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END-OF-LIFE MANAGEMENT OF PHOTOVOLTAIC PANELS IN AUSTRIA: CURRENT SITUATION AND OUTLOOK

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ABSTRACT

In recent years the end-of-life (EOL) management of photovoltaic (PV) panels has started to attract more attention. By including PV panels in the WEEE Directive in 2012 the European Union has introduced a concrete legislative framework regarding EOL for this sector. Several research investigations into specialized PV recycling processes have been conducted over the last years, although very few of the findings have been implemented on a commercial level up to now. Nowadays, recycling usually still takes place in general recycling plants for flat glass or waste electronics. In this work, the current situation regarding EOL management of PV panels in Austria is analysed by literature research and interviews with stakeholders relevant to the EOL of PV panels. The legislative framework (including national peculiarities) and its influence on current procedures regarding collection and subsequent treatment is shown. Furthermore, current recycling processes are described and a country specific prognosis model is created to assess the future development of waste quantities. Results show that the amount of PV panel waste arising in Austria at the moment is very small and therefore no dedicated recycling takes place. However, quantities will considerably rise in the upcoming years and will act as the main driving force for the implementation of an improved EOL management system including specialised recovery processes.

1. INTRODUCTION

The role of renewable energy sources has, in view of a sustainable energy supply, steadily increased and become more important in recent years. One key technology in this field is photovoltaics (PV). Worldwide PV capacity has increased from 1.5 GW in 2000 to over 500 GW in 2018 (Jäger-Waldau 2018), with projections of a further increase to over 4.500 GW in 2050 (Weckend et al. 2016). While the PV industry has drawn continuous attention and achieved improvements relating to issues like increased cell efficiency and lowered production costs, end-of-life (EOL) aspects have started to attract widespread attention only recently. This can be attributed to the long lifetime of PV panels and the thereby created gap between the time when a panel is being put into operation and its emergence as waste at EOL.

The European Union (EU) has introduced PV specific legislation by updating the Directive on waste electronical and electric equipment (WEEE) in 2012 and including PV in its scope (European Commission 2012). The directive contains important aspects like extended producer responsibility (EPR) in regard to financing the collection, treatment, recovery and disposal of WEEE, obligations relating to registration, information and reporting as well as targets for collection and recovery including recycling. As with all EU directives, each member state had to transpose its contents into national law (EUR-Lex 2018). In the field of WEEE and especially for PV this resulted in several country specific regulations, which influence the organisation of collection and recovery regarding EOL panels. When talking about EOL of PV panels, a distinction between the various technologies is important, as the different material contents (valuable as well as hazardous) are of significance for the recycling process. For this work, two main classifications are considered and distinguished – crystalline silicon (c-Si) panels and thin-film panels (e.g. CdTe, CIGS). Further details on the different technologies, their structure and the materials contained within can be found in Lunardi et al. (2018). At the moment, only few specialised recycling facilities for PV panels exist on a commercial level (Xu et al. 2018). This is mainly due to the fact that the amount of currently generated waste is low. As a result, stand-alone recycling plants are not economically feasible (Cucchiella et al. 2015; D'Adamo et al. 2017). For c-Si panels the processing at EOL nowadays

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takes place in existing recycling plants, e.g. flat glass recycling plants as well as general WEEE recycling plants. The process consists of mechanical separation of the major components (glass, metals and plastics) and usually does achieve legal compliance even without PV specific investments (Wambach 2017; Weckend et al. 2016). Thin-film panels are currently processed by combining mechanical and chemical steps. For CdTe panels, the company First Solar has established a (commercial) process that includes shredding the module, etching of the semiconductor layer, solid/liquid separation and subsequent purification of the different fractions, namely glass, laminate material and the semiconductor metals Cadmium and Tellurium (Komoto and Lee 2018). Looking ahead, several studies predict a high increase in the amount of PV waste on a global scale as well as for different regions during the coming years (Paiano 2015; Peeters et al. 2017; Santos and Alonso-García 2018). Associated with this, a lot of research regarding new PV specific recycling options has been conducted recently (Lunardi et al. 2018; Xu et al. 2018).

