Resources, Conservation & Recycling 146 (2019) 192–205

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Photovoltaic waste assessment: Forecasting and screening of emerging waste in Australia

Sajjad Mahmoudi[a], Nazmul Huda[a,*], Masud Behnia[b]

[a] School of Engineering, Macquarie University, NSW, 2109, Australia
[b] Macquarie Graduate School of Management, Macquarie University, North Ryde, NSW, 2109, Australia

ARTICLE INFO

Keywords:
EoL PV modules
PV waste management
Forecasting
Recycling
Circular economy

ABSTRACT

Australia has to meet the challenges of End-of-Life treatment of photovoltaic modules in coming years due to rapid growth of photovoltaic capacity during the last decades. This paper contributes towards the sustainable management of decommissioned solar panels through the estimation of PV waste flow between the years 2031–2047 based on the actual installation of the PV modules from 2001 to 2018, and the provision of a forecasting model applying on four major scenarios to project the waste generated from 2048–2060. Assuming three forecasting schemes, and consistent annual-growth-rate of PV installation for each scenario, the future PV waste was quantified. Considering the PV installation from 2001 to 2018, the cumulative waste is estimated to be 0.8 million tonnes until 2047. The mainstream of the waste is estimated to be glass and aluminium with 541,209 and 116,483 tonnes respectively, followed by 8375 tonnes of copper and 71,329 tonnes of steel. The PV waste includes various valuable substances which, if appropriately recycled, can bring significant economic benefit. With regards to all PV penetration scenarios in the electricity generation market until 2030, Australia is estimated to face around 1–8 million tonnes of decommissioned PV until 2060. The recovery of the EoL PV raw materials can lead to value creation of nearly 1.2 billion dollars. These findings can shed light on the possibility of a circular economy and suggest an active contribution of all parties and a very well-planned coordinated approach prevent the potential environmental impacts and maximize resource efficiency.

1. Introduction

The photovoltaic module, as one of the renewable energy sources which convert sunlight directly into electricity, is expected to be the leading type of electricity generation commodity in the future (Luo et al., 2008; Winneker, 2013; EPIA, 2016). Global solar panel capacity had a rapid uptake to 310 GW in 2016 (Moreno-Garcia et al., 2016; Osborne, 2016), which is predicted to rocket to 700 GW in 2020 (Research, 2016) and reached 4500 GW by 2050 (IRENA: Stephanie Weckend, 2016). In contrast with this significant growth rate, it is estimated that 1.7–8 million tonnes of end of life (EoL) PV panels will add to the waste stream by the end of the year 2030 globally, which can increase significantly to an estimated amount of 50–60 million tonnes by 2050 (IRENA: Stephanie Weckend, 2016).

Despite the significant progress in the development of renewable energy technologies, particularly photovoltaic modules, there remains a lack of research focus on management and recycling of End of Life (EoL) PV modules from different perspectives (Malandrino et al., 2017; Sica et al., 2018). Such an approach is critical towards keeping this technology environmentally friendly even after their typical operational lifetime. In addition, recycling of obsolete PV modules can efficiently reduce the natural-resources depletion (Hunt, 1976; Marwede and Reller, 2012; Azeumo et al., 2019) and decrease the production cost of current and emerging PV modules (Xu et al., 2018). While most of the research has been emphasized on enhancing the PV output and market, the EoL management of PV waste is very little explored in many PV consumer countries. Considering Australian scenario, there has been a lot of research on other e-waste items mostly on computer, television recycling (Islam et al., 2019; Dias et al., 2018; Dias et al., 2019a,b), however the emerging PV waste has not been quantified yet. Thus, assessment of the future PV waste stream is the most critical step towards policy, regulation and treatments leading to a circular economy and closed-loop supply chain (Paiano, 2015; Dominguez and Geyer, 2017; Domínguez and Geyer, 2018). In other words, forecasting the waste stream in parallel with material flow analysis acts as a powerful tool for the development of a proper strategy to deal with the

* Corresponding author.
E-mail address: nazmul.huda@mq.edu.au (N. Huda).

https://doi.org/10.1016/j.resconrec.2019.03.039
Received 2 October 2018; Received in revised form 22 March 2019; Accepted 25 March 2019

significant volume of this critical type of waste (Paiano et al., 2013).

The Clean Energy Regulator database of solar PV generators represents all the systems that have been installed under the Commonwealth Government's Renewable Energy Target (RET) scheme. It is noted that the data presented as the PV installations in Australia, included all of the installations including residential, commercial and utilities (APVI, 2018). However, most of the PV systems in Australia are small-scale residential, and increasingly, commercial rooftop installations. There are also a growing number of larger-scale PV power stations with a capacity of 100 kW or more.

Fig. 1 illustrates an overview of the photovoltaic-module capacity in the different Australian States. According to the Australian PV Institute (APVI), Queensland has the highest cumulative deployment rate of PV installation (2500 MW), followed by New South Wales and Victoria (1850 MW and 1350 MW respectively) (APVI, 2018). The distributed PV systems in South and Western Australia altogether stood at lower rates of 1500 MW roughly. It has to be underlined that the overall PV installation outlook indicates that small-scale PV capacity is still the major portion of the PV installation sector, although the large PV scale in Australia has been rapidly increased in recent years, particularly in QLD and NSW.

Fig. 2 depicts the PV panel installation in numbers in yearly and cumulative basis, while Table 1 presents the capacity of photovoltaic panels in MW based on the yearly and cumulative installation. As can be seen from Table 1 and Fig. 2, the annual PV power installation in numbers, as well as MW, increased remarkably, and according to the latest statistics in 2017, it reached 1330 MW (174,541 panels) installation per year compared to only 0.777 MW (134 panels) in 2001. In addition to this, the cumulative installation of PV modules had a considerable increase over the period; starting from 2001, with approximately 0.777 MW, compared to 7165 MW in 2017. It is worth noting that the overall installation of the PV panel in Australia has exceeded from 1.95 million panel tills September 2018 equals to 10,131.3 MW.

Table 2 shows the results of the three major reports published by the Australian government on the share of solar electricity generation. The model employed the E_4cast projections model (EnergyPLAN 26-09-2017; Lopion et al., 2018) which is a dynamic partial equilibrium model of the Australian energy sector. Average Annual Growth (AAG) percentages of PV in Australia in the latest report published in 2014 disclose a significant difference in terms of policy compared with the reports published in 2011 and 2012. In fact, it originates from the removing of a carbon pricing obligation in the 2014 report and employing of only the Renewable Energy Target (RET), leading to only 3% AAG, while both policies were considered in the 2011 and 2012 reports, resulting in 13.6% and 12.3% AAG respectively. Hence, it can be realized that the future of renewable energy market and its growth rate, particularly the PV market, in Australia would have significant uncertainty in the current environment of the market, investment level and government policies. Therefore, we consider the various AAG scenarios to cover the main possible trend of the PV waste flow stream.

The Australian Renewable Energy Agency (ARENA) published a report in November 2017 addressing Australia's opportunity in solar energy and ways to enhance the overall investment of solar-energy sector over the next ten years, resulting in more economic and social returns on this investment (ARENA, 2017). Table 3 forecasts the Installed PV capacity in Australia till 2030 based on various scenarios.

Salient findings of the literature reveal that the cumulative PV capacity in Australia over the last four years had a significant increase with a compound annual growth rate of 38% from 1.4 GW in 2011 to 5.1 GW in 2015 (ARENA, 2017). There is a strong national perception that this fantastic surge in the PV sector will keep its growth rate and increase its contribution to Australia's energy demand (ARENA, 2017).

Nonetheless, it is also observed that there is no solid forecast of the PV market share, and the results widely predict various PV penetration rates from only 4%[1] to 44%[2] by 2030 (ARENA, 2017). These wide ranges of forecasting derive from differences in methodology as well as assumptions, such as aggressive assumptions about costs, financial and policy circumstances for the suspicious scenarios in contrast with the very optimistic scenarios with 100% renewable-energy penetration. Therefore, it is impossible to simply decline any of the estimation scenarios.

With regard to the ARENA report, the outcomes of various forecasting scenarios about the solar-capacity growth rate and market vary considerably. However, it is estimated that forecasts near the middle for the PV capacity and installation rate, suggesting 12–18% compound annual growth rate (CAGR) corresponding to a 15-30% solar penetration, are feasible, with some ambitious plans for the PV installation rate and Australia's total electricity generation till 2030 (ARENA, 2017). In other words, to reach the 30-60% renewable-energy contribution in the electricity mix, PV technology as part of the potential renewable energy sector, can have an important contribution to reducing Australia's climate-change obligations and meet the renewable energy targets by 2030. To do so, this sector needs to supply 11-30% of the government's carbon abatement target gap by 2030 (ARENA, 2017).

Hence, the management of decommissioned photovoltaic panels is imperative to prevent the potential harmful effects on the environment by incineration and landfill (Malandrino et al., 2017). In terms of toxicity analysis, there are some studies which evaluate the components of PV modules form different perspective (Sinha et al., 2008; Coalition, 2009; Marwede and Reller, 2012; Cyrs et al., 2014). Also, various operations impacts of the disposal and recycling of EoL PV panels have been explored, concentrating on the economic feasibility and technological point of view (Choi and Fthenakis, 2010a,b,c, Kang et al., 2012; Choi and Fthenakis, 2014a,b). Some studies (Alsema et al., 2006, Sander 2007) have attempted to highlight the recoverability of discarded modules. For example, it has been demonstrated that glass as the primary composition of the PV module and aluminium as high-value metal, have recovery rates of 97% and 100% respectively, followed by 75% and 99% for indium and gallium respectively as rare metals, while copper as base metal and tellurium as a critical substance have roughly 80% and 99% respectively.

More recent work by Paiano (2015), Dominguez and Geyer (2017), Peeters et al. (2017), Domínguez and Geyer (2018) have made valuable contribution directions in analyzing, forecasting and material-flow analysis of EoL PV in Mexico, Italy, and Belgium. These studies demonstrate PV waste generation trends, while also highlighting the impact of recycling for the different materials used in different PV technologies, and foremost the essence of an early holistic strategy for the leading management of the PV waste stream. However, waste assessment as a critical step necessitates a local analysis of the PV waste stream for every PV consumer country. Here numerous studies underline the material composition of some of the metals embodied in various photovoltaic modules and explain the relevant issues (Radziemska et al., 2010; Monier and Hestin, 2011; Choi and Fthenakis, 2014a,b; Katsigiannis et al., 2015; Corcelli, 2018; Latunussa et al., 2016; Weckend, 2016).

