Modeling of Photovoltaic Waste Projection and Management Considering the Mozambique Scenario

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Abstract

The consumption of energy from fossil sources since the industrial revolution to the present day and the current demand for energy has stood out as the main causes of adverse weather phenomena and extreme events that the world experiences. as a way of reversing and dealing with this situation, renewable energy has proven to be the best solution, especially photovoltaic solar energy. Mozambique is a country with a high photovoltaic potential and therefore countless projects are in operation, under construction, and yet to be implemented. Accompanying this proliferation is important to estimate the waste generation is made for the next 20 or 30 years and an adequate management plan is elaborated. This study makes a projection of the generation of photovoltaic waste that will be generated in the coming years to reach the goal of solar electrification in Mozambique and, in addition to that, shows the best ways of dismantling photovoltaic plants. The projection of photovoltaic residues is based on the Weibull distribution function and then an optimization is performed in order to make the mathematical model more realistic. The results of this projection show the viable year for the start of photovoltaic waste management activities and therefore the amount of waste to be recycled and/or discarded.

Keywords:

Waste projection
Photovoltaic waste management
Modeling and optimization
Mozambique Solar Energy
Weibull distribution

1. Introduction

Renewable energy although sustainable and clean, little is known that these systems and their construction may not be fully sustainable (1). Sustainability is defined in several studies as meeting the needs of the present without compromising the needs of future generations, jointly meeting economic, social, and environmental aspects. (1) (2). Solar PV technology is the one that has grown the most among renewable energies, according to IRENA, the implementation of photovoltaic solar energy has grown without precedent since the beginning of the 2000s, and as this market grows, so does the future volume of waste photovoltaic panels (3).

Photovoltaic waste at the end of its useful life represents an environmental threat worldwide, the exponential growth recorded in the last decade has the potential to generate millions of tons of photovoltaic waste by the middle of the century. Inadequate waste management could lead to renewed energy poverty, requiring a neutral sustainability approach. (4).

With the growing increase in the volume of photovoltaic waste, some studies have been carried out in some countries, making the projection of photovoltaic waste by applying the two-parameter Weibull distribution function, to describe the probabilistic distributions of failures and degradation of photovoltaic modules, in the most of them considering the regular crashes and earlier crashes.

The present study deals with the projection of photovoltaic waste using the scenario of Mozambique, with the aim of analyzing the country's growth in this sector and being able to predict the produced quantity of certain components and provide theoretical bases on how to make solar energy in Mozambique sustainable and with an appreciable circular economy in the coming years.

Studies are currently being developed in order to make PV solar energy sustainable and in order to prepare the future scenario of dismantling photovoltaic installations in operation and construction in recent years. Among them, the most generic was proposed by IRENA (3) where a guiding model for the projection of photovoltaic residuals using the two-parameter Weibull probability distribution function is provided. Then many other studies have been carried out using reasoning and applying it in different scenarios and perspectives, such as the case of (5) studied about the projection of photovoltaic waste in China using two mathematical models, the first one to predict the installed capacity and the second (Weibull Distribution) to predict future flows of residual photovoltaic modules using various scenarios and addressing about the different factors that affect the earlier module failures such as plant maintenance and assembly. These models, in the optimistic scenario, predicted the year of the first disposal of photovoltaic modules and the accumulations until the year 2040. (6) studied the projection of photovoltaic waste applying in the first part of their work the Weibull mathematical model and the socio-environmental decision-making factors connecting them to energy purchase contracts, where they used data from c-Si and CdTe photovoltaic projects in the UAE, and , then elaborated an optimization model for PV waste management, looking at the total of future installations and possible PV replacements, considering financial constraints and decommissioning capacities. (7) in his article on the net benefits of recycling photovoltaic waste in China, he projected photovoltaic waste by combining a multifactor gray neural network model with the Weibull distribution model to predict the amount of photovoltaic waste including BoS, where he addressed about the different types of recycling of PV waste and its economic and environmental benefits, taking into account the different scenarios.

(4) carried out a social, economic and environmental analysis of photovoltaic waste, in his environmental life cycle analysis he found that recycling photovoltaic waste can significantly reduce human toxicity and freshwater ecotoxicity by approximately 78%, and with the recycling process It is possible to achieve the sustainability of solar energy. Several studies address this philosophical debate on the sustainability of photovoltaic solar energy due to the production of pollutants during the transformation of the raw material and also due to the amount of photovoltaic waste produced.

In this study, two main perspectives will be brought to photovoltaic systems, the first related to grid-connected main-grid systems such as photovoltaic power stations and the second perspective to mini-grid systems and off-grid systems. The present study will be based on the application of the Weibull probability distribution function and the cumulative probability distribution function for the calculation of PV residuals, and will take into account the different scenarios studied by (5) namely the optimistic scenario, baseline scenario and pessimistic scenario, and also applied the innovative model to determine the best year to start PV waste management proposed by (6) with the application of socio-environmental decision factors.

In systems connected to the grids, government projects were selected or included in the electrification plans created by the government in compliance with the 2030 electrification agenda. Mini-grids are projects carried out by FUNAE in compliance with the Energy for All program, where most of them are projects in areas where they are not covered by the national EDM network

1.1. Factors that contribute to solar panel failure

Currently, in Mozambique, there is a factory dedicated to the assembly of solar panels, the FUNAE Solar Panel Factory. The constituent components of photovoltaic modules are mostly sourced from China.

According to (5) in their approach to the quality of photovoltaic modules in China, they listed 4 main problems related to the failure of photovoltaic modules, and these can be added to others and applied in the scenario of Mozambique.

- Problems related to hot spots, cracks, snail tracks on modules, yellowing and cracking of backplates, corrosion and poor wind resistance, among other factors. These associated factors can cause some plants to decline in their production after two or three years of operation.
- Failures of PV module components and parts can also occur frequently. Generally, photovoltaic plants exhibit frequent failures in their first two to 6 years of operation and most of these failures occur in modules, inverters, and other key components. When photovoltaic modules have soldering or metallization failures, degradation of the encapsulating material or failure in the junction box and connector, these failures can occur in less time and reduce.
- The installation and maintenance of photovoltaic plants represent more than 1/3 of failures and safety problems (5) In Mozambique, most photovoltaic plants, mainly mini-grids, are managed as designs and the decay of photovoltaic modules and the inefficiency of power generation represent major challenges. Issues related to poor maintenance and difficulty in replacing damaged materials, as well as the creation of dedicated cleaning systems to avoid dust accumulation and shading, are also significant.
- Security accidents can happen frequently. Photovoltaic plants can be destroyed and/or damaged by strong winds, fires and other accidents.
- The integrity of the module components as well as the module itself during transport for assembly and installation.