Currently Austria is not one of the key PV markets, measured by already installed capacity. However, the steady increase in installations over the last years, combined with high goals regarding future developments in this field, make it interesting for the primary PV industry as well as the EOL sector. The aim of this work is to depict the current EOL situation of PV panels in Austria, elaborate on the different factors that have an influence on it and show how they are interconnected. This includes (1) investigation of PV related legislation with focus on the national particularities and their effect on the EOL system, (2) examination of current practices in regard to collection and recovery of EOL panels and (3) a country specific waste prognosis. This information can subsequently be used as the basis for future developments regarding a sustainable EOL management of PV panels.

2. MATERIALS AND METHODS

2.1 Legislative Framework

The WEEE Directive as well as the main documents for the national transposition in Austria were screened for information regarding photovoltaics. In addition, the corresponding regulations in other European countries, especially those relevant to the PV industry (Germany, Italy, France, Spain and the UK) were checked to identify similarities and differences between different implementations of the WEEE Directive throughout Europe. Additionally, relevant stakeholders in Austria were interviewed. This included:

- 2 PV panel producers,
- 3 waste management companies (that have received EOL panels for treatment),
- 2 WEEE compliance schemes and
- the national coordinating institution for WEEE, the so called Elektroaltgeraete Koordinierungsstelle (EAK).

Furthermore, information made available by European stakeholders (primarily compliance schemes) was used as a reference, mainly for double checking the information from the corresponding national legislative documents.

2.2 Current EOL management of PV panels

The main research method regarding current EOL practices were the qualitative interviews with the Austrian stakeholders mentioned in 2.1. The aim was to obtain information regarding the PV market in Austria (in general) with a focus on the emergence, collection and subsequent treatment of EOL PV panels on a national level. Although no fixed questionnaire was used, the following questions are an overview of the main aspects discussed with all interview partners:

- What quantities of PV waste are currently emerging in Austria and how is the collection organized?
- How does the treatment of EOL panels look like in Austria? What materials are recovered?
- How does the legislative framework influence the EOL management?
- How do you expect the Austrian PV market to develop in the coming years (installed capacity, used technology)?
- What, if any, changes do you expect regarding the EOL situation in Austria in the coming years and which factors will be the main drivers?

In addition, publications by the EAK as well as the National Waste Management Plan and its corresponding status reports were consulted. Literature about the progress in other countries along with ongoing research regarding EOL management of PV was also considered. Although there is no direct applicability for the current situation in Austria, this information can be relevant for future developments.

2.3 PV panel waste prognosis

The waste prognosis model is composed of two parts, namely the creation of an adequate Weibull function and the specification of the installed PV panel mass in the considered timeframe (2000 to 2050). Those aspects as well as the actual calculations are subsequently explained.

2.3.1 Weibull model

The Weibull distribution was originally proposed in 1937 to estimate machinery lifetime. Nowadays, the distribution is a broadly used statistical model in reliability engineering and life-time data analysis (Ng and Wang 2009). It is considered to be the most suitable approach to describe discard behaviour for electrical and electronic equipment (EEE) and has been applied frequently in scientific literature (Forti et al. 2018). In its easiest form, it only takes the wear out phase into account. This simplification is appropriate for this case, as a population of panels from many different manufacturers is assumed (Kleiss 2016). Therefore the cumulative failure probability (p_{cumm}) after a certain operational time can be described with Equation 1, according to Wambach and Sander (2015) and Weckend et al. (2016). The specific failure probability (p_{spec}) in a certain year x can be calculated by Equation 2.

$$F(x) = p_{cumm,after\ x\ years} = 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \quad (1)$$

Equation 1: Simplified Weibull function (wear out only)

$$p_{spec,in\ year\ x} = p_{cumm,after\ x\ years} - p_{cumm,after\ (x-1)\ years} \quad (2)$$

Equation 2: Failure probability in a certain year (x years after installation)

The two relevant parameters for Equation 1 are the shape factor α and the characteristic lifetime β. These values were adopted from Weckend et al. (2016) and are α = 5.3759 for the Regular Loss Scenario and α = 2.4928 for the Early Loss Scenario with a characteristic lifetime of β = 30 years in both cases. The assumption regarding lifetime was also supported by the interviewed stakeholders. The main difference between the considered scenarios is that the Regular Loss Scenario includes no early attrition, while the Early Loss Scenario also considers defects during the lifespan e.g. during transportation and installation. Further details on the scenarios can be found in Weckend et al. (2016). The obtained values fall in line with several other publications. Forti et al. (2018) for example mention an α-value of 3.5 (which sits in the middle of the two scenarios from Weckend et al. (2016). Considering the lifetime (= β), they suggest 25 years, which is also a common value found in literature.