The PV market is expected to continually grow since the community adopts photovoltaic technology according to its availability, green energy and getting more and more affordable electricity generation technology (Chine et al., 2014; EPIA, 2016; Moreno-Garcia et al., 2016). Accordingly, the Australian government recently announced that the PV waste flow will be the largest waste growth stream in coming years and needs to be treated appropriately (National-waste-policy, 2016). It has been suggested that developing recycling pathways would be an effective perspective for recovery of the valuable PV

[1] Bureau of Resource and Energy Economics – Australian Energy Projections to 2049-50

[2] AEMO 100 per cent renewables study

Fig. 1. Distribution of PV installation capacity in MW for the different States of Australia updated 25 Oct 2018 (figure generated from data provided in reference (APVI, 2018)).

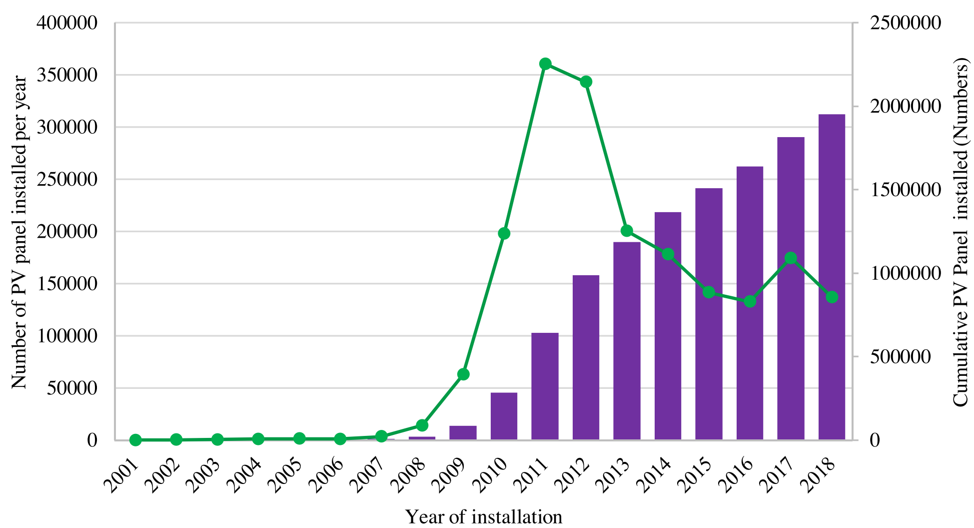


Fig. 2. Australian cumulative and yearly PV installation till Sep 2018 (figure generated from data provided in reference (APVI, 2018)).

Table 1
Annual and cumulative PV power installed in Australia (2001–2017) (MW) generated by author on data provided in Source: (APVI, 2018).

Year of PV installation	Annual PV power installed (a)	Previous cumulative PV power installed (b)	Cumulative PV power installed (c) c = a + b
2001	0.777	0	0.777
2002	0.699	0.777	1.476
2003	1.123	1.476	2.599
2004	1.341	2.599	3.94
2005	2.708	3.94	6.648
2006	22.102	6.648	28.75
2007	5.689	28.75	34.439
2008	20.137	34.439	54.576
2009	86.428	54.576	141.004
2010	390.381	141.004	531.385
2011	873.795	531.385	1405.18
2012	1049.75	1405.18	2454.93
2013	805.418	2454.93	3260.348
2014	822.766	3260.348	4083.114
2015	884.456	4083.114	4967.57
2016	867.428	4967.57	5834.998
2017	1330.05	5834.998	7165.048
2018/09	2966.221	7165.048	10,131.269

materials (Duflou et al., 2018), since the disposal of decommissioned PV panels imposes considerable costs on government. Also, from the environment and human-health point of view, photovoltaic modules may contain hazardous substances which do not allow us to simply landfill them. Hence, evaluation and screening of the PV-waste peculiarities at the national level in Australia is necessary to spotlight the upcoming challenges and pinpoint a proactive approach to managing this amount of waste before it comes to reality.

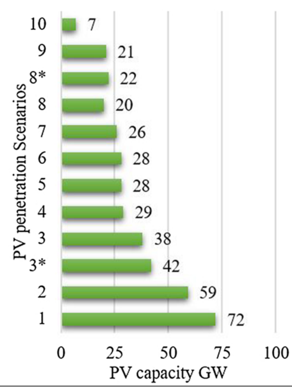
This paper contributes towards the sustainable management of PV technology at the end of its useful life by providing a forecasting model that estimates the PV waste flow in Australia for two different installation periods. Considering a 30 years' lifespan as the typical operational life of photovoltaic modules, the study presents the annual and cumulative waste stream of different PV technologies in megawatts (MW) as a function of the PV market share in Australia, followed by the waste production in tonnes according to the material inventory of the modules and the modules' specification. The data of PV technologies and the material embodied in different types of modules have been extracted and classified from various sources such as government and company reports, followed by peer-reviewed papers, to reach a high degree of validation on both quantitative and qualitative perspectives. The distribution of the waste flow in the different states of Australia as a function the current installation capacity (2001–17) are also presented

Table 2
Projected solar electricity generation in Australia (TWh) summarized from three different government reports in 2011, 2012 and 2014. (Syed and Penney, 2011; Syed, 2012, 2014).

Source	Publication Year	Level			Share		Average Annual Growth (AAG)
Australian PV Energy Projections	2011	2008–09	2019–20	2034–35	2008–09	2034–35	2008–09 to 2034–35
		< 1	4	5	< 1	1	13.6 %
	2012	2012-13	2034-35	2049-50	2012-13	2049-50	2012-13 to 2049-50
		1	25	62	< 1	16	12.3 %
	2014	2014–15	2014–15	2014–15	2014–15	2049–50	2014–15 to 2049–50
		2	3	6	1	2	3.0%

Table 3
Photovoltaic market pathways in Australia towards 2030 based on multiple scenarios elaborated by the author on data provided on reference (ARENA, 2017).

Scenario	solar penetration 1,2	PV Installation GW/year	Forecast methodology	PV capacity in 2030
1	44%	4.8	Future goal based forecast (i.e. 100% renewables)	
2	36%	3.9	Future goal based forecast (i.e. 100% renewables)	
3*	26%	2.7	Cost-based forecast * 3	
3	23%	2.3	Cost-based forecast	
4	18%	1.7	Policy based forecast (LRET)	
5	17%	1.6	Policy based forecast (LRET)	
6	17%	1.6	Policy based forecast (LRET) and cost	
7	16%	1.5	Carbon capture & storage scenario (no minimum share of renewables)	
8	12%	1.1	Policy based forecast (LRET) 4	
8*	14%	1.2	Policy based forecast (LRET) *	
9	13%	1.1	Policy based forecast (LRET)	
10	4%	0.1	Economic growth and industry production forecast	



[a]Estimated penetration based on electricity generation forecast of 299 TW h by 2030 and solar capacity of 21%.
[b]Other renewables such as wind and hydro power will also contribute in addition to indicated solar towards for overall renewable penetration.
[c]Modelled scenarios for a low case and high case using LCOE comparative analysis.
[d]Forecasted electricity generation of 360 TW h by 2030. Estimated solar penetration based on 299 TWh number and 26 G W installed capacity.

for 2047, demonstrating a quantitative data in tonnes that can be useful in order to design a reverse logistics supply chain based on the percentage of waste in each State. Moreover, the results of the material inventory of the PV waste are classified in five major types of waste including precious metals, base and special metals, hazardous metals, critical substances, other metals and other materials as an appropriate classification for a recycling strategy, regulation, and policy and environmental assessment. It is anticipated that the results of this research will provide opportunities towards a better understanding of EoL PV circumstances and support decision makers and researchers for further strategy and exploration respectively, whilst in parallel they act as a database for the future development of reverse-logistics scenarios, life-cycle analysis, economic feasibility studies (EFS), and policy and regulations.

2. Materials and method

The flowchart of the current study is depicted in Fig. 3 to provide a clear categorization of the current study framework and data. Across the following steps of the flowchart, it is observed that the PV waste estimation is divided into two fixed time periods, 2031-47 and 2048-60, since the future of the PV installation in Australia relies on various factors and, as mentioned earlier in the literature there are a variety of scenarios in PV growth rate and penetration in the market. This allows for a more realistic estimation and also provides a wide range of options for future exploration to be taken into account.

Evaluation of the Australian PV waste stream based on the installation capacity can provide clear insights for decision makers, scholars and authorities to design a proactive waste treatment plan from different perspectives such as disposal, recycling, recovery, reuse, reverse logistics, life cycle analysis, and policy. Hence, estimation of the annual and cumulative waste generation per technology and estimation of the material composition embodied in different modules is necessary.

The forecasting model applied in this study considers three waste estimation schemes comprising, early-loss, regular-loss and fixed loss. Both early-loss and regular-loss forecasting schemes are modelled using the Weibull function as shown in the Eq. (1).

$$P(t) = 1 - e^{-\left(\frac{t}{\tau}\right)^{\beta}} \tag{1}$$

Where, $P(t)$ is Weibull function, t equals to panel life in years, τ is the average lifetime of PV panels, and β is responsible for the typical S shape of the Weibull curve called shape factor.

The assumption of Weibull shape factors (β) in both schemes is originated from the systematic analysis of literature review as well as expert judgement for modelling PV panel loss probability (DeGraaff et al., 2011; Vodermeyer, 2013; Padlewski, 2014; IEA-PVPS, 2014b; IRENA: Stephanie Weckend, 2016) so that $\beta = 2.4928$ and $\beta = 5.3759$ are assigned for early-loss and regular-loss schemes respectively. It has to be underlined that both schemes assume a 30-year average lifetime for the photovoltaic panels and a 99.99% probability of loss after 40 years (ARENA, 2017).

The fixed-loss scheme, on the other hand, presumes that a module installed at a specific time will reach the end of life after a certain time period called lifetime and then it will be obsoleted so that it should be recycled or go for post-processing. This scheme considers 30 years as the average useful lifetime of a PV module, and afterwards, it becomes obsolete (ARENA, 2017; Dominguez and Geyer, 2017). Hence, the waste generation time is estimated using y = x + 30 where x and y are defined as the installation and waste production years respectively.