2. Methodology

2.1. Basic model training and data collection

The present study uses the method proposed by IRENA in (3), which goes through 3 main phases, namely, the transport of the panels, installation and disposal at the end of the panel's life. The future photovoltaic waste stream can be quantified according to the model described by the author, where the two main input factors are the conversion of the panels capacity (GW) to units of mass (tons) and estimated PV panel loss (probability of failures during the life cycle). Then two different scenarios are applied to the model using the Weibull distribution function, the regular-loss and the early-loss scenarios.

For the conversion of capacity (GW) to unit mass (Ton), IRENA proposes a correction factor assuming that the panels are becoming more powerful and lighter over time. This factor is based on a least squares exponential fit of the weight-to-power ratio as shown in figure 1.

To estimate the amount of photovoltaic waste by looking at the two scenarios above using the Weibull distribution, consider that in the regular loss scenario use a form factor of 5.3759 and consider the 30-year average lifetime of the PVs of c-Si and the maximum technical service life of 40 years. The early-loss scenario, many studies consider a form factor of 2.592 and therefore consider several sources of loss over the useful life of the panels, namely: 0.5% installation losses, 0.5% losses in the first two years of use, 2% losses after 10 years of use and 4% losses after 15 years of use (6).

The two-parameter Weibull distribution function β which is a shape parameter o and η which is a size parameter in its original form is presented as follows:

$$f(t,\beta,\eta) = \begin{cases} \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-(t/\eta)^{\beta}}, & x \geq 0 \\ 0 & x < 0 \end{cases} \qquad (1)$$

Where t represents the lifetime of the modules.

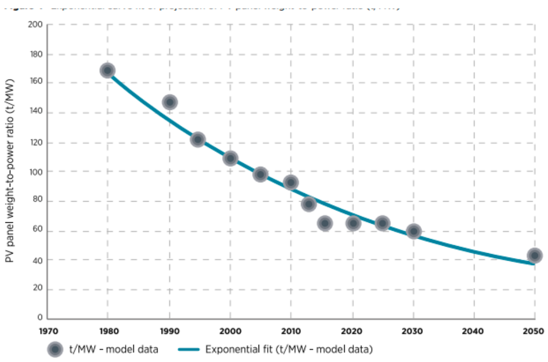

Figure 1: The weight-to-power ratio of PV modules (3)

Data collection was carried out mostly on websites and magazines accessible in Mozambique (8) and also in some companies in Maputo province such as the FUNAE solar panel factory, and the aluminum cable and rod factory in Beluluane called Midal Cables International.

Most of the photovoltaic power plant projects described in Table 1 have not yet been implemented and do not have a start date, part of them because the tender for awarding the builders and managers of the same is waiting to take place. These projects, for the sake of projection, assumed the start of operation in the year 2025. For the projects in mini-grids, described in Table 2, the sites and/or entities do not provide the start year, for the purposes of studies those already in implementation, 2019 was considered in this study as the start year, as this is the year in which that the implementation of this technology has become more widespread in various fields such as industry, home solar systems, among others.

2.2. Methodology for Waste Projection

For the projection of photovoltaic residues, a mathematical model based on the modified Weibull Distribution Function was developed in the study of (6).

In this model, projects will be analyzed in two categories, the first in relation to the specifications of the photovoltaic modules (mass of the chosen module and the nominal power) and the second the project specifications (beginning of operation of each project and the number total years).

$$TMp = FC * TPC \qquad \forall_p \ \epsilon \ P \tag{2}$$

$$f(t) = \frac{S}{ALT}\left(\frac{t-OYp}{ALT}\right)^{S-1} e^{-\left(\frac{t-OYp}{ALT}\right)^{S}} \qquad \forall_t \ \epsilon \ T, \quad \forall_p \ \epsilon \ P \tag{3}$$

$$F(t) = 1 - e^{-\left(\frac{t-OYp}{ALT}\right)^{S}} \qquad \forall_t \ \epsilon \ T, \quad \forall_p \ \epsilon \ P \tag{4}$$

Equation 2 is for converting capacity (GW) to tons, where FC is the conversion factor read in figure 1, this conversion is done for any project p that belongs to P projects. Equation 3 is the Weibull distribution function with parameters S and ALT and equation 4 represents the Weibull cumulative distribution function. The S parameter represents the form factor of the Weibull distribution and the ALT parameter represents PV Technology-specific Average lifetime

The projection of photovoltaic waste generation due to the various factors that influence the failure of photovoltaic modules takes into account that the lifetime of the panels is not the same for photovoltaic power plants connected to the grid and for rural electrification mini-grids. An analysis for the regular loss and anticipated loss scenarios is carried out for different years, with 30 years being the best scenario where projects have an optimistic average life, 25 being the baseline scenario for photovoltaic projects, and 20 years being the pessimistic scenario for the end of the life of a photovoltaic project, as described by (5).

2.3. Methodology to determining the year to start waste management

For the management of photovoltaic waste, a starting year must be determined, that is, the year in which the start of recycling operations and/or disposal of photovoltaic waste is appropriate.

The best year for waste management will be determined through iterations of the value of τ, which is the year where the amount of accumulated waste is reasonable to start the waste recycling or disposal process.

To determine the best year to start the waste management plan, the mathematical model proposed by (6)

$$EWp = \begin{cases} 0, & t<\tau \ \vee t<OYp \\ TMp[PWp*F(t)+(1-PWp)*f(t)], & t=\tau \\ TMp[RDp * f(t) + (1 - RDp)(1 - F(t) + f(t)], & t = OYp + PD \\ TMp*RDp*f(t), & t>OYp+PD \\ TMp*f(t), & otherwise \end{cases} \quad (5)$$

$$TEW = \sum_{p \,\epsilon\, P} EWp, \qquad \forall_t \ \ \epsilon \ T \quad (6)$$

Equation 5 represents the annual waste generation estimate for photovoltaic projects and it is divided into 5 conditional branches. The first branch is to avoid any mathematical errors in case the calculation year is less than the waste management year and/or less than the starting year of the project under study. The second branch calculates the photovoltaic waste accumulated during all years from the beginning of the project until the year of beginning of waste management, depending on the PWp factor that determines whether there was photovoltaic waste accumulated before the year τ. The third branch takes into account the calculation of the cumulative waste over all the years of the project until the last year of calculation, depending on the RDp factor that determines whether the photovoltaic modules must be reused or dismantled. The fourth branch verifies whether the PV modules will be dismantled or reused after the project duration period, and calculates the PV waste accordingly. The fifth branch calculates the amount of photovoltaic waste for the other years that were not covered by the previous restrictions.

Equation 6 represents the sum of the total annual estimate of photovoltaic waste from all projects under study, giving the total value of waste in tons.

