Sustainable End of Life Management of PV Solar Photovoltaic Waste: The Impact of Transportation

Marina Lunardi[1], Austen Frederickson[2], Richard Corkish[1], Ilke Celik[3]

[1]*The Australian Centre for Advanced Photovoltaics (ACAP), School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney 2052, Australia*
[2]*University of Wisconsin – Platteville, Department of Civil and Environmental Engineering, 1 University Plaza, Platteville- WI*
[3] *University of Wisconsin – Platteville, Sustainability and Renewable Energy Systems, Department of Electrical Engineering, 1 University Plaza, Platteville- WI*

Extended Abstract

At least 114 GW of photovoltaic (PV) systems have been installed and commissioned in 2019 worldwide, an average of 34% new installations annual growth (IEA-PVPS, 2020). Considering a circular economy perspective, this rapid progress in PV installations is essential (IEA-PVPS, 2020; Celik, et al. 2016) but it also creates a waste issue. Estimations show that end-of-life (EoL) solar modules may account for approximately 8 million tonnes/year by 2030 (IRENA, 2016).

A lot of progress has been achieved regarding EoL management alternatives solar modules. The European PV Cycle, for example, developed a process that can recycle a record of 96% of materials from each crystalline silicon (c-Si) PV module (PVCycle, 2018). Another successful example is the Full Recovery End of Life Photovoltaic (FRELP) process, which is an economically viable mechanical approach that aims to recover 100% of the materials from PV waste modules (Latunussa, et al. 2016). The Veolia and ELSi plants in Europe both claimed 95% recovery (Veolia, 2018; CORDIS, 2018). In the US, First Solar® developed a recycling process specific for EoL CdTe modules that can recover up to 90% of the glass for use in new products, and 95% of the semiconductor materials for use in new solar modules (First Solar, 2017).

The incorrect disposal of EoL PV modules is proven to cause several environmental problems (Fthenakis, 2000; Berger, et al., 2010). However, the transportation aspect of these processes is rarely considered (Frisson, et al. 2000; Kang, et al., 2012) so the results from these studies are hard to compare. One study including transportation showed significant impacts from this phase (Latunussa, et al., 2016), while another (Held, 2013) estimated that the transportation step could have low impacts in comparison with the overall process. The second study (Held, 2013) also showed that the distance travelled changes the impacts significantly. Because of that, it is important to continue studying this aspect of PV recycling. Additionally, the economic factors are also significant for the industrialisation of such recycling processes (Deng, et al. 2019).

This work aims to estimate and compare environmental and economic aspects of EoL alternatives for c-Si, CdTe and CIGS solar modules, including recycling processes, transportation and landfilling. The life cycle assessment (LCA) methodology is used to estimate the climate change impacts, considering data collected from the literature (Owens, 1997; Bhandari, et al., 2015; Celik, et al., 2017). For both analyses, the functional unit of this study is 1 m^2 of a PV module. The system boundaries are set to start at the modules' end-of-use until their "grave", including transportation from the deployment location to recycling sites and recycling sites to landfill (for the remaining materials). Also, a comparison of recycling and landfilling (entire module) scenarios for PV modules is presented and discussed.

The modelling is based on realistic data from published recycling methods. The FRELP process is assumed for c-Si. The material recovery rates of this method are from 94 to 100%, depending on the material (Latunussa, et al., 2016). For CdTe the First Solar® recycling process is used, where the material recovery rates are up to 95% (Sinha, 2013; Ravikumar, et al., 2016). The "innovative recycling" method (Rocchetti and Beolchini, 2015; Frisson, et al., 2000) is assumed to be used for CIGS. The calculations are based on the PV modules specifications collected from the industry (Table 1).

Table 1. Specifications of the PV technologies (c-Si (SunPower, 2019), CdTe (First Solar, 2015) and CIGS (Solibro, 2017)).

Per module	c-Si (glass/backsheet)	CdTe (glass/glass)	CIGS (glass/glass)
Output [Watt]	360	100	160
Surface area [m^2]	1.63	0.72	1.6
Weight [kg]	18.6	12	28
Weight [kg/m^2]	11.4	16.6	17.5
Volume (m^3)	0.075	0.058	0.104

The environmental and financial impacts are calculated based on the assumptions described in Table 1 and considering 1000 and 2000 km for all transport types. The cost of transportation is calculated by using the inventory data collected from the literature (based on the logistic & transport industry in the US) (Markert, et al., 2019). The calculations consider the average number of modules needed from each technology to produce 1MW energy output (Table 1). To assess the transportation of PV waste, we calculate the maximum volume of PV modules that a truck can carry considering the specifications of each technology. Based on the assumptions described, the economic analysis results for diesel-fuelled trucks are shown in Figure 1.

Figure 1. Cost of transportation by diesel-fueled trucks of c-Si, CdTe and CIGS PV modules (US$/$m^2$ modules).