The outcome of early-loss and regular-loss schemes can be observed

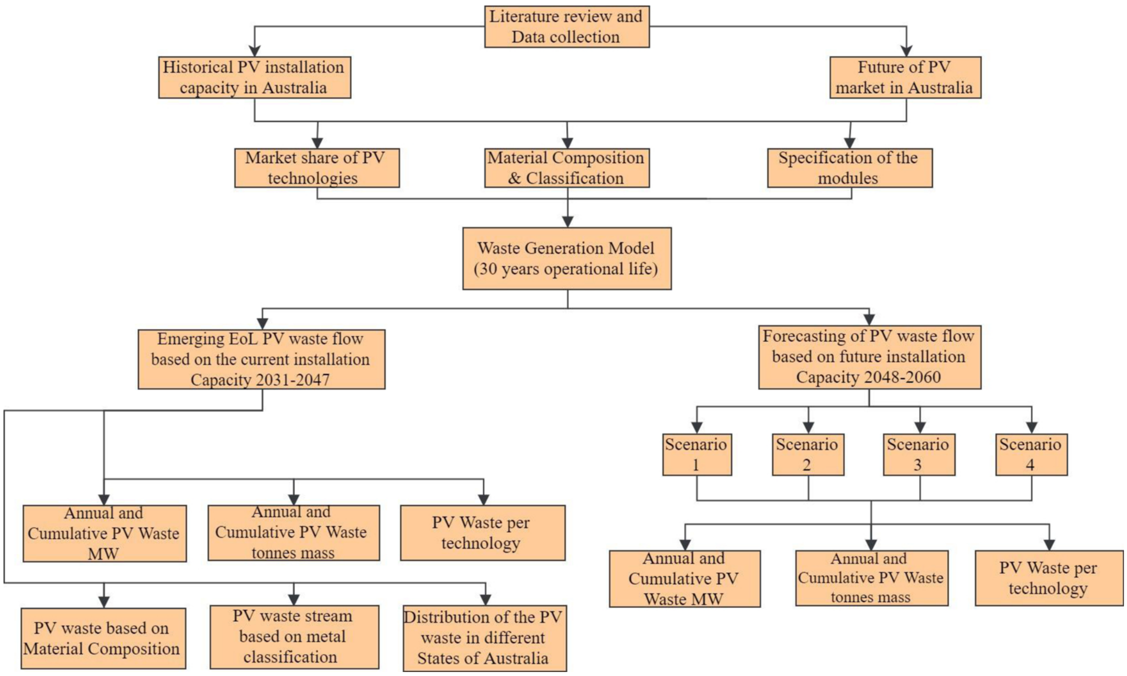


Fig. 3. Categorization and research framework of the study.

in Fig. 4. In line with the nominated β parameters, the results of Weibull function indicates an opposite response for regular-loss and early-loss schemes from the nominal lifetime point of 30 years. Thus, the probability of loss of the regular-loss scheme is higher than the early-loss scheme from 30 years onwards.

In order to calculate the cumulative PV waste generation for each scheme (regular-loss and early-loss), the Weibull function is multiplied to the weight of panels installed in a given year (2001–2017) to find the distribution of the PV waste generation over a 40-year period.

With regard to the essence of the historical and future market share of the PV technologies for the projection of the photovoltaic waste stream, the global market share of past, current and future PV modules from 1980 to 2030 is illustrated in Fig. 5 by collecting data from several reliable sources (BIO, 2011; Paiano, 2015; Weckend et al., 2016; Fraunhofer, 2018). It should be noted that the PV industry in Australia is very bounded, as there is almost no PV cell manufacturing and the majority of the PV modules are imported from the international market (ARENA, 2017). Accordingly, the market share of the PV technologies is considered to be equivalent to the global PV market share. As can be seen, the graph shows a substantial reduction in the production of c-Si modules as the first generation of PV technologies dropped to a 43% market share in 2030, while the emerging technologies face a growing trend; OPV, CPV, and particularly advanced c-Si will grow remarkably in the coming years. Additionally, a-Si is a PV type that will gradually leave the market by the year 2020, while the share of Thin-film technology such as CdTe and CIGS fluctuate marginally during the period and do not show any considerable market share in 2030.

Also, in order to make the estimation of the PV waste flow more accurate, the market share of emerging PV modules like organic and concentrative PV modules are added to the datasets alongside the current technologies such as crystalline and thin-film. PV panel is categorized into eight different classes including c-Si, a-Si, CdTe, CIGS, OPV, CPV, Advanced c-Si and others for waste projection per technology in accordance with the IRENA: Stephanie Weckend, 2016 classification. The available material inventory of the different PV modules is given in Table 4, in order for calculation of the annual mass flow of the waste in tonnes for each type of PV module. In this case, there was a limitation for the material inventory of the emerging PV modules as they are still under development and consequently not available in the references yet (BIO, 2011). Generally, knowing the details of the material shares embodied in PV technologies allows calculating the annual and cumulative material composition of the PV waste (Peeters et al., 2017; Marwede and Reller, 2012, 2014). It also gives an opportunity to classify them according to their types, comprising precious metals, base and special metals, hazardous metals, critical substances, other metals and materials like glass and EVA (Mahmoudi et al., 2018).

To find the mass in tonnes of PV waste per technology as effectively as possible, the specification of the different PV technologies including PV brand, area, power, weight, efficiency and in particular the average weight is given in Table 5. This facilitated to calculate the average of the data for each technology for calculation of the total mass in tonnes. Regarding the average weight value, since the proportion of the kg/Wp

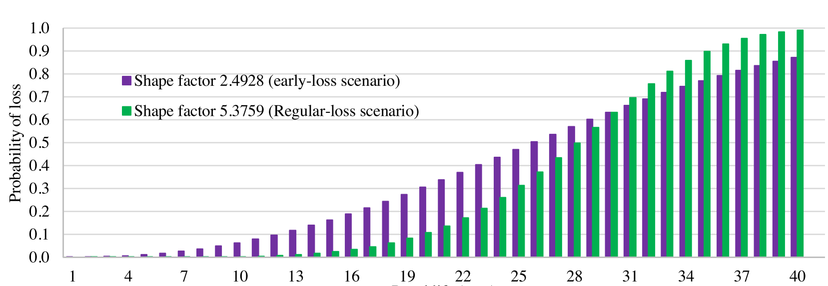


Fig. 4. Probability of loss based on Weibull curve with three different shape factors.

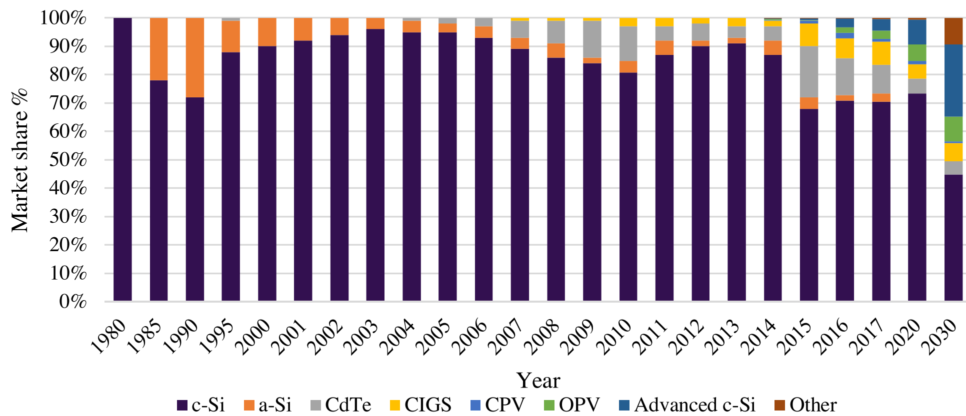


Fig. 5. Global Market Share of PV technologies across years elaborated by the author on data provided in BIO (2011), Paiano (2015), Weckend et al. (2016), Fraunhofer (2018).

Table 4
Average material composition and classification of PV modules per technology (Dominguez and Geyer, 2017).

Metal Inventory		c-Si [%]	a-Si [%]	CdTe [%]	CIGS [%]
Precious Metals	Ag	5.77E−02			
Base and Special metals	Al	1.65E+01	4.16E+01	9.04E−02	8.58E+00
	Cu	7.31E−01	8.99E−01	3.01E+00	2.84E−01
	Ni	1.06E−03	–	–	–
	Fe	–	7.45E−04	–	–
	Ti	5.20E−06	–	1.39E−07	–
	Sn	5.86E−05	–	1.39E−06	5.68E−02
	Zn	7.81E−06	3.72E−04	1.81E−07	5.68E−02
	Cr	–	5.65E−04	1.81E−02	–
	Mn	–	9.37E−04	–	–
	Mo	–	–	–	5.68E−02
Hazardous metals	Cd	–	5.13E−03	1.20E−01	1.71E−01
	Pb	4.67E−03	–	4.22E−03	–
	Se	–	–	–	5.68E−02
Critical substances	Mg	5.20E−01	1.31E+00	–	2.67E−01
	Ga	–	–	–	5.68E−02
	In	–	1.16E−02	–	2.84E−02
	Te	–	6.42E−03	1.20E−01	–
Other metals	Si	7.91E−01	2.57E−03	3.01E−01	–
	Steel	9.51E+00	3.98E+01	1.20E+00	–
Other materials	EVA	6.50E+00	1.59E+01	3.61E+00	5.12E+00
	Glass	6.54E+01	4.59E−01	9.15E+01	8.53E+01

for each technology can vary based on the size, weight, efficiency and other characteristics of the panels; the details of the various PV module brands were collected from various available resources. Then, the (kg) per unit power (Watt) from Ecoinvent database 3.3 was applied in the forecasting model as the most comprehensive material composition data.

To quantify the annual total mass of the EoL PV modules in Australia, the relevant data tabulated in Tables 3–5 is substituted in the Eq. (2) based on (Paiano, 2015):

$$w_y = \sum_{x=1}^{y} u_x w$$
$$u_x = \text{MW/year}$$
$$w = \text{weight (tonnes) per MW}$$
$$x = \text{year}$$
$$y = \text{year of waste generation } (x+30) \qquad (2)$$

w_y is the total mass of PV EoL per year

The calculation proceeds by considering two different time periods for the estimation of photovoltaic waste flows and the results are broken down into the microscopic level. The first waste estimation series covers the waste generated between 2031 and 2047 based on the current annual installation of PV modules in Australia, while the second estimation predicts the PV waste stream of the future installation capacity covering the years from 2048–2060, employing four major local PV market projection scenarios. Hence, analysis of the EoL PV streams in Australia has been evaluated based on both exact and forecast PV installation data. The waste assessment method used in this study was adapted from two recent investigations by Paiano (2015), Dominguez and Geyer (2017).

3. Results and findings

3.1. PV waste projection from 2031 to 2047

An in-depth analysis of the PV waste generation in Australia has been carried out in this section. To this aims, it is necessary to first look into the results of the PV waste generation comparing various forecasting schemes based on the actual historical PV installation in Australia. Fig. 6 illustrates the cumulative decommissioned PV panel results in tonnes over 30 years. Also, it compares the estimation results of this study with the IRENA report 2017 as a reference.