The parameters of the equations are presented below.:

Socio-environmental decision-making binary factors	
PWp	1 if there are previous PV Technology-specific wastes, before PV waste projection or the operation of a PV waste dismantling facility. 0 otherwise

RDp	1 if the remaining PV Technology-specific modules, at the end of its PD, are planned to be reused. 0 Otherwise – planned to be dismantled.
	Parameters
OYp	Operation-starting years, in project site p
PD	Total numbers of years for the Project Duration, in PV project site p.
TPC	Total Power Capacity installed in PV project site p
TMp	Total Mass of all modules, in tonnes, installed in PV project site p.
EWp	Estimated Waste, in tonnes, coming from PV project site p, during year t
TEW	Total Estimated Waste coming from all PV project sites, in tonnes, during year t.

2.4. Methodology for waste management

The photovoltaic waste management model was designed to estimate the amount of photovoltaic waste that will be reused, recycled and recovered at the end of the panels' useful life. The estimate will be based on the weights of the photovoltaic panels determined in the waste projection.

In this study the projection will be made for the components of photovoltaic modules namely: solar cell, glass, aluminum frame, encapsulant, backsheet, cables, conductors and other metals. The glass cover in a photovoltaic module represents the largest weight of the device, usually around 70%, another percentage is distributed in the frame that represents about 16% of the weight and other components such as the backsheet and EVA, metals and silicon itself which represent approximately 13% (9).

The Weibull cumulative distribution function will be used for each material and added to the equation in order to determine the amount of accumulated photovoltaic panel component waste, considering the regular failure and early failure scenarios for grid-connected systems. , as well as for off-grid systems and mini-grids in the 30, 25 and 20 year average life perspectives. Next, the potential generation of waste by components will be estimated to predict possible gains from recycling process, if applied to the year 2040, 2050 e 2060.

3. Presentation of results and discussion

3.1. Results and discussion of photovoltaic waste projection

The collection of data presented here was carried out for the most part in the (8) and a visit to the FUNAE Solar Panels Factory and the company Midal Cable International was carried out, where some data related to the maintenance and operation of the solar energy production plants were obtained. Grid-connected solar projects are shown in Table 1, and off-grid and mini-grid solar PV projects are shown in Table 2.

Table 1: Data of Grid-connected photovoltaic plants in Mozambique (8)

Project	**Capacity (MW)**	**Status**
Mocuba	30	Comissioned in 2019
Metoro	30	Construction completed and awaiting comercial operation
Cuamba I	15	Under construction
Cumba II	30	PPA signed
Pemba/Mecufi	20	PPA signed
Dondo	30	Awared in may 2022m construction planned for first quarter 2023
Manje	30	Pre-qualification Tender launched for in November 2022
Chimbunila	30	Pre-qualification Tender launched for in November 2022
Chimuara	30	Pre-feasibility studies
Zitundo	30	Pre-feasibility studies
Nicoadala	30	Pre-feasibility studies
Macia	20	Pre-feasibility studies
GET FIT	30	Pre-feasibility studies
Small Scale Solar PV Portifolio (IFC)	50	Pre-feasibility studies

Table 2: Data of Off-grid and mini-grid projects (8)

Project	**Capacity (kW)**

Midal Cables International - Beluluane	2200
Balama Graphite Mine – Cabo Delgado	11000
Others	445
Mini-grid Projects by Provinces (FUNAE)	
Niassa	1683
Nampula	620
Cabo Delgado	333
Sofala	280
Zambezia	505
Tete	470
Manica	298
Inhambane	640
Gaza	160
Maputo	260
Solar villages	192

The model was applied to grid-connected photovoltaic power plants as well as mini-grids together with off-grid systems. The results presented here are in line with the steps proposed by (3), in TEW tons and early and regular loss scenarios.

Without the creation of a waste management plan for the future, it is estimated that Mozambique by the year 2040, from photovoltaic plants already installed or planned, will have around 10 thousand tons, as shown in figure 2, and about 400 tons, as shown in figure 3, of photovoltaic waste that has been uninstalled and discarded in landfills, occupying large areas and being a potential source of various environmental and social problems.

