire rating (UL 790)	Class C

VERSION 2.0 FRAME
- Compatible with "Top-Down" mounting methods
- Grounding Locations:
  4 corners of the frame

VERSION 2.5 FRAME
- Compatible with both "Top-Down" and "Bottom" mounting methods
- Grounding Locations:
  - 4 corners of the frame
  - 4 locations along the length of the module in the extended flange[1]

Figure 5 Specification sheet of studied 250 W solar panel

MODEL: GS-S-150-Fab36

High Efficiency Mono-crystalline
Photovoltaic Module

Grape Solar™
Clean Power. Today.

c UL us LISTED

Overview

- High efficiency solar cells (approx. 19%) with quality silicon material for high module conversion efficiency and long term output stability and reliability.
- Rigorous quality control to meet the highest international standards.
- High transmittance, low iron tempered glass with enhanced stiffness and impact resistance.
- Unique frame design with strong mechanical strength for easy installation.
- Advanced encapsulation material with multilayer sheet lamination to provide long-life and enhanced cell performance.
- Outstanding electrical performance under high temperature and weak light environments.

Applications

- Any large or small on-grid /off-grid solar power stations.
- Commercial/industrial building roof-top and ground systems.
- Residential roof-top and ground systems.

Warranty

- 10 year limited product warranty on materials and workmanship.
- 25 year warranty on >80% power output and 10 year warranty on >90% power output.
- Refer to warranty document for detailed warranty information.

Certifications

- ETL UL-1703 ISO 9000:2000
- CE TUV IEC61215 IEC61730

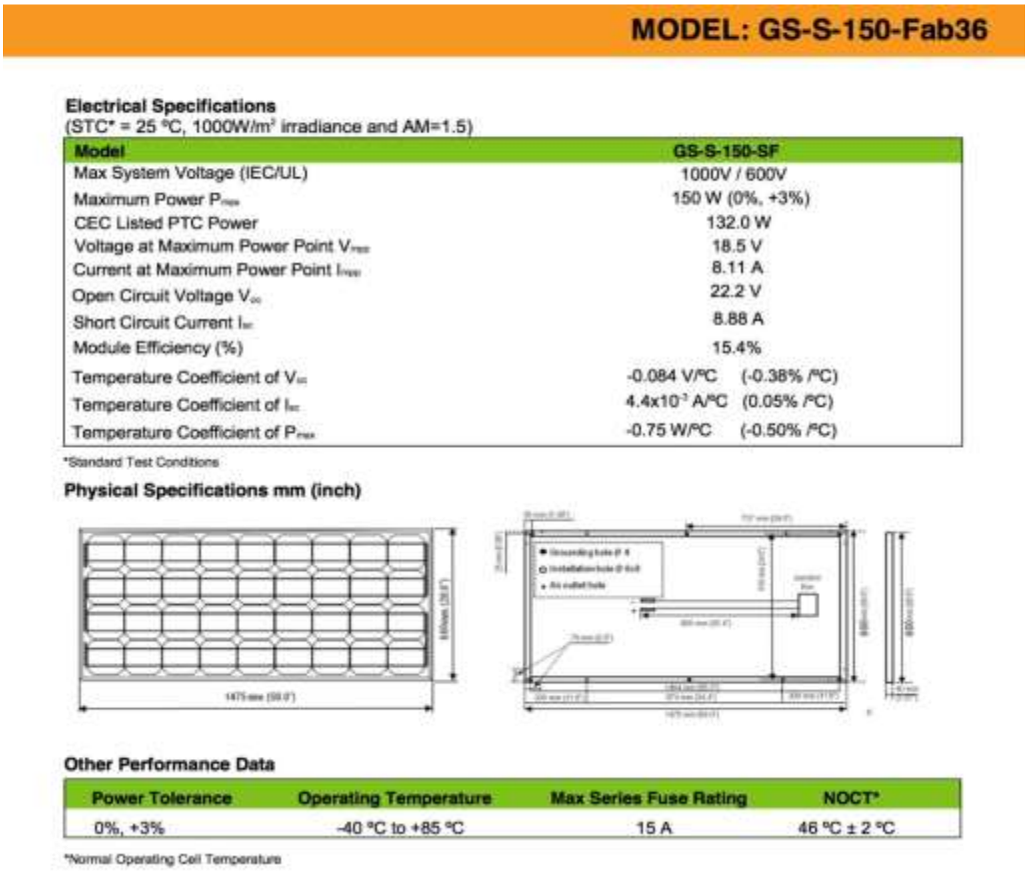
ISO CE

Mechanical Specifications

Characteristic	Details
Cell Size	156mm x 156mm (6.14” x 6.14”)
Module Dimension (L x W x T)	1474mm x 660mm x 40mm (58.0” x 26.0” x 1.57”)
No. of Cells	4 x 9 = 36
Weight	12.0 kg (26.4 lbs)
Cable Length	900mm (35.4”) for positive (+) and negative (-)
Type of Connector	Tyco
Junction Box	IP65 or IP67 Rated
No. of Holes in Frame	8 draining holes, 8 installation holes, 2 grounding holes

Rev.01• 0911

Figure 6 Specification sheet of 150 W solar panel (part 1)



MODEL: GS-S-150-Fab36

Electrical Specifications
(STC* = 25 °C, 1000W/m^2 irradiance and AM=1.5)