The result of the regular-loss scheme shows that the PV panel waste accounts for 4500 tonnes by 2017 with an increase estimated to about 36,000 tonnes in 2030. An even more substantial growth to nearly 700,000 t is predictable by 2047. The early-loss scheme evaluates much higher PV waste flow within the period which is because the early-loss scheme supposes PV panel failure at the early stages of its life has a higher rate in contrast with the regular-loss scheme. On the other hand, the fixed-loss (30 years scheme) presents that the PV waste streams are not considerable till 2040, but then its growth rate would be sharp to more than 800,000 tonnes by 2047.

Meanwhile, the results of this study are hardly distinguishable from the values reported by IRENA 2017 and confirm our findings.

It should be noted that, since PV modules are allocated to the category of a durable commodity with a low failure rate, only their end-of-life waste stream (fixed-loss scheme) is taken into account in this paper for the rest of analysis and results. In other words, photovoltaic panels' early failure, constant accidental failure, and wear-out failure rates are assumed to be negligible in comparison with the PV panel waste generated at the end of its typical operational life; thus, other kinds of PV wastes are ignored in this paper. However, the fixed-loss (30 years' lifetime) scheme is still robust and covers the primary purpose of the study which is a quantitative estimation of the PV waste in Australia.

Appendix A Table A.1 shows the yearly amount of PV waste generation for each photovoltaic technology from 2031 to 2047 in MW. It should be noted that the first column indicates the year-by-year waste production instead of the cumulative waste. Furthermore, the

Table 5
Photovoltaic panel specification (Dominguez and Geyer, 2017), BIO.

Dataset	PV module	Area [m^2]	Power [Wp]	Weight [kg]	Efficiency [%]	Average weight [kg/Wp]
Ecoinvent 3.3	c-Si	1.46	224	23	15.3	0.103
Perseidsolar		1.69	225	25	13.3	0.111
First Sunergy		1.59	230	23	14.4	0.100
BIO Intelligence Service		–	–	–	–	0.102
Ecoinvent 3.3	a-Si	2.3	128	18.86	5.6	0.147
Sharp		1.4	130	26	9.3	0.200
Sunelec		1.42	100	24	7	0.240
Kaneka		1.22	110	18.3	9	0.166
Polar Photovoltaic		–	52	13.7	–	0.263
Golden sun Solar		–	55	14.4	–	0.262
Ecoinvent 3.3	CdTe	0.72	65	12	9	0.185
First Solar		0.72	85	12	11.8	0.141
GE		0.72	78	13	10.8	0.167
Antec Solar		–	50	16	–	0.320
Ecoinvent 3.3	CIGS	0.72	80	12.6	11	0.157
Xsunx		1.6	160	28	10	0175
Stion		1.09	135	16.8	12.3	0.124
TSMC		1.09	145	17.5	13.3	0121
Global Solar		–	60	9	–	0.150
Axun Tek Solar		–	80	15	–	0.188
(Paiano, 2015)	Emerging technology/CSP	–	–	–	–	0.1

percentages of the PV waste for each technology throughout the 30-year period is shown in Fig. 6. Since the majority of the PV waste panel generated in this period consists of the first and second generations of PV technologies (over 97%), the third generation of PV modules is negligible in the current waste stream, less than 3% in 2047. Instead the third generation, as a growing technology, would be more considerable from 2048 onward because of its better efficiency and consequently more market share. In contrast to the waste a-Si photovoltaic module, which demonstrates almost a constant share during the period, in Fig. 7, c-Si reaches the highest share amongst all of the technologies. Also, continuous growth is observed for CIGS and CdTe, particularly from 2043 onwards.

As illustrated in Fig. 8, in the period 2031 and 2047 it is expected that the total amount of PV waste in tonnes will be equal to 817,941 t, corresponding to the PV modules installed during the period 2001 – 2017. As can be seen from the column chart, the grand total of PV waste flow is not significant in the period 2031–2039 (less than 16,000 t) because of low awareness about the benefits of photovoltaic modules as well as the costs of the PV installation. However, the waste stream will surge considerably after 2039 owing to government support public and more publicity of PV panels from 2011 to 2017. Once again, it is underlined that the most popular PV waste in 2047 is expected to be c-Si modules (Sander et al., 2007; Latunussa, 2016) with 590,827.5 t (70.3%), followed by CdTe with 119,466.9 t (15.44%).

Moreover, the annual mass flow of PV wastes based on the material composition of each technology are calculated according to their market share as well as specification for the modules installed between 2001 and 2017 for different technologies including c-Si, a-Si, CdTe, and CIGS. Then the results as supplementary information are given in Appendix B.1, B.2, B.3 and B.4 for further details.

To compare the proportion of waste that will be generated in the year 2047 per material, the material inventory of PV waste in Australia and the recycling yields of each material are illustrated in Tables 6 and 7. It is apparent from the results that Australia is estimated to face about 1 million metric tonnes (mt) of the non-metal and metal embodied in distinct PV modules solely installed in Australia for a 30-year period (2001-17). The most remarkable result to emerge from the economic analysis is that the possible economic value creation from the estimated amount of PV waste generated till 2047 considering the current commodity price of the PV waste material flow is around 1.2 billion US$. Thus, it can be realized that the recycling of PV modules at the end of their operational life could be a very reasonable option if the authorities legislate the proper policy and management.

The results of material inventory (Fig. 9a) represent that the main composition of the PV module waste flow belongs to non-metal materials by totally 608,302 t mass (73%) including glass and EVA with 66.8% and 6.5% respectively, followed by 14.9% for Aluminum as major portion of the metal-based PV waste. Based on the metal type of PV waste, they are divided into five categories (Fig. 9b). The first category accounts for the precious metals like Ag by 340.9 t. Furthermore, it is observed that 16% of the PV waste belongs to the base and special metals as the second category with 124,978 t. Less than 1% of the PV

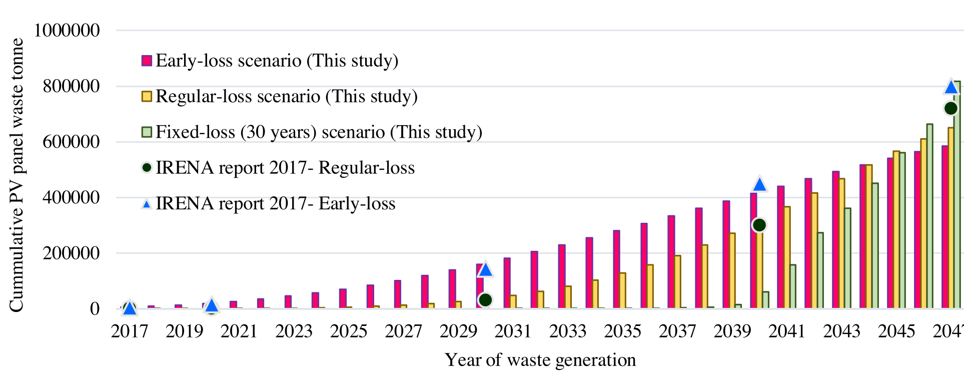
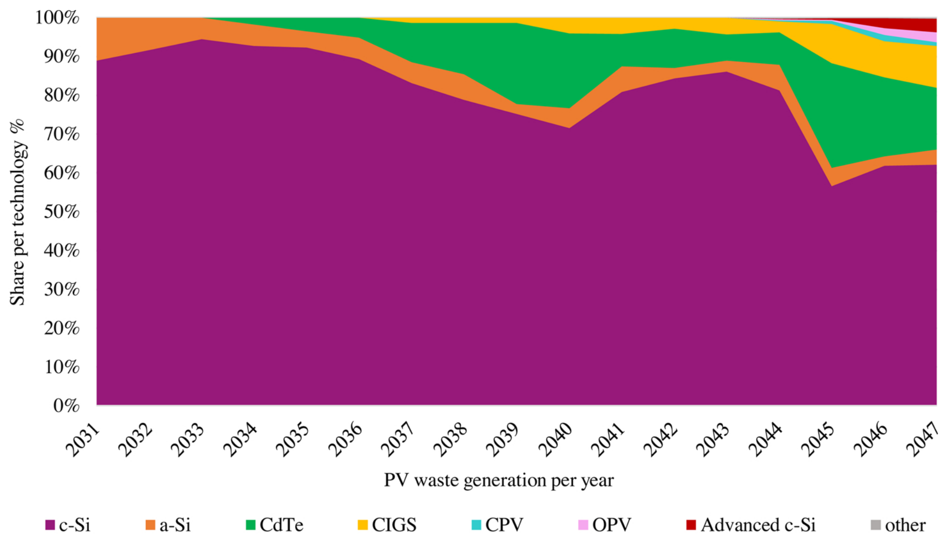
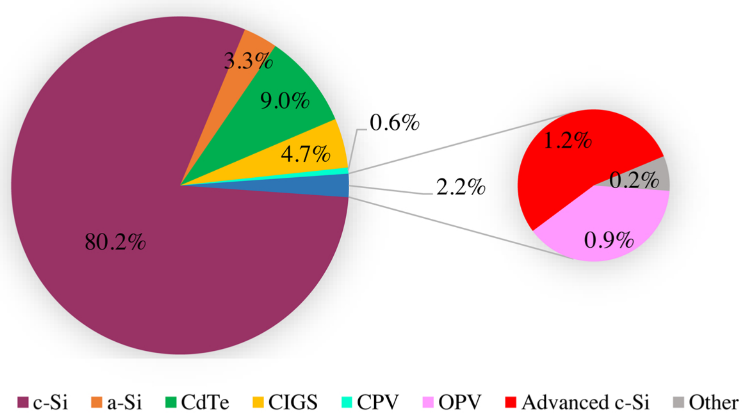


Fig. 6. Cumulative waste estimation of Australian end-of-life PV panels (tonnes) 2017 – 2047.



a) Annual PV waste generation per technology till 2047 based on the historical installation between 2001 and 2017 in Australia



b) Percentage of cumulative PV waste generation in 2047 for different PV technologies

Fig. 7. Overall trend of PV waste generation per technology in Australia from 2031 to 2047.