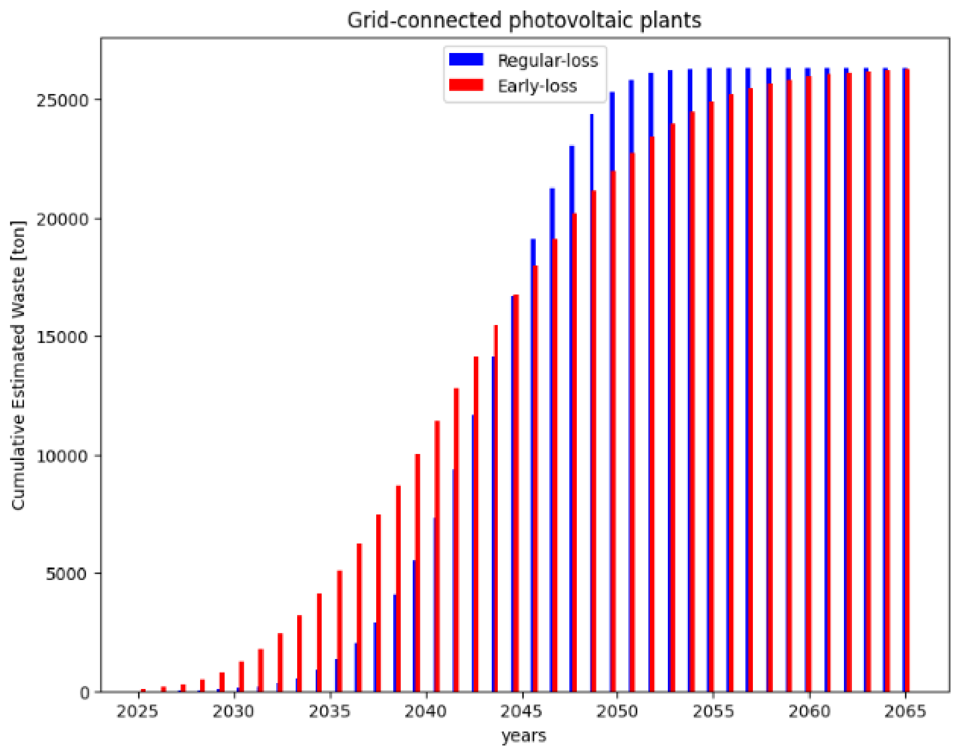

Figure 2: Cumulative Estimated Waste by Grid-connected PV plants, using ALT=30

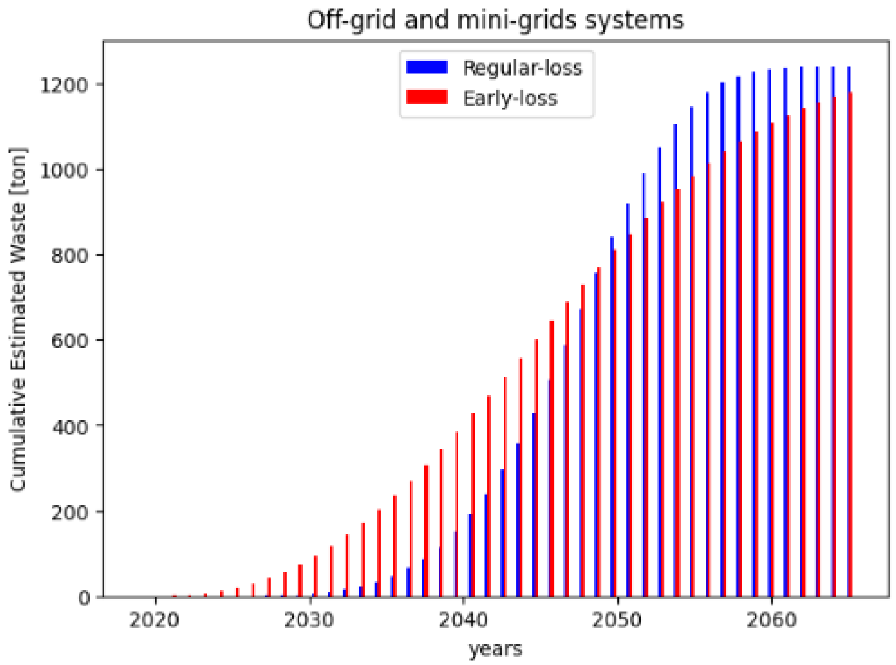

Figure 3: Cumulative Estimated Waste by Off-grid and mini-grids systems, using ALT=30

Iterative tests of the different scenarios were carried out, figure 1 and 2 represent the best scenario ALT=30 years. The results for the baseline scenario and the pessimistic scenario for waste generation are shown below in figures 4 and 5, respectively. The curves presented show the shorter the average life of the photovoltaic panels, the more accentuated they are, verifying an acceleration in the generation of PV waste, as was also observed by (7) (5).

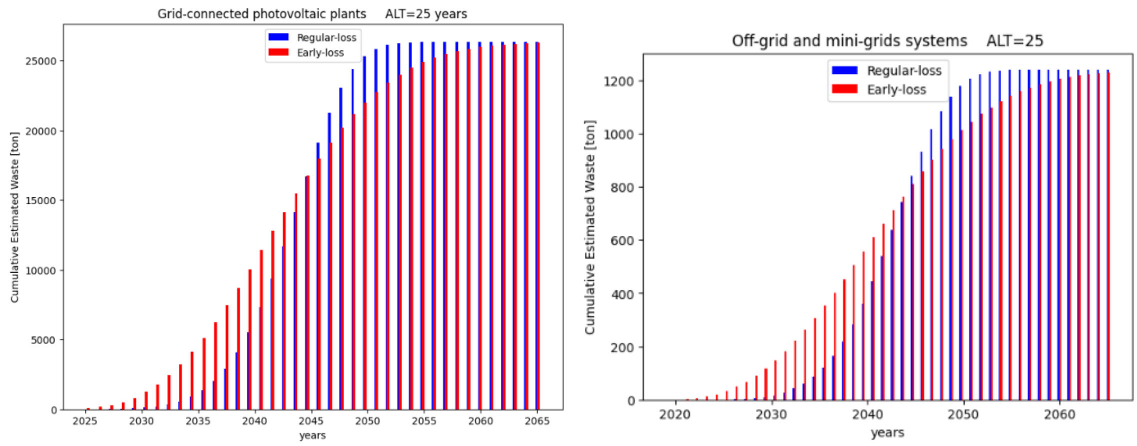

Figure 4: Cumulative Estimated Waste using ALT=25, by (a) Grid-connected PV plants and (b) Off-grid and mini-grids systems

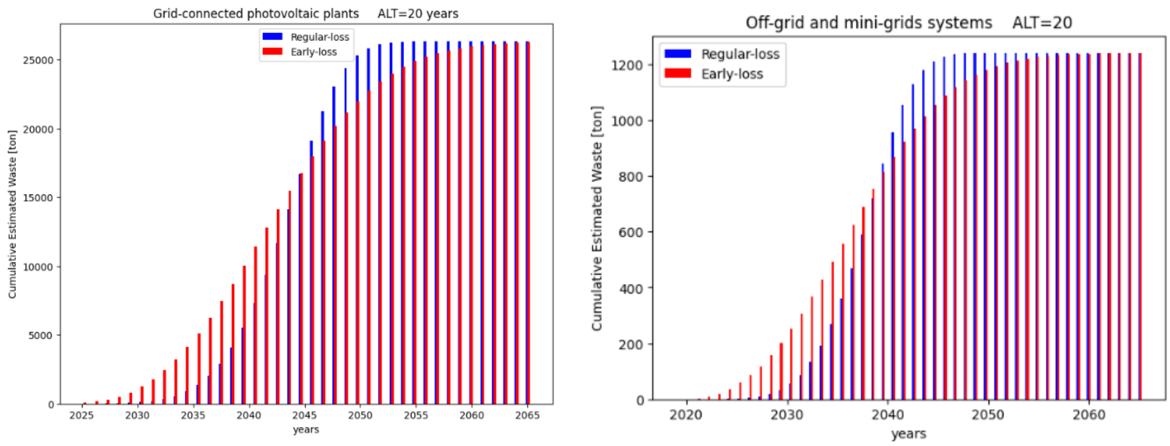

Figure 5: Cumulative Estimated Waste using ALT=20, by (a) Grid-connected PV plants and (b) Off-grid and mini-grid systems

The installation of mini-grids for rural electrification due to issues of maintenance during operation, cleaning and operation logistics may fail much sooner than the pessimistic 20-year scenario, in some cases reaching 15 years or less according to its study illustrated (5). The results related to the Weibull distribution are similar to the results found in previous publications and the perspective of analyzing different scenarios and different applications (photovoltaic power plants connected to the grid vs mini-grid systems and off-grid) constitutes an important differential and allows the decision-making regarding the level of proliferation. At the level of Mozambique, it is also important to re-study aspects related first to the arrival of the grid in regions where mini-grids operate, which will either make it no longer necessary to use mini-grids in that location, or they will be used simultaneously with the mains electricity if the need so permits. Secondly, more studies on the efficiency and longevity of the panels need to be carried out, in order to assess the longevity of power plants for rural electrification and domestic consumption.

This value will be below the actual value, as the present study only looked at projects already executed and/or already planned that are in the process of being tendered or awarded by managers and builders. The trend in the national energy market is that numerous projects and private initiatives for the installation of photovoltaic solar systems and rural electrification may arise in the short term.

The new electrification law nº 12/2022 appears as one of the biggest incentives for private initiatives, which in turn increases the need for a waste management and recycling plan in order to make the use of renewable energy in Mozambique sustainable, robust and with significant cost reduction.