2.3.2 Yearly installed PV panel mass

Historic data regarding installed PV capacity in Austria is available in Biermayr et al. (2018) for the timeframe 2000 to 2017 (shown in Figure 1). Installation numbers before 2000 were very small and therefore negligible. From 2018 on, a yearly capacity increase projection based on the qualitative research (compare to 2.2) was used. An average value of 400 MW of new PV capacity per year from 2020 to 2050 was deemed reasonable by the stakeholders questioned. For the transition years, values of 250 MW for 2018 and 300 MW for 2019 were used.

The conversion from installed PV-power to panel-mass was based on values taken from Weckend et al. (2016). Between each of the directly adopted values (see Table 1), a linear integration was done to simulate a steady decline in average weight to power ratio over the corresponding years.

2.3.3 Calculation of projected waste

By multiplying the mass of PV panels installed in a certain year with the specific failure probability for all subsequent years (here, relative values e.g. 5 years after installation are used), a yearly waste distribution for those panels was achieved. The summation of all values arising in the same year (here, absolute values like 2025 are considered), results in the total waste amount for each year.

3. RESULTS AND DISCUSSION

3.1 Legislative Framework

In Austria the transposition of the European WEEE Directive was achieved by updating the Elektroaltgeraeteverordnung (EAG-VO) in 2014. The EPR as well as the definition of a producer, which includes (1) manufacturers, (2) resellers, (3) importers and (4) direct sellers (by distance communication) were unalteredly adopted. In general, EEE can be classified as business to consumer (B2C) or business to business (B2B) products. The B2C classification applies to equipment intended to be used in private households and to equipment used in other areas which, because of its nature and quantity, is similar to that for private households. Equipment not meeting the aforementioned characteristics is classified as B2B. All PV panels put on the market are classified as B2B products in Austria, not considering whether they are actually used by businesses or private households. The arising waste is therefore always classified as professional waste. This is in stark contrast to most EU member states where PV pan-

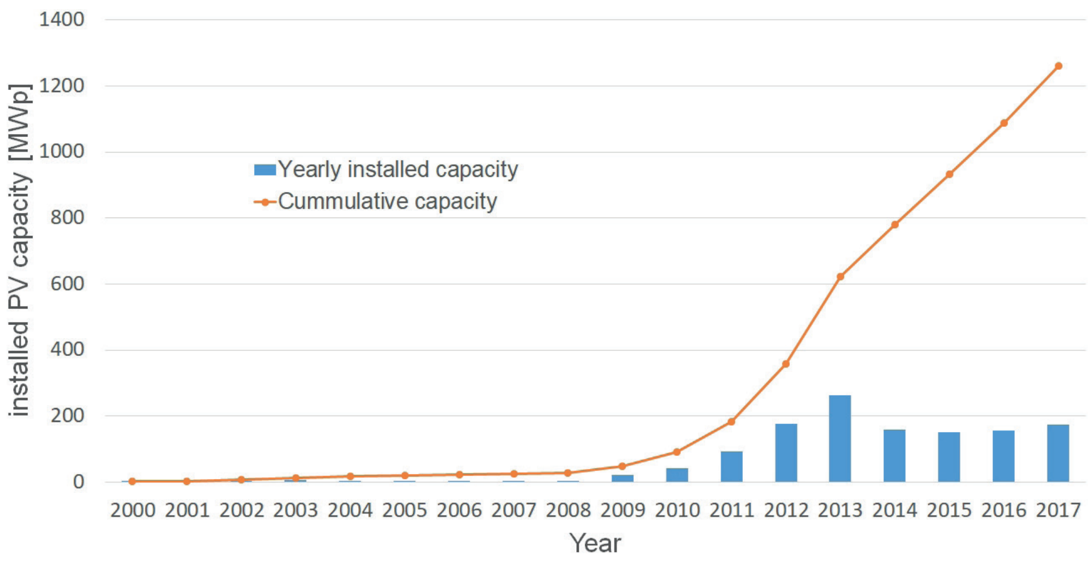

FIGURE 1: Installed PV capacity in Austria from 2000 to 2017 according to Biermayr et al. (2018).

TABLE 1: Weight to power ratio of PV panels according to Weckend et al. (2016).