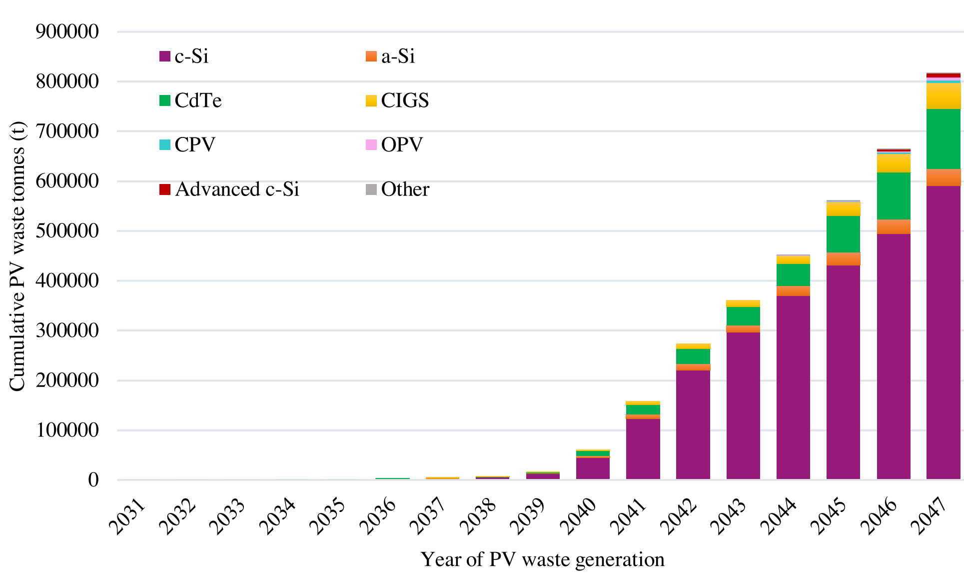


Fig. 8. Australian cumulative waste generation of PV in tonnes (t) per technology from 2031 to 2047.

Table 6
Waste inventory and economic value share of EoL PV panel generated till 2047.

Material	Quantity tonnes (t)	Mass share %	Commodity price [$/kg] (Domínguez and Geyer, 2018)	Economic value creation (US$)
Ag	340.9	0.043	646.55	$220,408,895.00
Al	116,483	15	1.9	$221,317,700.00
Cu	8375.4	1	6.1	$51,089,940.00
Ni	6.3	0.0008	12.6	$79,380.00
Ti	0.030886	0.000004	0.64	$19.77
Sn	30.5017	0.004	15.9	$484,977.03
Zn	30.3463	0.004	2.1	$63,727.23
Pb	32.6	0.004	2.05	$66,830.00
Mg	3,665.4	0.5	4.7	$17,227,380.00
Si	5,033.9	0.6	2.998	$15,091,632.20
Steel	71,329.6	8.94	3.042	$216,984,643.20
EVA	50,914.3	6.38	0.83	$42,258,869.00
Glass	541,209.3	68	0.79	$427,555,347.00
Fe	0.3	0.00004	0.6	$180.00
Cr	21.8	0.003	9.9	$215,820.00
Mn	0.3	0.00004	0.005	$1.50
Cd	236.1	0.03	1.1	$259,710.00
In	19.1	0.002	460	$8,786,000.00
Te	145.6	0.02	89	$12,958,400.00
Mo	30.2	0.004	17.8	$537,560.00
Se	30.2	0.004	50.3	$1,519,060.00
Ga	30.2	0.004	295	$8,909,000.00
Total	797,965.4	100%		$1,245,815,071.93

Table 7
Recycling yields of material contained in PV modules.

Material	Recovery yields%	Source
Ag	95	Latunussa et al. (2016)
Al	99.7	Yi et al. (2014), Paiano (2015)
Cu	100	Latunussa et al. (2016)
Ni	41	Sibley (2011)
Ti	52	Sibley (2011)
Sn	32	Goe and Gaustad (2014)
Zn	27	Sibley (2011)
Pb	96	Goe and Gaustad (2014)
Mg	33	Sibley (2011)
Si	99.9	Yi et al. (2014)
Glass	95	Paiano (2015)
Fe	90	Dominguez and Geyer (2017)
Cr	20	Sibley (2011)
Mn	37	Sibley (2011)
Cd	95	Marwede et al. (2013); Held and Ilg (2011)
In	90	Redlinger et al. (2015)
Te	95	Anctil and Fthenakis (2013); Paiano (2015)
Mo	18	Goe and Gaustad (2014)
Se	89	Tao and Yu (2015)
Ga	90	Redlinger et al. (2015)

waste that will be generated in Australia till the year 2047 includes hazardous materials (3rd category) like Cd, Pb, and Se with 299 t, followed by critical substances (4th category) with 38,660 t (˜0.5%). Finally, 10% of the waste stream consists of other types of metals including Si and steel with 76,363 t. It can be observed from Fig. 9c that glass makes up most of the economic value of PV waste flow by 2047, followed by Silver, Aluminum and Steel with 18%, 18% and 17% sequentially.

Fig. 10 provides detailed information of the PV waste amount and also the percentage of the waste per Australian State which can mainly be used for choosing the locations of the recycling centers on the basis of cumulative PV waste flows. To do so, designing a holistic reverse logistics supply chain is necessary to minimize the logistics costs and feasibility of the recovery of the backward flow of the PV waste (Islam and Huda, 2018). It entails the logistic networks which be designed based on the optimum transportation method including distance traveled, the fuel type and price, lorry fuel efficiency, type of vehicle, and other logistics services costs provided by the reverse logistics companies.

The evidence from the results reveals that Queensland is expected to generate the highest amount of PV waste with 237,136 t (˜32%). New South Wales represents 24% of the total waste with 211,740 t in 2047. Victoria and South Australia have a lower waste generation amount with 145,534 t and 95,745 t over the period respectively. However, the proportion of the waste in Tasmania and the Northern Territory accounts for the lowest amount of waste with about 2% of the total.

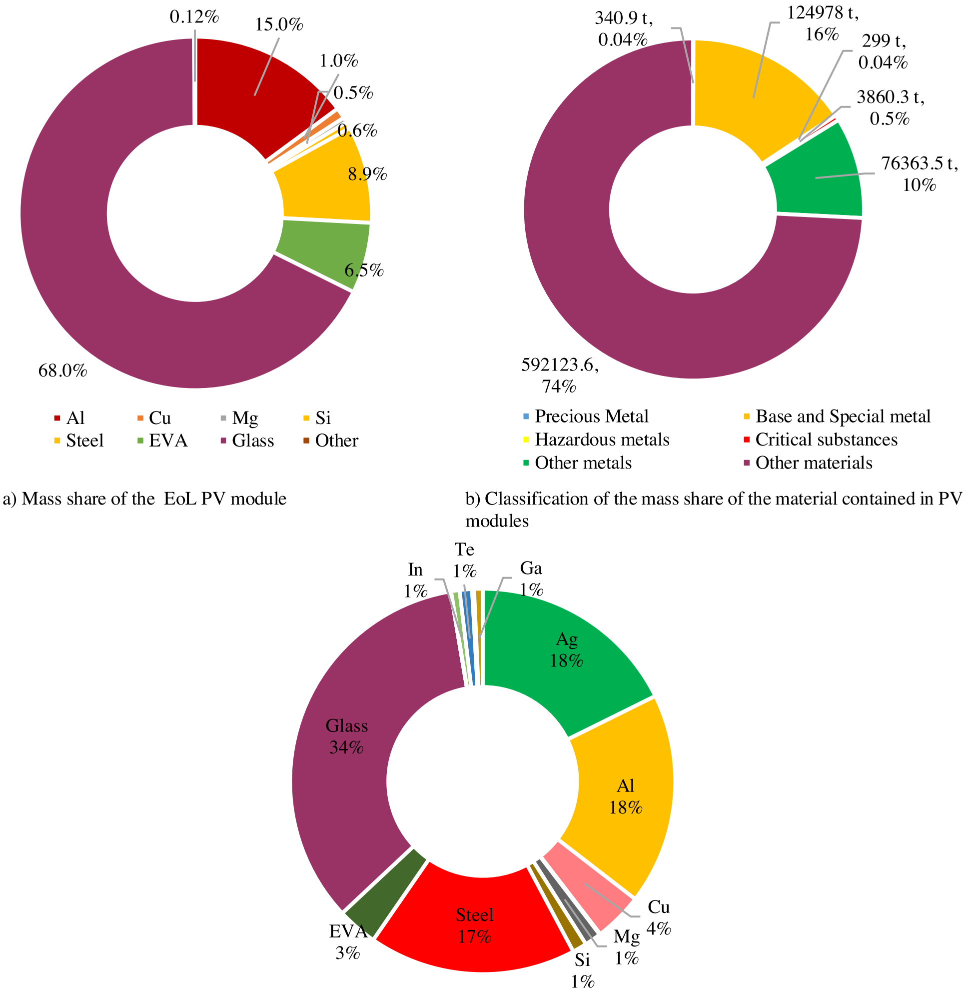
A proper structure of the reverse-logistics networks can prevent potential environmental impacts while transferring the waste from consumer locations to the recycling centers. It has to be underlined that the expenses of the disposal can be also affected by the installation scales of PV panels as an influential factor. Thus, it needs to be carefully carried out while designing the reverse logistics networks. For example, current PV waste estimation results indicates that the utility-scale of PV modules is more common in Queensland and New South Wales, followed by South Australia and Victoria respectively. Therefore, it could play a critical role for the reduction of logistics costs and environmental risks if the recycling plant or take back centers be allocated close to these states.

3.2. Forecasting of the waste from 2048–2060

The second part of the study focuses on forecasting the PV waste flow based on the future installation capacity of PV modules in Australia for the 12 years' period from 2018 to 2030. As shown in Fig. 11, there is a wide range of scenarios for the future stream of PV waste. It should be noted that PV waste flow is heavily dependent on various parameters which can affect the PV installation capacity and rate in Australia, such as policy, economic growth, cost, emission reduction scenario, and renewable energy target; for which reason it is difficult to make concrete forecasts regarding the amount of PV waste at the end of life. Hence, PV waste flow is very case sensitive and affected by the aforementioned parameters, which can lead to different amounts of waste at the end of the forecasting period, varying from 8465 MW to 69,565 MW.

In the analysis, four scenarios, weak (4%), current installation rate (14–16%), moderate (26%) and strong (44%) are considered for PV installation rate in Australia between 2018 and 2030, which are representative of the various PV penetrations in the electricity mix (Table 8), are defined and employed in presenting solar waste projection outcomes from 2047 to 2060. Scenario 1 represents the worst economic condition (0.1 GW/year), while scenario 4 shows 100% renewable energy penetration rate as the super optimistic scenario (4.8 GW/year). The second scenario is based on the current PV installation rate showing the impact of government subsidies and certainly the awareness of people about the benefits of solar power. The moderate scenario accounts for the carbon capture scenario with a very serious effort (2.7 GW/year). All in all, according to the current experience of PV installation with all the upsides and downsides, the 1st and 4th scenarios look more unrealistic. In contrast, it is expected that scenario 2 would be the most likely scenario among the others. Hence, in the following sections, the discussion focuses more on the PV waste flow forecast based on scenario 2, which accounts for around 14-16 percent PV penetration till 2030, resulting in nearly 2.7 million tonnes (mt) of waste till the end of the timeframe.