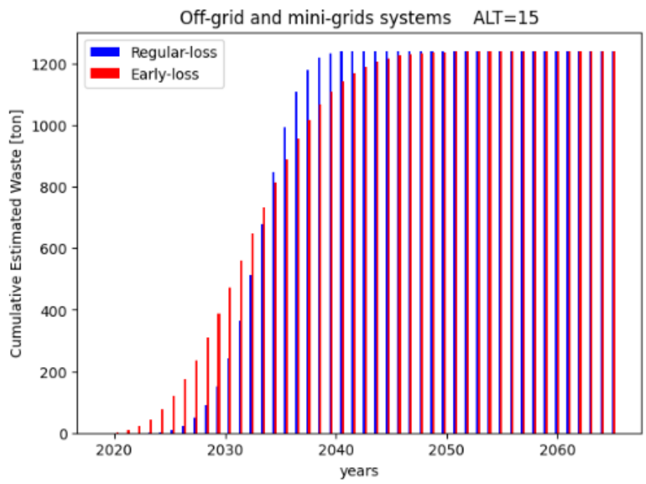

Figure 6: Cumulative Estimated Waste using ALT=15, by Off-grid and mini-grid systems

Another important factor to be studied in Mozambique is the installation of photovoltaic panels in industries, which can also fail earlier due to environments with aggressive atmospheres to which they are exposed, as shown in figure 1.

Figure 7: Solar panels exposed to an industrial environment on the roof of a factory (Midal Cables International)

3.2. Determining the year to start waste management

To determine the best year to start photovoltaic waste management and start a management plan for recycling, reduction and reuse, years (τ value) were assigned. The years chosen were 2023, 2030 and 2035 as shown in figures 8 to 10, and it was considered in this test that there is already photovoltaic waste before the start of the dismantling operations or projection of photovoltaic waste and also that all PV waste produced will be reused.

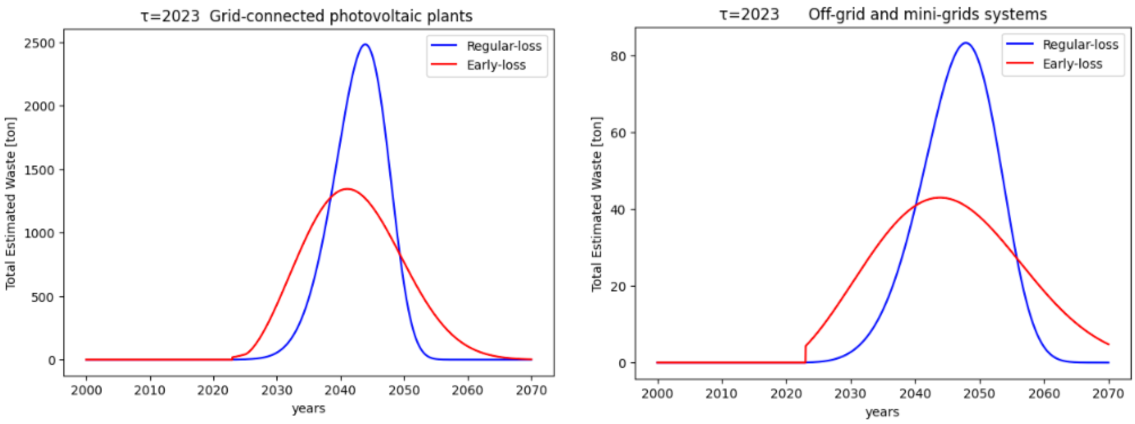

Figure 8: Annual estimate of photovoltaic waste if waste management starts in the year 2023, assuming que PWp=1 and RDp=1, for (a) grid-connected photovoltaic plant, (b) off-grid and mini-grids.

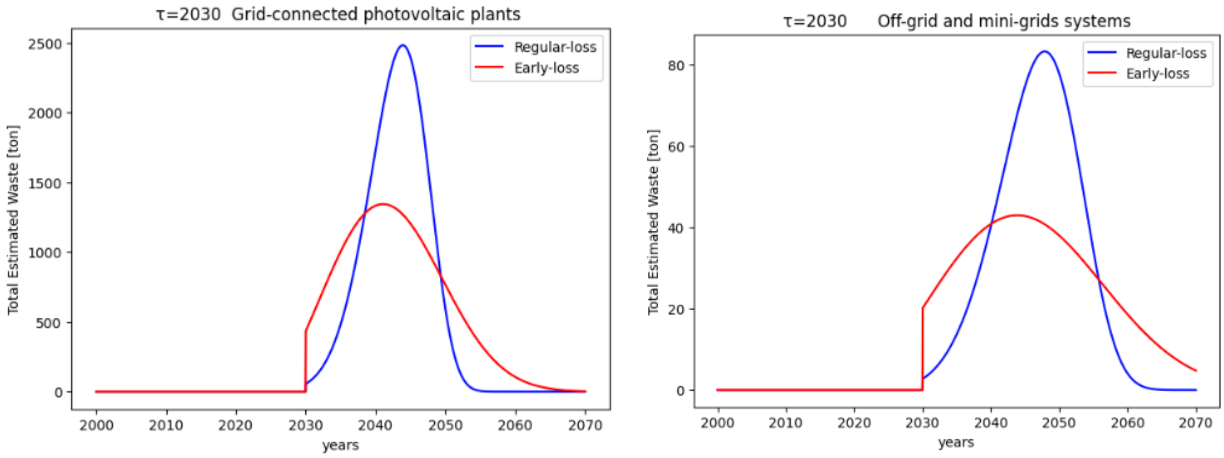

Figure 9: Annual estimate of photovoltaic waste if waste management starts in the year 2030, assuming que PWp=1 and RDp=1, for (a) grid-connected photovoltaic plant, (b) off-grid and mini-grids.

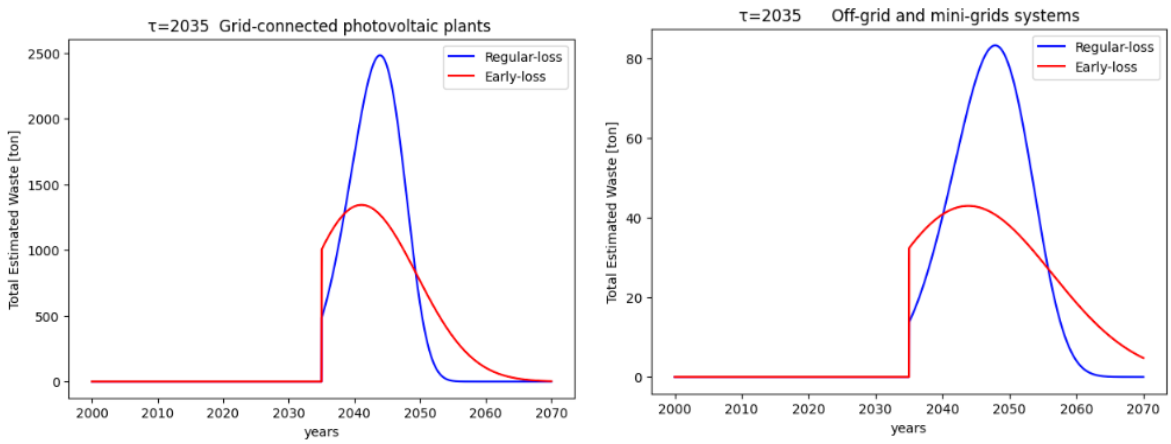

Figure 10: Annual estimate of photovoltaic waste if waste management starts in the year 2035, assuming que PWp=1 and RDp=1, for (a) grid-connected photovoltaic plant, (b) off-grid and mini-grids.