As discussed, the cost of transportation depends on the type of product being transported (weight and size). Results show that c-Si modules (glass/backsheet) have the lowest shipping cost per module area based, primarily because they have lower weight density per unit power. A higher quantity of CdTe modules can be carried at once (these modules are smaller than the other two options – Table 1), but their output (in watts) is lower than the other two technologies, so a higher number of CdTe modules would be necessary to produce the same 1MW energy output. The analysis also shows that the financial costs of transportation for carrying PV modules for either 1,000 or 2,000 km using trucks are very similar (the difference is only 12%). The reason is that, because this study is considering US, as the distance of transportation increases the unit cost of transportation decreases drastically. Hence, the financial costs are not substantially influenced by the distance travelled, but the environmental impacts are - due to the use of fuels (particularly fossil-fuels) during transportation. In that case, the closer the recycling plant is from the solar farm, the better.

Besides the recycling process and transportation impacts, it is also important to compare the environmental effects of landfilling PV modules. Figure 2 shows the results of climate change associated with the EoL phase of c-Si, CdTe and CIGS PV modules.

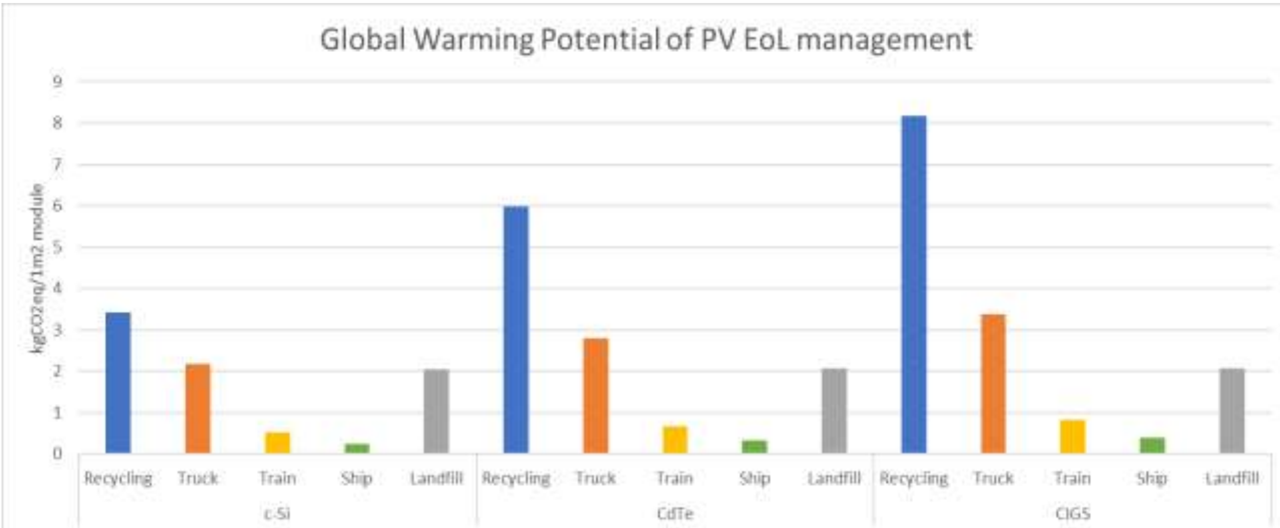

Figure 2. Climate change impacts of PV EoL management (considering an average between 1000 and 2000 km for distance travelled).

Figure 2 shows that the climate change impacts of CIGS modules are always higher than c-Si and CdTe PV modules, due to the weight of the CIGS modules, which are higher than the other technologies. When comparing the transportation types chosen, the diesel-fuelled truck has the highest climate change impacts. In contrast, shipping has the lowest climate change effects − around 15 times less compared to transportation by trucks.

In summary, results show that c-Si modules have the lowest impacts mainly because of its higher energy output. Also, because we considered that the unit cost of transportation ($/km) decreases as the travelled distances increase, the results show that the finantial costs of transportation for carrying PV modules for either 1000 or 2000 km are very similar. It is crucial to notice that environmental impacts from this stage of the process would increase significantly if the recycling plant is far from the waste collection. The environmental impact assessment showed that the $CO_{2\text{-eq}}$ emissions associated with transporting CIGS modules are always higher than c-Si and CdTe PV modules due to it's low energy output. The results confirm that diesel-fueled trucks have the highest environmental impacts (per m^2 of module) among the other transportation types analysed. Finally, the analysis of the climate change impacts of different EoL scenarios for PV modules showed that the emissions per m^2 of module are more significant for recycling processes than for the landfill scenario, and, so, more environmentally friendly recycling and recovery methods should be developed.