To obtain better insights on the future PV waste generated in Australia, the projection results for all scenarios is presented in Fig. 12. Accordingly, the total amount of waste stream is projected to vary from about 1 million tonnes (mt) to 8 mt in 2060. Thus, the cumulative amount of waste will surge gradually till 2047, becoming critical in 2060 based on any of the proposed scenarios except scenario 1. Besides, the PV waste stream based on the type of panel for scenario 2 is presented in Table 9. Hence, the results clearly show that the end-of-life



a) Mass share of the EoL PV module

b) Classification of the mass share of the material contained in PV modules

c) Economic value shares of materials in PV panel waste

Fig. 9. material inventory of end-of life waste flow of PV panels generated in Australia including c-Si, a-Si, CdTe technologies CIGS by 2047.

management of photovoltaic modules can be a significant problem in Australia over the next decades if appropriate measures are not considered by now. To overcome this great challenge that is coming in near future, a very well-coordinated and effective strategy should be adopted to manage this high volume of EoL PV waste better.

4. Discussion

In about a decade (from the early 2030s), Australia will face serious challenges regarding the sustainable management of photovoltaic (PV) waste concerning the environment, economics, policy, disposal, and recycling. In the latest update on the sustainable management of

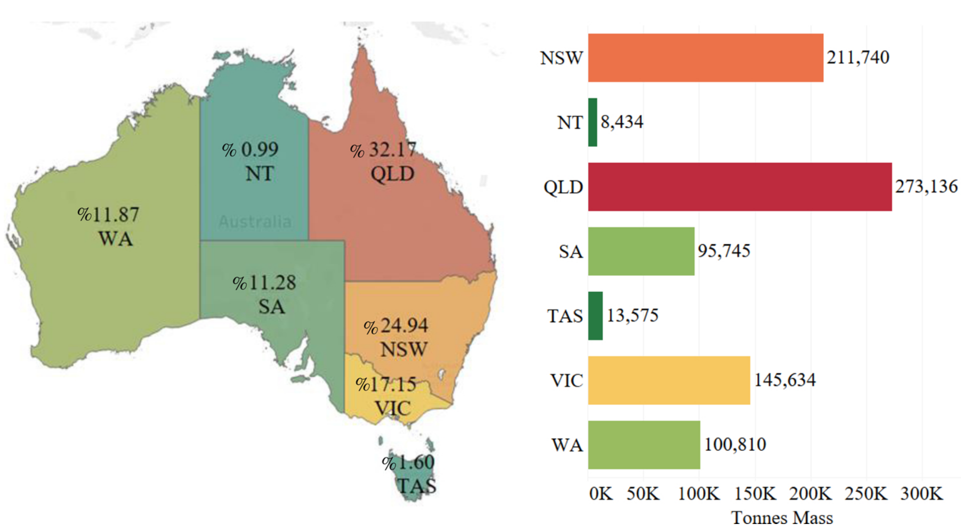


Fig. 10. PV waste share distribution in % and mass in tonnes for the States of Australia in 2047.

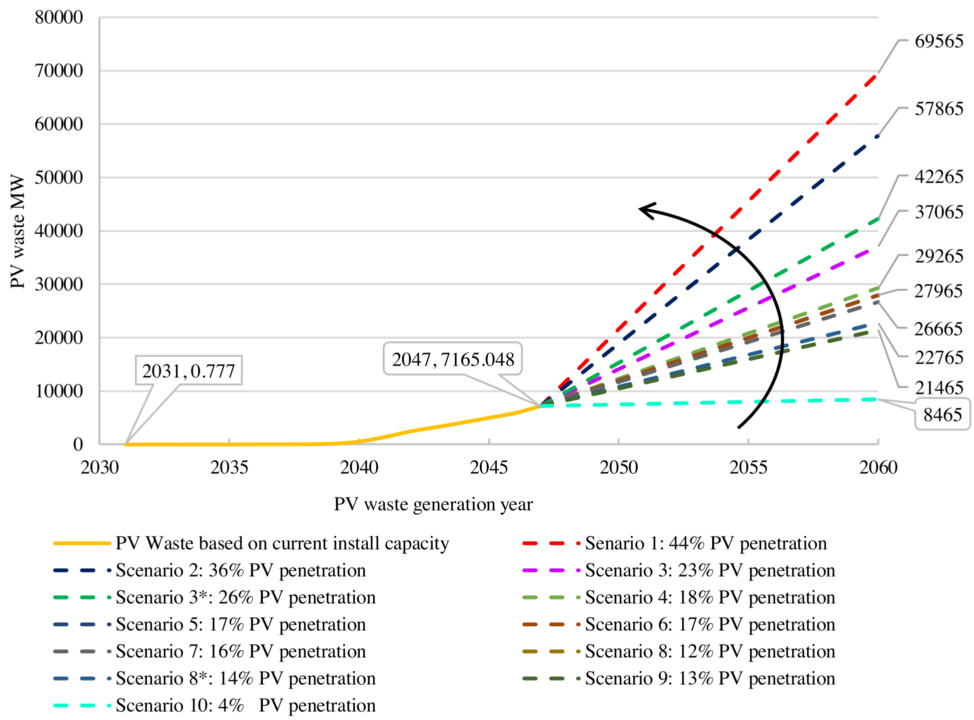


Fig. 11. PV waste flow (MW) in Australia based on the current installed capacity from 2030 to 2047 and projection of the total PV waste stream between 2047 and 2060 using 10 different scenarios.

electronic waste in Australia, the authorities specified a new product stewardship scheme for photovoltaic solar panels and batteries (Goverment, 2018). It is pleasing that the Reclaim PV company, with a take-back and reclaiming scheme, was founded in 2014 by the directors of S.M.A.R.T. Pty Ltd, which intends to establish collection and dismantling centers across Australia and Oceanic region (PV, 2014; Spence, 2016). However, implementation of adequate management strategies is still needed for holistic management of EoL PV with respect to its complex materials.

One of the preliminary steps toward proactive management of the emerging PV waste stream is monitoring the relevant waste flow in terms of quality and quantity of waste on a timely basis, as well as long-term forecasting. Hence, establishing a monitoring system which records every type of discarded module could be the first step in better handling the challenge so that the status of that module could be instantly pursuable. The assessment results presented in this study will act as a valuable resource to all parties and authorities to develop the relevant regulations and policy. The findings of the current study show the necessity of a comprehensive plan in order to develop an articulate framework as an imperative. It seems that there are significant gaps in the following sectors as critical components of the PV waste management systems (Fig. 13).

PV waste can be considered as a secondary mining industry because of the variety of metals embodied as well as its huge market. The latest import statistics in Australia indicate that some of the materials and metals common in PV modules are parts of the import sector including Aluminum US$1.78B (0.78% of total import), Copper US$791 M (0.35%), Iron and steel US$1.57B (0.69%), Glass and glassware US $842 M (0.37%) (Trading-Economics, 2017). On the other hand, glass with about 70% of the PV panel's weight is the predominant recycling material in the PV waste stream, estimated at nearly 541,209.3 tonnes by 2047. Moreover, PV panel treatment allows for recovering 116,483 tonnes of aluminium and 8375 tonnes of copper, which are expected to be released on the secondary material market by 2047. Steel is also a significant component which can bring substantial added value after recovery of 71,329.6 tonnes. Thus, the development of appropriate recovery and recycling procedures, as well as technologies, are imperative owing to their significant financial value as well as their continuous generation (McDonald and Pearce, 2010). Clearly, the recovery of the emerging PV waste flow can supply some materials that Australia currently imports from the global market. Hence, if the recovery cost overweighs the import expense, then definitely the recovery of the raw materials of obsolete photovoltaic modules is a potentially beneficial option. However, it should be taken into account that the analysis of the environmental impacts of the recovery of EoL PV materials is imperative to prevent any threats and human-health risks (Faircloth et al., 2019), resulting in a serious environmental burden. Accordingly, it is highly recommended to establish research centers which can develop various methods and models of recovering PV waste material in order to discover an ecological perspective which has the lowest environmental risk and the highest recovery rate. At the moment, it is known as a global problem all around the world. In terms of

Table 8
Forecasting scenarios for the PV waste generated between 2047 and 2060 (GW).

Scenario	Installation Condition	PV Penetration	Total amount of waste[a] in 2047	Total amount of waste[a] in 2050	Total amount of waste[a] in 2060
1	Weak	4%	–	7.5 GW	8.5 GW
2	Current rate	14-16%	7 GW	11 GW	24 GW
3	Moderate	26%	–	15 GW	42 GW
4	Strong	44%	–	21.5 GW	69.5 GW

[a] The amount of waste for each scenario was rounded.

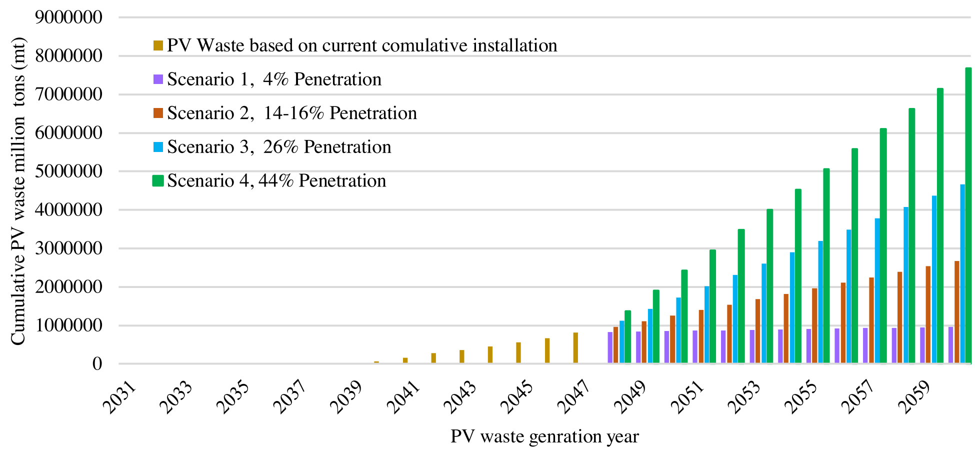


Fig. 12. Amount of estimated PV waste generated in Australia for four different forecasting scenarios (2031–2060).

Table 9
Cumulative waste generation in tonnes per technology Scenario 2.