The amount of waste generated until 2023, which was the first year chosen, for both scenarios (regular and early loss) is too low to start waste management, being for the Grid-connected photovoltaic plants at 0.03 Tonnes and for Off-grid and mini-grids systems in values of 0.025 tonnes and 6.67 tonnes in regular-loss and anticipated-loss scenarios, respectively.

The total magnitude of photovoltaic waste in the year 2030 and 2035 appears to be reasonable for starting the waste management plan or starting a unit dedicated to the dismantling of photovoltaic waste. Both τ present values above that justify the beginning, being necessary for decision-making a pre-feasibility study, not being the focus of the present study, it is reasonable to admit that values below 1000 tons from all projects at national level may not be adequate in terms of costs and benefits.

Figures 11 show the results obtained from the estimated annual total of PV residues for each technology, in a regular-loss and early-loss scenario when τ = 2035 assuming that (PWp = 0 e

RDp = 1), that is, the absence of previous PV residuals and the remaining PVs will be reused at the end of the PD, then figure 12 shows the results obtained if there are no previous PV residues and the remaining PVs will be reused at the end of the PD (PWp = 1 e RDp = 0,∀p ∈ P), and finally figure 13 assumes the non-existence of if there are no previous PV residues and the remaining PVs will be dismantled at the end of the PPA (PWp = 0 e RDp = 0, ∀p ∈ P).

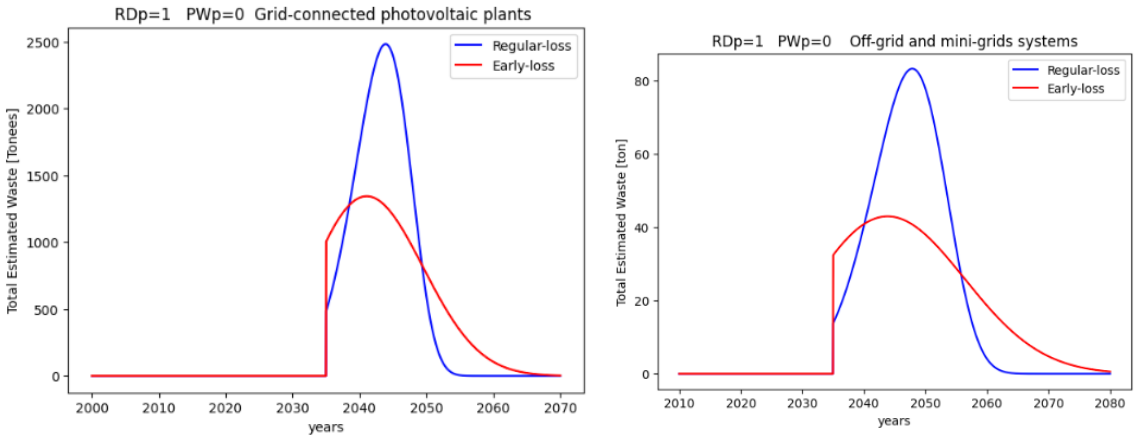

Figure 11: Annual estimate of photovoltaic waste if waste management starts in the year 2035, assuming que PWp=0 and RDp=1, for (a) grid-connected photovoltaic plant, (b) off-grid and mini-grids.

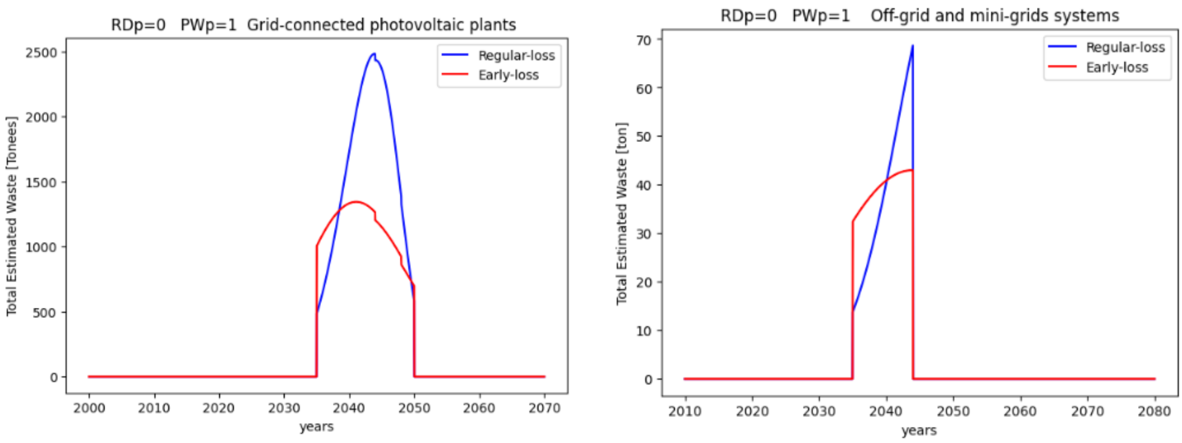

Figure 12: Annual estimate of photovoltaic waste if waste management starts in the year 2035, assuming que PWp=1 and RDp=0, for (a) grid-connected photovoltaic plant, (b) off-grid and mini-grids.

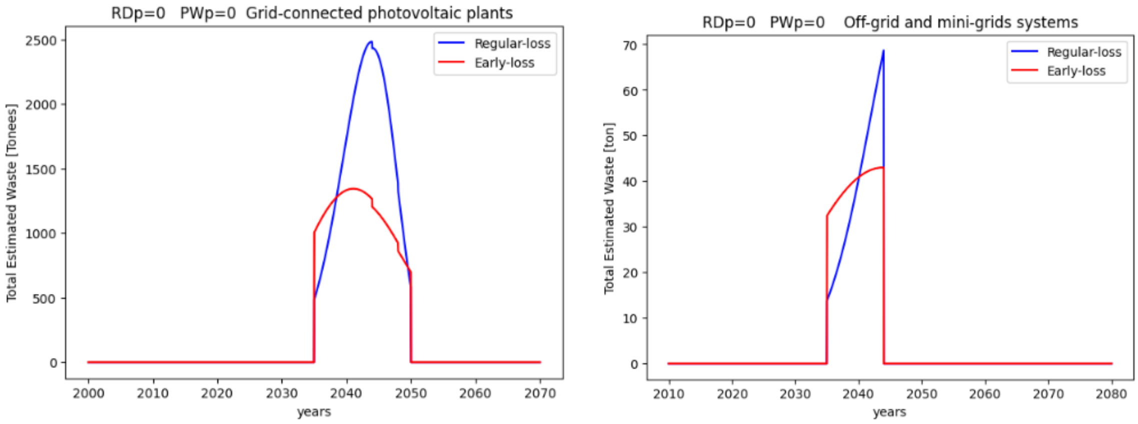

Figure 13: Annual estimate of photovoltaic waste if waste management starts in the year 2035, assuming que PWp=0 and RDp=0, for (a) grid-connected photovoltaic plant, (b) off-grid and mini-grids.