References

Berger, W., Simon, F.G., Weimann, K., and Alsema, E.A., 2010, 'A novel approach for the recycling of thin film photovoltaic modules.' Resources, Conservation and Recycling, 54(10), p711-718.
Bhandari, K. P., Collier, J.M., Ellingson, R.J. and Apul, D. S., 2015, 'Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis.' Renewable and Sustainable Energy Reviews, 47, p133-141.
Celik, I., Mason, B.E., Phillips, A.B., Heben, M.J. and Apul, D., 2017, 'Environmental impacts from photovoltaic solar cells made with single walled carbon nanotubes.', Environmental science & technology, 51(8), p4722-4732.
Celik, I., Phillips, A.B., Song, Z., Yan, Y., Ellingson, R.J., Heben, M.J., and Apul, D., 2017, 'Environmental analysis of perovskites and other relevant solar cell technologies in a tandem configuration.', Energy & Environmental Science, 10(9), p1874-1884.
Celik, I., Song, Z., Cimaroli, A.J., Yan, Y., Heben M.J. and Apul, D., 2016. 'Life Cycle Assessment (LCA) of perovskite PV cells projected from lab to fab.' Solar Energy Materials and Solar Cells, 156, p157-169.
CORDIS. 2018. State-of-the-art solar panel recycling plant [Online]. CORDIS. Available: https://cordis.europa.eu/article/id/238592-stateoftheart-solar-panel-recycling-plant [Accessed 22/6/2020 2020].

Deng, R., Chang, N.L., Ouyang, Z., and Chong, C.M., 2019, 'A techno-economic review of silicon photovoltaic module recycling.' Renewable and Sustainable Energy Reviews, 109, p532-550.
Frisson, L., Lieten, K., Bruton, T., Declercq, K., Szlufcik, J., De Moor, H., Goris, M., Benali, A. and Aceves, O., 2000. 'Recent improvements in industrial PV module recycling.', 16th European Photovoltaic Solar Energy Conference. Glasgow, 1-5 May.
Fthenakis, V.M., 2000, 'End-of-life management and recycling of PV modules.' Energy Policy, 28(14), p1051-1058.
Held, M., 2013, 'LCA screening of a recycling process for silicon-based PV modules.' Proceedings of the 3rd International Conference on PV Module Recycling. Rome, 28 February.
IEA-PVPS, 2020, 'International Energy Agency-Photovoltaic Power Systems Programme, 2020.', Snapshot of Global PV Markets.
IRENA, I., 2016, 'End-Of-Life Management: Solar Photovoltaic Panels.' International Renewable Energy Agency and the International Energy Agency Photovoltaic Power Systems.
Kang, S., Yoo, S., Lee, J., Boo, B., and Ryu, H., 2012, 'Experimental investigations for recycling of silicon and glass from waste photovoltaic modules.' Renewable Energy, 47, p152-159.
Latunussa, C. E., Ardente, F., Blengini, G.A., and Mancini, L., 2016, 'Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels.' Solar energy materials and solar cells, 156, p101-111.
Markert, E., Apul, D. and Celik, I., 2019, 'Economic Analyses of Solar Panel Recycling.', (submitted for publication).
Owens, J., 1997, 'Life‐cycle assessment: Constraints on moving from inventory to impact assessment.', Journal of industrial ecology, 1(1), p37-49.
PV Cycle. 'PV Cycle Breakthrough in PV module recycling.', Available from: http://www.pvcycle.org/press/breakthrough-in-pv-module-recycling/, Accessed on: 1/Mar/2018.
Ravikumar, D., Sinha, P., Seager, T.P. and Fraser, M.P., 2016, 'An anticipatory approach to quantify energetics of recycling CdTe photovoltaic systems.', Progress in Photovoltaics: Research and Applications, 24(5), p735-746.
Rocchetti, L. and Beolchini, F., 2015, 'Recovery of valuable materials from end-of-life thin-film photovoltaic panels: environmental impact assessment of different management options.', Journal of Cleaner Production, 89, p59-64.
Sinha, P., 2013, 'PV Recycling Policies and Technology', First Solar, Available from: <http://ieapvps. org/fileadmin/dam/Sinha.pdf.
First Solar, 2015, 'First Solar Series 4™, advanced thin film solar technology', module datasheet, Available from: <http://www.firstsolar.com/en-AU/-/media/First-Solar/Technical-Documents/Series-4-Datasheets/Series-4V2-Datasheet.ashx>.
First Solar, 2017, 'Modules recycling'.
SunPower, 2019, 'Residential AC Module', Available from: < https://us.sunpower.com/sites/default/files/media-library/data-sheets/sunpower-x-series-residential-solar-panels-x22-360-datasheet-514618-revc.pdf>
Solibro, 2017, "SOLIBRO SL2 CIGS thin-film module - Generation 2.2 | 125 -145 Wp", Available from: <https://solibro-solar.com/fileadmin/image/05_News_Downloads/Downloads/Data_sheets/G2.2/Solibro_datasheet_SL2_G2-2_2017-04_Rev03_EN.pdf>