Annual Projection of PV End-of-Life Volume and Hazardous Materials in Australia Until 2050

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This study contributes towards the sustainable management of end-of-life PV modules through the projection of PV waste flow in Australia covering the five regions in the National Electricity Market from 2007 to 2050. The projection is based on two time periods. For the first period the estimated PV waste is based on the actual installation of PV modules from 2007-2019. For the second period (2020-2050) the projection model considers three scenarios of future electricity demand (central change, slow change and step change), two different PV installation pathway (linear and ramp pathway) and two different PV waste generation scenarios (early-loss and regular-loss) to project future PV waste stream until 2050. The main findings show that the cumulative PV waste volume in Australia from 2007-2019 can reach approximately 16 kilotonnes, including 10 kilotonnes of glass, 2 kilotonnes of aluminium, 0.2 kilotonnes of other precious metals and 7.2 tonnes of hazardous metal. The cumulative PV waste volume will increase by more than 200 times by 2050, with 960-1300 kilotonnes of PV waste in Australia. The volume of annual PV waste in Australia will reach 20 kilotonnes, the estimated minimum waste volume to enale economically viable recycling infrastrure, in 2031. However, new cost-effective and environmental-friendly PV recycling technologies should be developed before this time so local Australian businesse can run profitable large-scale PV recycling facilities after 2031, to achieve the sustainable management of PV waste and reduce the consumption of raw materials. This will also minimize the environmental impacts derived from landfilling PV waste.

1. Introduction

The signatory countries of the Paris agreement, including Australia, aim to mitigate climate change by limiting greenhouse gas emissions, targeting net zero emission by 2050 (ClimateWorks Australia, 2017). One approach to achieve this goal is shifting our energy generation from fossil fuels to renewable energy (RE). Solar photovoltaics (PV) can account for approximately 60% of the renewable energy growth according to IEA (2019). However, as the average lifetime of solar module is around 30 years, several PV systems will reach the end of their life (EOL) in the near future. Therefore, PV waste management should be studied at an early date in order to plan a sustainable management strategy for future PV waste volume.

2. Methodology

Figure 1 shows the process used to develop an annual based projection of PV EOL volume and cumulative materials in Australia until 2050.

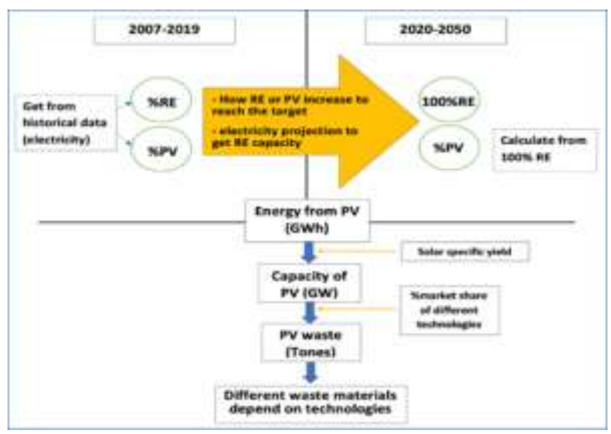

Figure 1 The processes of PV waste volume projection

2.1 Historical electricity generation by RE and PV (2007-2019)

Historical electricity generation from the National Electricity Market (NEM) was collected to determine the energy contributed by PV from five regions in the NEM, NSW (including ACT), QLD, VIC, SA and TAS (AER, 2020), together with PV installed capacity data from the Australian Photovoltaic Institute (APVI, 2020).

2.2 Projection of electricity demand (2020-2050)

The forecasted electricity demand from 2020-2039 was taken from AEMO (AEMO, 2019b) while the electricity demand from 2040-2050 was forecasted considering three scenarios (central change, slow change and step change) using the same average annual growth rates in the long-term period (10-20 years) forcasted by AEMO (AEMO, 2019).

2.3 PV percentage projection on the future electricity generation (2020-2050)

The percentage PV contributing to future electricity generation from 2020-2050 was projected considering the specific RE target of each state. The net zero emission target from the Paris Agreement was used for the states which do not have a specific RE target as presented in table 1.

Table 1 %RE and %PV in specific target year

States	2019		2022		2030		2050	
	%RE	%PV	%RE	%PV	%RE	%PV	%RE	%PV
NSW	13.75	5.33			50	8	100	57.08
QLD	9.23	7.63			50	32.09	100	62.09
VIC	20.27	4.85			50	22.69	100	52.69
SA	51.59	11.58			100	40.62	100	40.62
TAS	95.81	1.47	100	3.99	100	3.99	100	3.99

2.4 PV generation and capacity per year

The precentage of PV generation (see 2.3) and the annual forecasted electricity demand (see 2.2) were used to calculate the required PV energy (GWh) in the different target year (AEMO 2019). Then the PV generation was converted to the required PV capacity (GW).

2.5 The projection of annual installed PV capacity from 2020-2050

The annual installed PV capacity was assumed using two pathways, linear and ramp. The linear pathway was assumed to have uniformly annual installation, while the ramp pathway was assumed to grow exponentially according to Queensland Renewable Eenergy Expert Panel (2016).

2.6 The projection of annual and cumulative PV waste

The annual and cumulative PV waste was estimated by applying the Weibull distribution function as shown in equation (1).

$$F\ (t) = 1 - e^{-(t/T)^{\alpha}} \qquad (1)$$

The time in year (t) is 0 - 40 years, and the average lifetime of PV panel (T) is assumed to be 30 years according to IRENA, 2016. α is the shape factor, which controls the typical S shape of the Weibull curve. This study compared two PV module losses scenarios. Early loss considers higher possibility of infant failure due to improper installation or transport, while regular loss only considers intrinsic module failure. The shape factors are 2.4928 for early-loss and 5.3759 for regular-loss (IRENA 2016).