This mathematical model makes it possible to determine the appropriate year for the start of waste management. The mathematical model in equation 4 when $t > OYp + PD$ returns a value equal to 0 since it assumes that all the photovoltaic waste after the end of the project duration is discarded and the project ends. This is due to the fact that these projects are considered to have the same start year, as shown in Figure 13 (b).

The results presented here are in accordance with the expectations of the authors of this mathematical model, and the consideration of socio-environmental factors has a great impact on decision-making and optimization of photovoltaic waste management. Although photovoltaic solar technology has a short implementation time in Mozambique, the potential for waste generation in the coming years is high and a prior management plan must be created.

3.3. Discussion and result of waste management

For an effective management of photovoltaic waste, this study, using the amounts estimated in the previous section, makes an assessment of the specific generation potential of each waste generated by the photovoltaic modules in order to predict the best methods and their viability for recovery and recycling. Figures 14 to 17 show the cumulative amounts of waste, broken down into components, that will be generated in the years 2040, 2050 and 2060. The values were obtained by applying the Weibull cumulative distribution function, for the scenarios of regular loss and anticipated loss both for panels installed in photovoltaic power plants connected to the grid, as well as for off-grid systems and mini-grids.

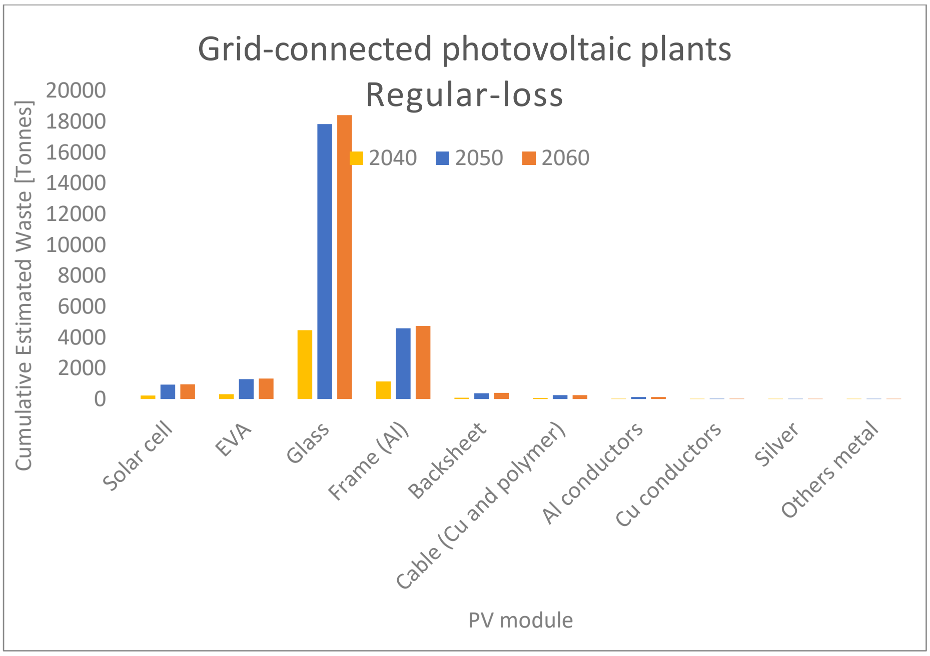

Figure 14: Cumulative estimated waste of PV module components, by Grid-Connected PV plant

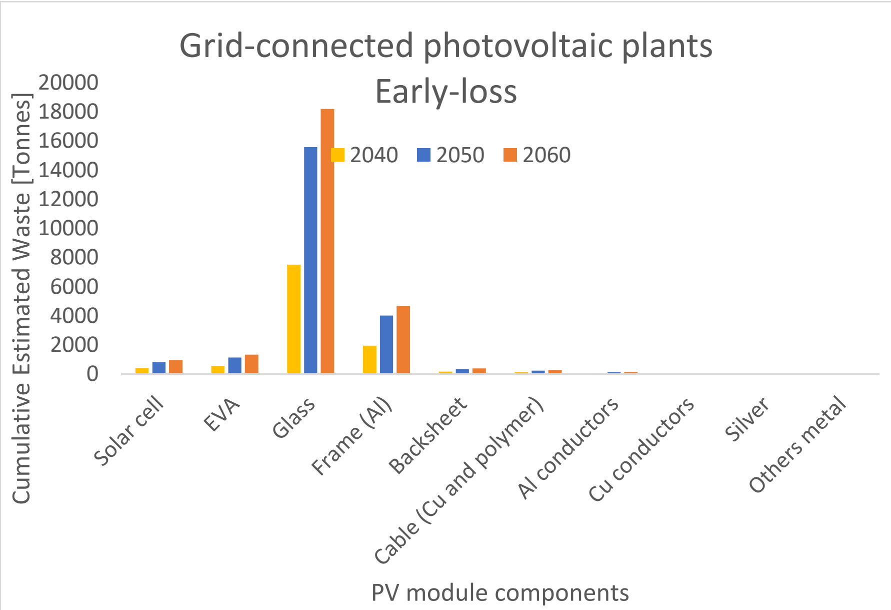

Figure 15: Cumulative estimated waste of PV module components, by Grid-Connected PV plant (early-loss)

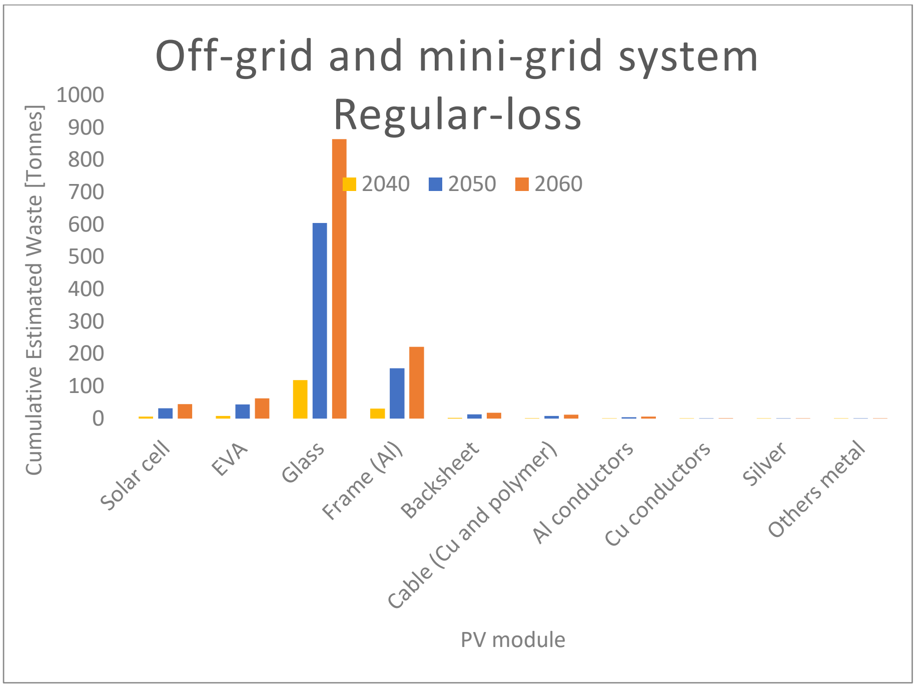

Figure 16: Cumulative estimated waste of PV module components, by off-grid and mini-grid systems (regular-loss)