Year	c-Si	a-Si	CdTe	CIGS	CPV	OPV	Advanced c-Si	Other
2048	686030	38265	139669	67574	5542	11265	15807	1782
2049	782706	40176	156023	80092	7015	17592	25080	2476
2050	880855	40176	168529	90705	8575	25132	36390	3256
2051	975187	40176	180915	101563	10057	33049	49897	5167
2052	1065704	40176	193180	112667	11461	41343	65601	8209
2053	1152404	40176	205325	124014	12787	50014	83502	12382
2054	1235288	40176	217350	135607	14035	59062	103600	17686
2055	1314356	40176	229255	147445	15205	68487	125895	24121
2056	1389608	40176	241040	159528	16297	78289	150387	31687
2057	1461044	40176	252704	171856	17311	88468	177076	40384
2058	1528663	40176	264248	184428	18247	99024	205962	50212
2059	1592466	40176	275672	197246	19105	109957	237045	61171
2060	1652454	40176	286975	210308	19885	121267	270325	73261

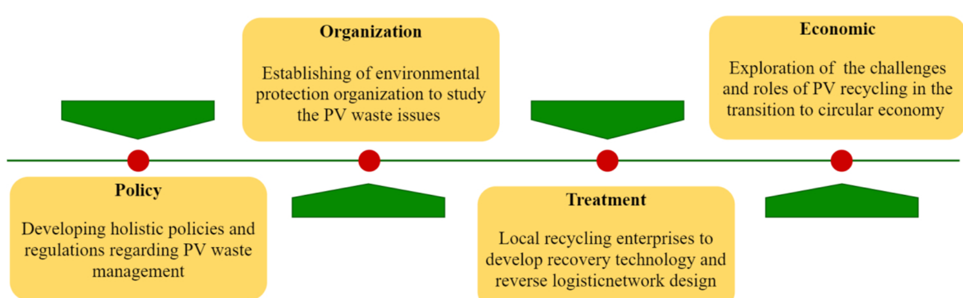


Fig. 13. The major gaps in the Australian EoL PV sector.

guaranteeing the economic feasibility of PV waste recycling, it requires a proper policy lead to creating an incentive for different parties to get involved in the end of life PV management sector (D'Adamo et al., 2017; Choi and Fthenakis, 2010a,b,c). Current global policy and regulation on the management of electronic waste products, and in particular the EoL PV sector, clearly indicate that there is no other option than reusing, recovering and recycling of E-Waste because of the serious environmental impacts, as well as a commitment in terms of preventing resource depletion and obviously the reduction of waste (Berger et al., 2010; Latunussa, 2016; Gaustad et al., 2018). To this end, the management of decommissioned PV panels entirely relies on designing a circular economy as well as policy and regulations supporting the plan from both economic and environmental points of view, as neither can be ignored.

As shown in Fig. 14, EoL photovoltaic modules can be considered as an above-mine for some obvious reasons. Firstly, we do not need to dig in the ground to extract materials and substances. Secondly, because of the various types of raw material embodied in the different types of photovoltaic modules followed by their significant volume of waste flow, a reasonable economic value share can be envisaged. It also prevents the huge environmental burdens arising from the mining industry. Considering the weakest PV scenario (scenario 1 with 4% PV penetration), a value creation of nearly US$ 1.2 billion is predicted causing to the potential ability for the production of nearly 50 million new panels with the same material composition. This estimation is based on the average recovery rate of 72%, and current market commodity price by the existing global regulations of PV panel recycling which respond to the question of how likely the PV recovery sector is to create a circular economy. Finally, following a cradle-to-grave or cradle-to-cradle or EoL management (zero-burden) approaches to deal with obsolete PV panels entails active contribution of all players including producers, importers, dealers, system operators, utilities,

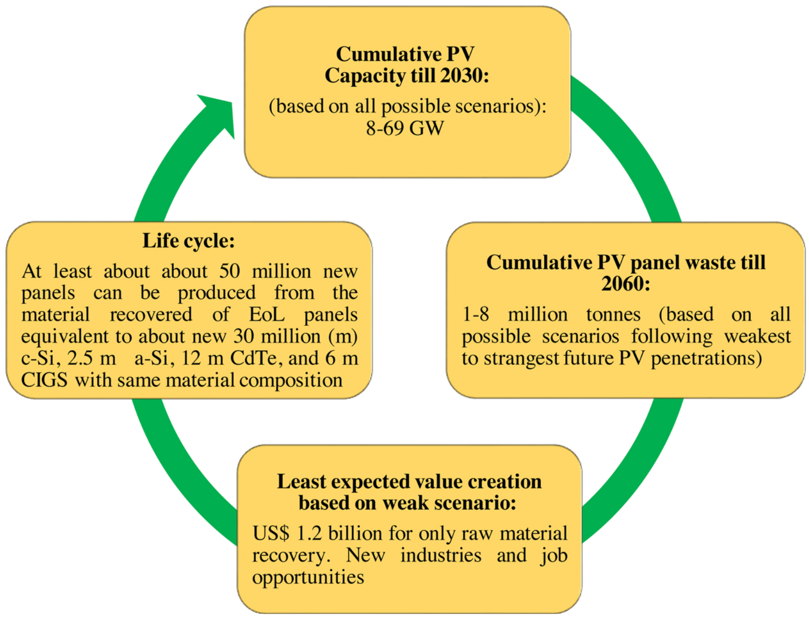


Fig. 14. Closed-loop EoL photovoltaic waste pathway towards a circular economy in 2060 (modified by the author on data provided on (IRENA: Stephanie Weckend, 2016).

municipalities, governments, waste treatment companies and end-users to guarantee a circular economy of photovoltaic waste management systems.

5. Conclusion

To conclude, the recycling pathways of EoL photovoltaic modules in Australia are currently incomplete. The findings presented in this paper reveal valuable information regarding the massive EoL PV waste generated in two different time periods comprising 2031–2047 and 2048 – 2060. The results of the former period were calculated based on the actual PV installation until 2018 leading to a cumulative waste amount of around 1 million tonnes by the year 2047. The mainstream of the waste in this period is estimated to be glass and aluminium with 541,209.3 and 116,483 tonnes respectively, followed by 8375.4 tonnes of copper and 71,329.6 tonnes of steel. A forecasting model was also employed by considering four scenarios to provide a more accurate prediction of the future PV waste generated based on one of the PV penetration models in the Australian electricity generation mix. Then, the end-of-life solar waste flow from the year 2048–2060 was projected leading 1–8 million tonnes of mass considering scenarios1-4 respectively. The results of the weakest scenario as the least possible scenario in the electricity generation market of Australia until 2030 illuminated a strong possibility of the circular-economy through the recovery of the materials contained in the PV waste flow by 2060 leading to significant economic value creation of US$1.2 billion. It is also expected that the raw material recovered through recovery process provides the opportunity to produce whether about 50 million new panels with the same material composition or being used in the completely new production process for manufacturing of a new product. Finally, this paper highlights the necessity of developing an appropriate policy to manage the emerging PV waste stream in Australia better to ensure a reliable and sustainable recycling procedure maximizing resource efficiency.

Acknowledgments

The first author acknowledges funding support from Macquarie University under the International Macquarie University Research Training Pathway scholarship program (iMQRTP).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.03.039.

References

Alsema, E., de Wild-Scholten, M., Fthenakis, V., 2006. Environmental impacts of PV electricity generation-a critical comparison of energy supply options. 21st European Photovoltaic Solar Energy Conference.
Anctil, A., Fthenakis, V., 2013. Critical metals in strategic photovoltaic technologies: abundance versus recyclability. Prog. Photovolt. Res. Appl. 21 (6), 1253–1259.
APVI, 2018. Australian PV Institute (APVI) Solar Map. accessed from. Funded by the Australian Renewable Energy Agency. pv-map.apvi.org.au.
ARENA, A.R.E.A., 2017. Advancing Solar in Australia Through RD&D Investment Report 2017. ARENA has c, ARENA. .
Azeumo, M.F., Germana, C., Ippolito, N.M., Franco, M., Luigi, P., Settimio, S., 2019. Photovoltaic module recycling, a physical and a chemical recovery process. Sol. Energy Mater. Sol. Cells 193, 314–319.
Berger, W., Simon, F.G., Weimann, K., Alsema, E.A., 2010. A novel approach for the recycling of thin film photovoltaic modules. Resour. Conserv. Recycl. 54 (10), 711–718.
BIO, 2011. Study on Photovoltaic Panels Supplementing the Impact Assessment for a Recast of the WEEE Directive. Final Report. BIO Intelligence Service, Paris.
Chine, W., Mellit, A., Pavan, A.M., Kalogirou, S.A., 2014. Fault detection method for grid-connected photovoltaic plants. Renew. Energy 66, 99–110.
Choi, J.-K., Fthenakis, V., 2010a. Design and optimization of photovoltaics recycling infrastructure. Environ. Sci. Technol. 44 (22), 8678–8683.
Choi, J.K., Fthenakis, V., 2010b. Economic feasibility of recycling photovoltaic modules. J. Ind. Ecol. 14 (6), 947–964.
Choi, J.K., Fthenakis, V., 2010c. Economic feasibility of recycling photovoltaic modules: survey and model. J. Ind. Ecol. 14 (6), 947–964.
Choi, J.-K., Fthenakis, V., 2014a. Crystalline silicon photovoltaic recycling planning: macro and micro perspectives. J. Clean. Prod. 66, 443–449.
Choi, J.K., Fthenakis, V., 2014b. Crystalline silicon photovoltaic recycling planning: macro and micro perspectives. J. Clean. Prod. 66, 443–449.
Coalition, S.V.T., 2009. Toward a Just and Sustainable Solar Energy Industry. Silicon Valley Toxics Coalition, San Jose.
Corcelli, F., Ripa, M., Leccisi, E., Cigolotti, V., Fiandra, V., Graditi, G., Sannino, L., Tammaro, M., Ulgiati, S., 2018. Sustainable urban electricity supply chain–Indicators of material recovery and energy savings from crystalline silicon photovoltaic panels end-of-life. Ecol. Indic. 94 (3), 37–51.
Cyrs, W.D., Avens, H.J., Capshaw, Z.A., Kingsbury, R.A., Sahmel, J., Tvermoes, B.E., 2014. Landfill waste and recycling: use of a screening-level risk assessment tool for end-of-life cadmium telluride (CdTe) thin-film photovoltaic (PV) panels. Energy Policy 68, 524–533.
D'Adamo, I., Miliacca, M., Rosa, P., 2017. Economic feasibility for recycling of waste crystalline silicon photovoltaic modules. Int. J. Photoenergy 6.
DeGraaff, D., Lacerda, R., Campeau, Z., 2011. Degradation mechanisms in Si module