The annual and cumulative PV waste in GW was converted to waste volume in tonnes by assuming the average weight-to-power ratio of c-Si solar modules from IRENA (2016). The weight-to-power ratio of other solar cell technologies was taken from Domínguez and Geyer (2017). The market share of each solar cell technology and the material composition in differnt PV modules (including BOS) were taken from Mahmoudi *et al*. (2019) to calculate the PV waste volume.

3. Results and findings

As shown in figure 2, cumulative PV waste will reach 960 kilotonnes by 2050 in the regulor-loss scenario, which is 200 times more than the culmulative waste by 2019. The early-loss projection estimates much higher total PV waste steams, with 1300 kilotonnes by the end of 2050. This is because early-loss scenatio assumes a higher percentage of early PV panel failure than the regulor loss scenario.

The mainstream of PV waste is mainly taken by NSW, QLD and VIC. Choi and Fthenakis predicted that 20 kilotonnes is the minimum amont of annual waste to run profitable PV recycling infrastructure (Choi and Fthenakis, 2014).The total annual PV waste generated from five states will reach 20 kilotonnes/year by 2030-2031, however, NSW and QLD will reach 20 kilotonnes/year of annual PV waste between 2040-2044, which is earlier than VIC that will reach that volume by 2045-2049.

The annual percentage of each material group in PV waste depends on the market share of different solar cell technologies and advance in those technologies. The percentage of hazardous metals will slightly increase from 0.04% in 2010 to 0.08% in 2050 as shown in

Table 2. This is because the market share of thin-film solar cell technology is expected to increase after 2020 (Mahmoudi et,al 2019), which constitutes more hazardous metals such as Cd and Se. This also bring the problem of proper treatment toxic Cd and Se used in thin-film PV modules.

The mainstream of PV waste was projected in Australia by 2050 is glass and aluminium at approximately 720-1070 kilotonnes and 110-165 kilotonnes respectively as presented in Table 3.

Table 2 The annual percentage of five material groups in Australia (central change) with linear installed pathway and early-loss scenario.

Material lists		Year				
		2010	2020	2030	2040	2050
Precious Metals Base and special metals (Ag, Al, Cu, Ni, Fe, Ti, Sn ,Cr, Mn, Mo)		14.9%	14.7%	12.6%	12.6%	12.6%
Hazardous metals (Cd, Pb, Se)		0.04%	0.04%	0.08%	0.08%	0.08%
Critical substances (Mg, Ga, In,		0.46%	0.45%	0.40%	0.40%	0.40%
Other metals (Si, Steel)		9.4%	8.2%	6.1%	6.1%	6.1%
Other materials	EVA	6.3%	6.0%	5.6%	5.6%	5.6%
	Glass	69%	71%	75%	75%	75%

Table 3 The comparison of mainstream waste in Australia between 2019 and 2050.

Year	Scenarios	Glass	Aluminium
		kilotonnes	
2019		10	2
2050	Linear pathway/ Early-loss	1070	165
	Linear pathway/ Regular-loss	800	122
	Ramp pathway/ Early-loss	970	150
	Ramp pathway/ Regular-loss	720	110

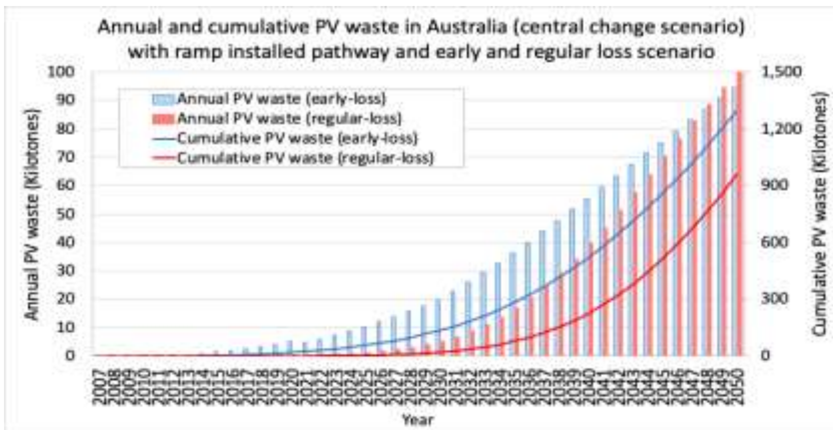

Figure 2 The annual and cumulative PV waste in Australia (central change scenario) with ramp installed pathway and early and regular-loss scenarios, 2007-2050.

4. Discussion and conclusion

This study provides a comprehensive waste projection model to assess the volume of end-of-life PV modules in Australia by including three levels of future electricity demand, two PV installation pathways and two waste generation scenarios. The cumulative PV waste forecasted in this study is 960-1400 kilotonnes in 2050, which is higher than 900-950 kilotonnes forecasted by IRENA, 2016.The forecasting from IRENA was 33% lower than this study for early-loss scenario and 15% for regular-loss scenario. This is because the rapid cost-reduction in PV manufacturing is driving faster rate of PV growth in Australia. As a result, the total volume of installtion and decomission in this study is higher than the prediction made in 2016. The cumulative PV waste estimated by Mahmoudi et,al. (2019) is around 800-1000 kilotonnes by 2047, which is within the range of the result in this study, which shows the cumulative PV waste in 2047 is around 675-1125 kilotonnes, depending on the scenario.

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