Year	Weight to power ratio [t/MW]
2000	110
2005	100
2010	90
2015	70
2030	60
2050	45

els are classified as B2C products, e.g. the UK and France (GOV.UK 2018; Solar Waste, n.d.) or a differentiated system with both B2B and B2C classification is used as it is the case in Germany and Italy (Deutscher Bundestag 2015; Malandrino et al. 2017).

While all EOL PV panels are considered professional waste, a distinction is made between historic and new PV panels. This is of relevance when determining who is responsible for financing the collection and treatment at the EOL stage. In this regard the date on which the panel was put on the market is relevant, with the 1st of July 2014 being the cut-off date. For PV panels put on the market in Austria before this date, the responsibility lies with their owner at the EOL stage when no replacement with new equivalent products takes place. However, if the old panels are substituted, the producer of the new panels is responsible for financing the collection and treatment of the old ones. In case of panels put on the market after the cut-off date, the responsibility of financing the EOL costs lies with the original producer whether or not a replacement with new panels takes place. These aforementioned stipulations were taken from the WEEE directive, although the exact cut-off date is a national particularity.

In regards to the six WEEE categories specified in the European directive, Austria has implemented an adaptation with six modified categories. PV panels are a separate "collection and treatment category" and have specific recycling targets, although the values are equal to those for large equipment, which is where PV panels are classified in the WEEE directive. Those targets, as of the 15th of July 2018, are (1) 85 w. % in regard to recovery and (2) 80 w. % concerning preparation for re-use and recycling. However, the target regarding collection (65 w. % of EEE put on the market on average in the last three years in the respective member state) is not applied to the different categories but rather across the sum of all WEEE (European Commission 2012). The share of PV panels in regard to all EEE put on the market is currently about 3.35 w. %, while their share regarding collection is even lower with 0.02 w. % (EAK 2018).

3.2 Current EOL Management of PV panels

3.2.1 EPR and Collection of EOL PV panels

The previously mentioned B2B classification of all PV panels on the one hand simplifies the EOL requirements for producers. Contrary to the case of B2C EEE no financial guarantee is needed and it is not compulsory to take part in a compliance scheme as a producer of historic waste. On the other hand, this setup does not really encourage the implementation of a nationwide solution but rather facilitates stand-alone approaches that are feasible for the individual producers. This is further supported by the previously mentioned fact that PV panels make up only 0.02 w. % of collected EEE.

In regard to PV panels put on the market today, three options are available to producers for fulfilment of the EPR:

1. Implementation a self-organised take-back
2. Taking part in a compliance scheme on a voluntary basis
3. Usage of the compliance scheme as a service provider

In case of the self-organised system all responsibilities, including the obligatory documentation and reporting to the authorities, are assumed by the producer directly. Old PV panels are first taken back by the producer and subsequently handed over to a treatment facility. Taking part in a compliance scheme works in the same way as it does for other WEEE. At the time of putting the panels on the market, a fee, in relation to the amount of panels, is paid to the compliance scheme. By doing so, most of the responsibilities are transferred to the scheme. At the moment the fee for PV panels is 0.12 Euro per piece for several compliance schemes in Austria (ERA 2018; Interseroh 2018). The last option can be seen as a merged solution between the other two, where no fee is paid upfront but rather the costs arise at the time the compliance scheme is used as a service provider when EOL is reached. In this case, individual agreements are established between the producer and the compliance scheme as to what aspects of the EPR are covered by the service and what parts the producer has to fulfil themself. The stakeholder interviews have shown that nowadays the self-organised system and the service provider system are the ones primarily used by Austrian PV panel producers. The amount of licensed PV panels, meaning the use of a classical compliance scheme, is marginal.