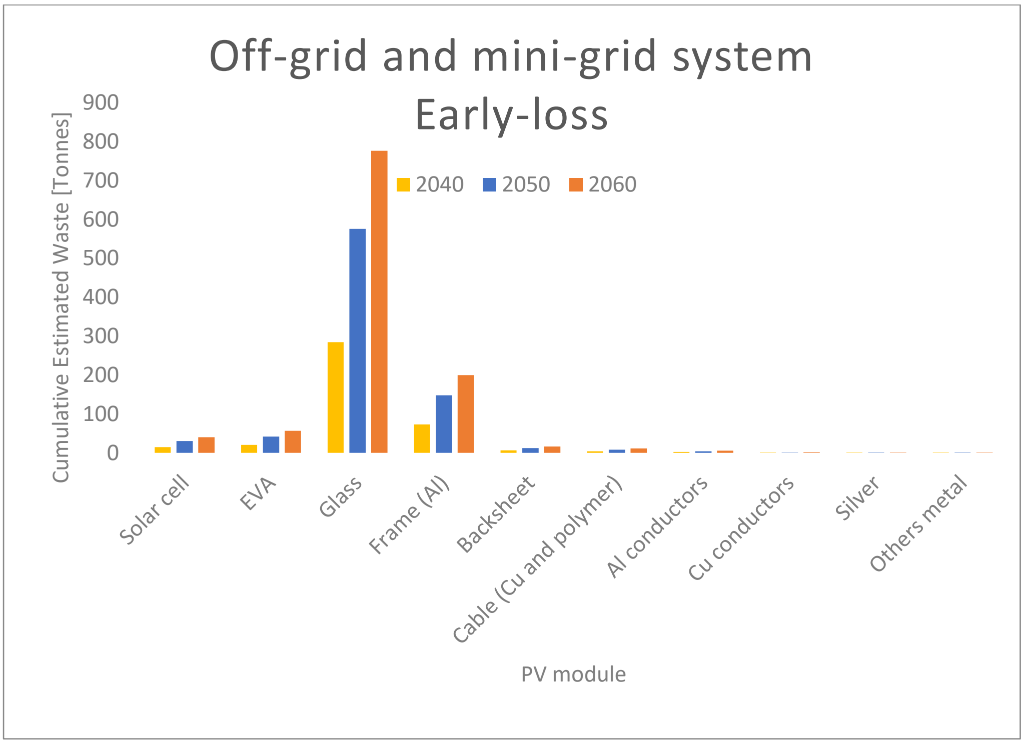

Figure 17: Cumulative estimated waste of PV module components, by off-grid and mini-grid systems (early-loss)

The percentages of waste generation from the c-Si-based photovoltaic panels presented here was determined by (10) in his study on photovoltaic panel recycling and metal recovery. Previous research on projecting the amount of PV waste generated by components shows that glass is one of the biggest pollutants and has the greatest potential for land use if disposed of in landfills. The current photovoltaic waste recycling processes still do not present attractive economic viability and focus on recycling glass and aluminum as an environmental responsibility.

Mozambique does not have a dedicated glass processing and recycling unit, which would imply building one. Determining factors of economic and environmental pre-feasibility taking into account the aspects related to the logistics of transport and resale of recycled materials was studied as a complementary part of this study, looking at the current scenario of Mozambique and extending research to the possibility of transformation into other products of higher commercial value at present.

4. Conclusion

Mozambique is still an emerging country in terms of solar energy and with a low contribution to its PV solar energy matrix compared to other countries and scenarios such as those studied by (5) (6), however, it has a high energy potential and mainly a potential for generating solar PV energy capable of supplying most of its energy demand.

Although solar PV technology has little installed capacity, predicting the amount of waste from PV modules helps to better understand the growth trend and provides a theoretical research basis for decision making regarding waste management in order to have a sustainable implementation. and ensure a circular economy (1).

In order to obtain a reasonable waste forecast, factors such as quality and installation of PV modules, operation and maintenance of large-scale projects such as grid-connected photovoltaic plants and off-grid systems and mini-grids, which affect the average life were considered. of PV panels. In this way, a mathematical model for the projection of photovoltaic waste proposed by (3) and optimized by (6) which considers two socio-environmental decision factors and the following conclusions can be reached:

- The best year for photovoltaic waste management is the year 2035, considering prior accumulation of waste and that in this process recycling and/or reuse of PV modules will begin.
- The largest generation of photovoltaic waste on a large scale will be produced in the period between 2035 and 2045 where in this period in an optimistic and baseline scenario (ALT=30) and regular failures, 1 ton of to 17 thousand tons of waste will be produced, respectively. These values will be for the large power stations connected to the network described in table 1 where the operation and maintenance are carried out in an adequate and regular way.
- If the various factors that cause photovoltaic module failures earlier are considered, before the year 2035 there will already be a cumulative total of up to 5,000 tons of PV waste, and therefore the year of starting waste management should be re-discussed for further early.
- Although presenting smaller magnitude values, off-grid and mini-grid systems have the potential to produce PV waste more quickly, as there are different factors that shorten their average lifetime. In the pessimistic scenario discussed in this work, around 900 tons could be produced by the year 2035, which corresponds to around 72% of its maximum waste generation capacity, taking into account the currently installed capacity, which in this scenario would be reached in 2045 both with regular-loss as well as early-loss.
- The creation of units dedicated to the recycling of photovoltaic panels in Mozambique may only show some viability of construction from the year 2035, however several factors such as the logistics of collecting and transporting waste to the place where the unit is installed may condition this process. Recycling glass has so far proved to be the best option in economic, environmental and social terms.

Associated with this work, studies still need to be carried out to assess the feasibility of a recycling production unit or the assembly of several small-scale units at different points, as well as the installation of sorting and physical separation coupled with the solar energy production facilities. The model of recycling and recovery of valuable metals constituents of photovoltaic modules will also be studied and more models suitable for the current scenario in Mozambique will be presented.

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