technologies observed in the field; their analysis and statistics. NREL 2011 Photovoltaic Module Reliability Workshop.
Dias, P., Bernardes, A.M., Huda, N., 2018. Waste electrical and electronic equipment (WEEE) management: an analysis on the Australian e-waste recycling scheme. J. Clean. Prod. 197, 750–764.
Dias, P., Bernardes, A., Huda, N., 2019a. Economic and Political Pressure on WEEE Recycling: An Example from Australia and Brazil.
Dias, P., Bernardes, A.M., Huda, N., 2019b. Ensuring best E-waste recycling practices in developed countries: an Australian example. J. Clean. Prod. 209, 846–854.
Dominguez, A., Geyer, R., 2017. Photovoltaic waste assessment in Mexico. Resour. Conserv. Recycl. 127, 29–41.
Domínguez, A., Geyer, R., 2018. Photovoltaic waste assessment of major photovoltaic installations in the United States of America. Renew. Energy.
Duflou, J.R., Peeters, J.R., Altamirano, D., Bracquene, E., Dewulf, W., 2018. Demanufacturing photovoltaic panels: comparison of end-of-life treatment strategies for improved resource recovery. CIRP Ann. Manuf. Technol. 67 (1), 29–32.
EnergyPLAN. (26-09-2017). E4Cast. EnergyPLAN. from https://www.energyplan.eu/othertools/national/e4cast/.
EPIA, 2016. European Photovoltaic Industry Association. from. http://www.epia.org/home.
Faircloth, C.C., Wagner, K.H., Woodward, K.E., Rakkwamsuk, P., Gheewala, S.H., 2019. The environmental and economic impacts of photovoltaic waste management in Thailand. Resour. Conserv. Recycl. 143, 260–272.
Fraunhofer, 2018. Photovoltaics Report, Fraunhofer ISE. from. . https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf.
Gaustad, G., Krystofik, M., Bustamante, M., Badami, K., 2018. Circular economy strategies for mitigating critical material supply issues. Resour. Conserv. Recycl. 135, 24–33.
Goe, M., Gaustad, G., 2014. Strengthening the case for recycling photovoltaics: an energy payback analysis. Appl. Energy 120, 41–48.
Goverment, A., 2018. Meeting of Environment Ministers (MEM). from. http://www.environment.gov.au/about-us/mem.
Held, M., Ilg, R., 2011. Update of environmental indicators and energy payback time of CdTe PV systems in Europe. Prog. Photovolt. Res. Appl. 19 (5), 614–626.
Hunt, L.P., 1976. Total energy use in the production of silicon solar cells from raw materials to finished product. 12th Photovoltaic Specialists Conference.
IEA-PVPS, 2014b. Trends in photovoltaic applications 2014. Survey Report of Selected IEA Countries between 1992 and 2013, IEA-PVPS T1-25:2014.
IRENA: Stephanie Weckend, I.-P. A. W., Garvin Heath, 2016. End -Of-Life Management: Solar Photovoltaic Panels. IRENA and IEA-PVPS.
Islam, M.T., Huda, N., 2018. Reverse logistics and closed-loop supply chain of waste electrical and electronic equipment (WEEE)/E-waste: a comprehensive literature review. Resour. Conserv. Recycl. 137, 48–75.
Islam, M.T., Dias, P., Huda, N., 2019. Comparison of E-Waste Management in Switzerland and in Australia: A Qualitative Content Analysis.
Kang, S., Yoo, S., Lee, J., Boo, B., Ryu, H., 2012. Experimental investigations for recycling of silicon and glass from waste photovoltaic modules. Renew. Energy 47, 152–159.
Katsigiannis, Y., Katsamaki, A., Rentoumis, M., Koulouridakis, P., Athanailidis, I., Bilalis, N., 2015. Evaluation of photovoltaic recycling methods using environmental indicators. Sol. Cells 3 3.3.
Latunussa, C.E., Ardente, F., Blengini, G.A., Mancini, L., 2016. Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Sol. Energy Mater. Sol. Cells 156, 101–111.
Lopion, P., Markewitz, P., Robinius, M., Stolten, D., 2018. A review of current challenges and trends in energy systems modeling. Renew. Sustain. Energy Rev. 96, 156–166.
Luo, D.-w., Zhang, G.-l., Zhang, J., 2008. LI jun1, LI Ting-ju1, 2 (1. School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, China; 2. State Key Laboratory of Materials Modification by Laser, Ion and Electron Beams, Dalian 116024, China); Principle and Research Progress on Preparation Solar Grade (SoG) Silicon by Metallurgical Route. Found. Technol. 12.
Mahmoudi, S., Huda, N., Alavi, Z., Behnia, M., 2018. Material flow analysis of the end-of-life photovoltaic waste in Australia. In: DEStech Trans. Environ. Energy Earth Sci. (iceee). International Conference on Energy, Ecology and Environment (ICEEE 2018). ISBN: 978-1-60595-590-2 ISSN: 2475-8833.
Malandrino, O., Sica, D., Testa, M., Supino, S., 2017. Policies and measures for sustainable management of solar panel end-of-life in Italy. Sustainability 9 (4), 481.
Marwede, M., Reller, A., 2012. Future recycling flows of tellurium from cadmium telluride photovoltaic waste. Resour. Conserv. Recycl. 69, 35–49.
Marwede, M., Reller, A., 2014. Estimation of life cycle material costs of cadmium telluride–and copper indium gallium diselenide–photovoltaic absorber materials based on life cycle material flows. J. Ind. Ecol. 18 (2), 254–267.
Marwede, M., Berger, W., Schlummer, M., Maurer, A., Reller, A., 2013. Recycling paths for thin-film chalcogenide photovoltaic waste—current feasible processes. Renew. Energy 55, 220–229.
McDonald, N.C., Pearce, J.M., 2010. Producer responsibility and recycling solar photovoltaic modules. Energy Policy 38 (11), 7041–7047.
Monier, V., Hestin, M., 2011. Study on photovoltaic panels supplementing the impact assessment for a recast of the WEEE directive. Final Report, ENV. G 4. pp. 6.
Moreno-Garcia, I.M., Palacios-Garcia, E.J., Pallares-Lopez, V., Santiago, I., Gonzalez-Redondo, M.J., Varo-Martinez, M., Real-Calvo, R.J., 2016. Real-time monitoring system for a utility-scale photovoltaic power plant. Sensors 16 (6), 770.
National-waste-policy, 2016. http://www.environment.gov.au/protection/waste-resource-recovery/national-waste-policy/product-stewardship/legislation/product-list-2016-17.
Osborne, M., 2016. IHS Forecasts Global Solar Market to Top 69GW in 2016. from. http://www.pv-tech.org/news/ihs-forecasts-global-solar-market-to-top-69gw-in-2016.
Padlewski, S., 2014. DEC-Selecting-Right-BOM-for-Solar-Modules, Dupont (2014, viewed October 2014) from Dupont,. www.dupont.com/content/dam/assets/products-and-services/solar-photovoltaic-materials/assets/DEC-Selecting-Right-BOM-for-Solar-Modules.pdf.
Paiano, A., 2015. Photovoltaic waste assessment in Italy. Renew. Sustain. Energy Rev. 41, 99–112.
Paiano, A., Lagioia, G., Cataldo, A., 2013. A critical analysis of the sustainability of mobile phone use. Resour. Conserv. Recycl. 73, 162–171.
Peeters, J.R., Altamirano, D., Dewulf, W., Duflou, J.R., 2017. Forecasting the composition of emerging waste streams with sensitivity analysis: a case study for photovoltaic (PV) panels in Flanders. Resour. Conserv. Recycl. 120, 14–26.
PV, R., 2014. Reclaim PV. from. http://reclaimpv.com/.
Radziemska, E., Ostrowski, P., Cienian, A., Sawczak, M., 2010. Chemical, thermal and laser processes in recycling of photovoltaic silicon solar cells and modules. Ecol. Chem. Eng. S 17 (3), 385–391.
Redlinger, M., Eggert, R., Woodhouse, M., 2015. Evaluating the availability of gallium, indium, and tellurium from recycled photovoltaic modules. Sol. Energy Mater. Sol. Cells 138, 58–71.
Research, G., 2016. Global PV Demand Outlook 2015–2020: Exploring Risk in Downstream Solar Markets. from. . https://www.greentechmedia.com/research/report/global-pv-demand-outlook-2015-2020#gs.Bf=I6NA.
Sander, K., Schilling, S., Reinschmidt, J., Wambach, K., Schlenker, S., Müller, A., Springer, J., Fouquet, D., Jelitte, A., Stryi-Hipp, G., 2007. Study on the Development of a Take Back and Recovery System for Photovoltaic Products. PV Cycles, Bruxelles (Belgique).
Sibley, S.F., 2011. Overview of Flow Studies for Recycling Metal Commodities in the United States. US Geological Survey.
Sica, D., Malandrino, O., Supino, S., Testa, M., Lucchetti, M.C., 2018. Management of end-of-life photovoltaic panels as a step towards a circular economy. Renew. Sustain. Energy Rev. 82 (3), 2934–2945.
Sinha, P., Kriegner, C.J., Schew, W.A., Kaczmar, S.W., Traister, M., Wilson, D.J., 2008. Regulatory policy governing cadmium-telluride photovoltaics: a case study contrasting life cycle management with the precautionary principle. Energy Policy 36 (1), 381–387.
Spence, A., 2016. Solar Panel Recycler Leads Australia in Emerging Industry. from. https://reneweconomy.com.au/solar-panel-recycler-leads-australia-in-emerging-industry-99038/.
Syed, A., 2012. Australian Energy Projections to 2049–50. from. https://archive.industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aep/australian-energy-projections-to-2050.pdf.
Syed, A., 2014. Australian Energy Projections to 2049-50. from. https://archive.industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aep/aep-2014-v2.pdf.
Syed, A., Penney, K., 2011. Australian Energy Projections to 2034–35. Bureau of Resources and Energy Economics, Canberra.
Tao, J., Yu, S.R., 2015. Review on feasible recycling pathways and technologies of solar photovoltaic modules. Sol. Energy Mater. Sol. Cells 141, 108–124.
Trading-Economics, 2017. Australia Imports. from. https://tradingeconomics.com/australia/imports-by-category.
Vodermeyer, C., 2013. Photovoltaics Long Term Reliability and Typical Error Patterns. from. www.agcs.allianz.com/assets/Global%20offices%20assets/Germany/Expert%20Days%202013/11%20Vodermayer_Photovoltaics%20Reliability.pdf.
Weckend, S., Wade, A., Heath, G., 2016. End-of-Life Management: Solar Photovoltaic Panels. NREL (National Renewable Energy Laboratory (NREL)), Golden, CO (United States).
Winneker, C., 2013. Global Market Outlook for Photovoltaics 2013–2017. European Photovoltaic Industry Association.
Xu, Y., Li, J., Tan, Q., Peters, A.L., Yang, C., 2018. Global status of recycling waste solar panels: a review. Waste Manag. 75, 450–458.
Yi, Y.K., Kim, H.S., Tran, T., Hong, S.K., Kim, M.J., 2014. Recovering valuable metals from recycled photovoltaic modules. J. Air Waste Manage. Assoc. 64 (7), 797–807.