3.2.2 Treatment of EOL PV panels

According to the EAK in 2016 and 2017 a total of 12 respectively 22 tonnes of PV panel waste was reported and collected (EAK 2017, 2018), although the actual number might be higher due to the fact that a part of the arising PV waste is reported under a wrong category or not reported at all. As previously mentioned, this amount makes up only 0.02 w. % of all collected EEE. These very low quantities are the main reason why no dedicated recycling plant for PV panels exists in Austria. As a consequence, no uniform way of treatment for EOL panels is used at the moment (BMNT 2018). Although a flat glass recycling plant is available, treatment of PV panels is not performed at this facility as it is the case in other European countries e.g. Germany and Belgium. The recovery and recycling process in Austria is performed by different parties including waste management companies (usually those already active in WEEE treatment) and the scrap industry. An individual recycling approach, dependent on the type of panel (c-Si or thin-film) and its condition (e.g. broken glass plate, electrical fault) is implemented. Usually panels are stored until a reasonable number of similar panels is reached, regarding the aforementioned criteria (technology and condition). Details about the recoverable materials depending on the different technologies can be found in Lunardi et al. (2018). Treatment in most cases starts with a manual step for removing the aluminium frame (if applicable) and the junction box with cables. Subsequently, mechanical processes are applied for crushing the panel and separating it into different streams containing profitable materials (e.g. metals, glass) that can be sold. Valuable materials, e.g. silver in c-Si panels or the semiconductor material from thin-film panels are not specifically recovered. At the moment it is unclear how long this treatment system will remain feasible, but stakeholders agree that the rise in waste quantities will at some point induce the need for a more autonomous EOL management system for PV panels. According to some stakeholders, the increase in waste could also lead to the adoption of more specific legislation regarding the recycling process (e.g. the need to recover certain valuable materials or to remove hazardous ones), although they do not think it will happen in the next years.

3.3 Waste projections

Figure 2 shows the probability of failure in a certain year after installation for both applied scenarios (Regular Loss and Early Loss). The Regular Loss distribution shows a higher and more concentrated peak, meaning that most failures will occur in a shorter timespan during the latter part of the product life, while the Early Loss distribution shows failures that are spread out more evenly over the whole lifetime.

The results of the prognosis model can be seen in Figure 3. The waste prognosis shows a significant increase of PV panel waste in Austria for the upcoming years, e.g. an increase by a factor of 30 to 200 in a 10-year-timespan (2016 to 2025) depending on which scenario is considered. The threshold of 2.000 tonnes per year will be reached in 2031 (Regular Loss) or in 2024 (Early Loss) respectively. This can be seen as the critical amount in regard to the construction of a specialized PV recycling plant, when considering the fact that a currently active commercial plant in France treated around 1.800 t in 2018 (Veolia 2018). Comparing the Austrian prognosis to those of other regions, a similar trend can be observed regarding the relative distri-

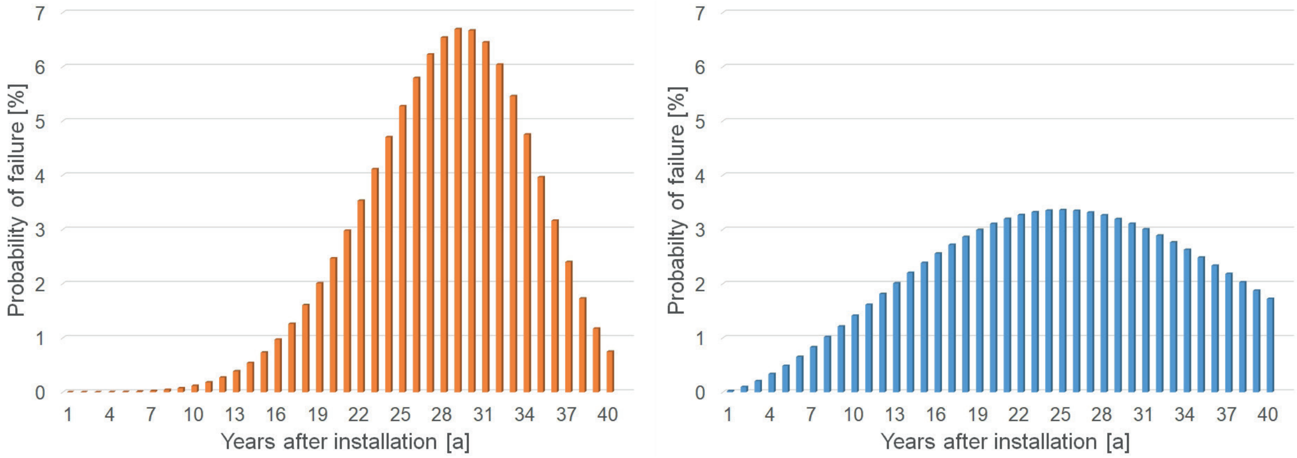

FIGURE 2: Specific probability of failure according to Weibull function (a) Regular Loss scenario, (b) Early Loss scenario.