Model	GS-S-150-SF
Max System Voltage (IEC/UL)	1000V / 600V
Maximum Power P_{max}	150 W (0%, +3%)
CEC Listed PTC Power	132.0 W
Voltage at Maximum Power Point V_{mpp}	18.5 V
Current at Maximum Power Point I_{mpp}	8.11 A
Open Circuit Voltage V_{oc}	22.2 V
Short Circuit Current I_{sc}	8.88 A
Module Efficiency (%)	15.4%
Temperature Coefficient of V_{oc}	-0.084 V/°C (-0.38% /°C)
Temperature Coefficient of I_{sc}	4.4x10^{-3} A/°C (0.05% /°C)
Temperature Coefficient of P_{max}	-0.75 W/°C (-0.50% /°C)

*Standard Test Conditions

Physical Specifications mm (inch)

Other Performance Data

Power Tolerance	Operating Temperature	Max Series Fuse Rating	NOCT*
0%, +3%	-40 °C to +85 °C	15 A	46 °C ± 2 °C

*Normal Operating Cell Temperature

Figure 7 Specification sheet of 150 W solar panel (part 2)

Table 3 Input parameters for 150W and 250W PV modules

Sources: (a) Grape Solar, n.d. (b) SolarWorld, n.d.

	150W PV module [a]	250W PV module [b]
Module Dimension	1474mm×660mm×40mm	1650mm×992mm×40mm
Cell size	156mm×156mm	156mm×156mm
M_{module}	12 kg	21.2 kg
N_{cell}	36	60
W_{per_cell}	4.17 W	4.17 W
L_{cu}	0.9 m	1.05 m
M_{lead}	6.4 g	12.7 g

Table 4 shows the input data related to the components used in PV modules. The column Market price includes recent value of aluminium, refined glass, copper, silver and polysilicon, as well as the maximum and minimum values found from the 20-year historical data. The glass price is assumed constant. It can be observed that the silver price is much higher than the value of the other materials, and the price of polysilicon has experienced a tremendous variation in the past 10 years.

Table 4 Input data

Sources: (a) SolarWorld, n.d. (b) Atlas Steels, 2013 (c) BIS, 2011 (d) Index Mundi, n.d. (e) Green Rhino Energy, n.d. (f) NetBalance, 2013 (g) The Engineering ToolBox, n.d. (h) International Copper Association, 2014 (i) Index Mundi, n.d. (j) Yi et al., 2014 (k) BullionVault, 2015 (l) ITRPV, 2015 (m) Royal Society of Chemistry, n.d. (n) Radziemska and Ostrowski, 2010 (o) Ciszek, 2014 (p) Paggi et al. 2013 (q) TOTAL, n.d. (r) ITRPV, 2012

	Quantity	Thickness/ Radius (mm)	Density (kg/m^3)	Recovery rate (%)	Market price ($/kg)		
					Recent	Maximum	Minimum
Aluminium frame	1	1.35[a]	2700[b]	100[c]	2.42[d]	3.74[d]	1.69[d]
Glass layer	1	3.2[a]	2500[e]	95[f]	0.15[f]		
Copper cable	2	2[a]	8940[g]	100[h]	7.5[i]	10.56[i]	2.17[i]
Silver				100[j]	650[k]	1426[k]	219[k]
Silicon wafer		0.18[l]	2329[m]	80[n]	27.5[l]	652.5[o]	23.3[o]
EVA layer	2	0.5[p]	930[q]	0			
Tedlar layer	1	0.1[p]	1500[r]	0			

It is clear from Table 5 that the silver usage in c-Si solar cells has been significantly decreased in recent years, while the annual installed capacity shows a different trend which increased to a peak value of 841 MW/year in 2012 and then dropped to 545 MW/year in 2014. Therefore, to estimate the average mass of silver/module in current PV installations, an average mass over the last five years has been calculated taking into account both the reduced silver consumption, and the changing installations with time. It is assumed that 90% of the installed PV modules consist of 4.17 W c-Si solar cells shown in Table 3. In order to reduce the effect of the data set with extremely high silver content but very low PV installation or vice versa, the affected factor, $(M_{Ag\_h} \times C_{pv})/114$, where 114 is the average value of $M_{Ag\_h} \times C_{pv}$ for the five years, has been applied for the estimation of silver content for each year. The value utilised in the calculation of net profit is 0.19g/cell, which is the average of silver consumption for c-Si cell production from 2010 to 2014.

Table 5 Estimation of Silver Content

Sources: (a) ITRPV, 2012 (b) APVI, 2014 (c) ITRPV, 2015

	Silver content M_{Ag_h} (g/cell)	Annual PV installation C_{pv} (MW)[b]	$M_{Ag\_h} \times C_{pv}$	Affected factor F_a $(M_{Ag\_h} \times C_{pv})/114$	Estimated amount of recycled silver $(F_a \times M_{Ag\_h})$ (g/cell)
2010	0.3[a]	310	93	0.8	0.2
2011	0.25[a]	653	163	1.4	0.3
2012	0.2[a]	841	168	1.4	0.3
2013	0.14[c]	656	92	0.8	0.1
2014	0.1[c]	545	54	0.5	0.04
Average			114		0.19

Table 6 PV CYCLE annual financial data

Sources: (a) PV CYCLE, 2012 (b) PV CYCLE, 2013 (c) PV CYCLE, 2014

	2011[a]	2012[b]	2013[c]
Processed modules (tonnes)	1,400	3,700	3,067
Total costs (k$)	1660	2764	3826
Average cost ($/tonne)	1186	747	1247
Net profit (k$)	1.9	773	-467
Average net profit ($/tonne)	1.3	209	-52.2