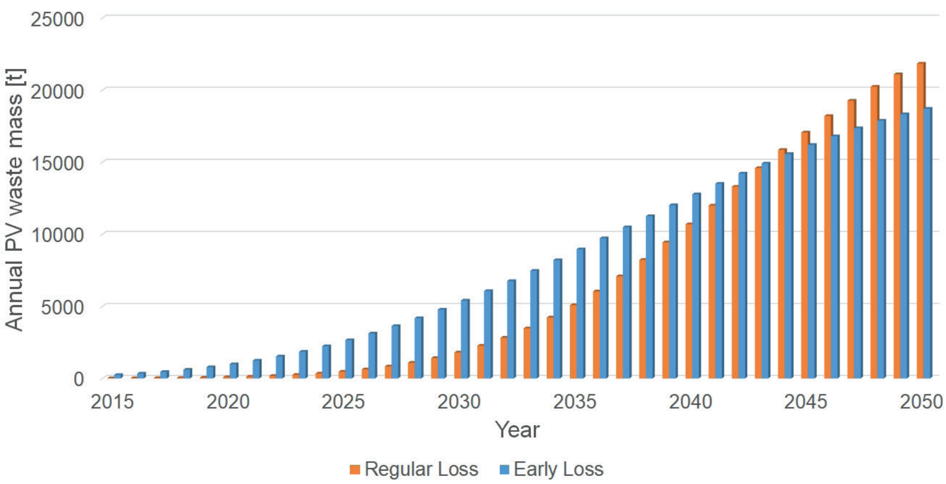

FIGURE 3: PV panel waste projection for Austria.

bution of PV panel waste for the coming years although the absolute values for Austria are lower. This was expected and can be explained by the lower amount of installed PV capacity. It is important to note that there are several uncertainties regarding this prognosis, the main ones being (1) the projection of future installed capacity and (2) the non-inclusion of one-time effects like repowering, meaning the replacement of still working panels with new ones with higher efficiency. While these uncertainties have to be kept in mind, it has to be noted that the capacity projection is rather conservative (e.g. PV Austria (2018) indicates a much larger growth in the coming years) and does not influence the short-time prognosis significantly, as only a small amount of those panels will emerge as waste in the next years. Additionally, repowering is probably not as big of a factor in Austria compared to other countries like Italy or Spain because most installations are not operated as commercial plants and are therefore not mainly profit oriented. A comparison shows that the waste quantities according to the Regular Loss Scenario for 2016 and 2017 correspond rather well with the real numbers published by the EAK (EAK 2017, 2018). Therefore, the present prognosis can be seen as a good basis in regard to future waste quantities. Still, continuous monitoring and evaluation of the EOL situation should be performed. The collection of more statistical data (e.g. if the real lifetime corresponds with the 30 years that have been assumed) will enable a more reliable and precise forecast, which in turn will be a more concrete basis for future decisions.

4. CONCLUSIONS AND OUTLOOK

The situation regarding EOL management of PV panels in Austria was investigated. Concerning the legal framework for photovoltaic waste, it was shown that although legislation in all EU member states is based on the WEEE-Directive, specific national characteristics exist and influence the way EOL processes are set up. The applied B2B classification for all PV panels in Austria (in combination with the different options available for EPR fulfilment) enables a flexible approach for the producers but also somewhat hinders the implementation of nationwide EOL solutions. Stakeholder interviews showed that at the moment collection and subsequent treatment of EOL panels in Austria is performed in a decentralized way by several different parties. The applied recycling technologies are not PV specific but rather combinations of manual and mechanical process steps accounting for the type and condition of the respective panels. As this approach complies with the mandatory recycling rates, there is (at least currently) no need or incentive for change in this regard. The applied prognosis model however shows a significant increase in PV panel waste for the upcoming years. Even the more conservative approach (Regular Loss) predicts an increment of the factor 30 from 2016 to 2025. This increase is also seen as the main driver regarding changes to the EOL management system and adoption of PV specific recycling technologies, by the interviewed stakeholders. These will be important for guaranteeing the long-term reliability of EOL activities while potentially also increasing the economic potential of recycling processes. Therefore, it is necessary to continuously monitor the EOL situation, in order to obtain more reliable data. This will enable more precise predictions, which subsequently should be used as reference for future decisions regarding the EOL management of PV panels.

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