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Waste solar panel generation in Viet Nam: waste estimation and management orientation

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Abstract. Solar energy has emerged as a prominent solution to address the rising energy needs of expanding populations and combat climate change. While the advancement and proliferation of solar photovoltaics have significantly contributed to the decarbonization of energy systems, the improper disposal of end-of-life solar panels could potentially result in significant environmental impacts. Moreover, lack of or inadequate information on the quantity of obsolete solar panels and their related environmental impacts, as well as proper incentives, and regulatory policies on waste solar panel management are major hinderances for the safe disposal of waste solar panels and their materials. In this case study, surveys at solar panel manufacturers, solar power plants, and rooftop solar systems were conducted. The collected information and data are then used to derive solar panels' lifespan and estimate the amount of waste solar panels till 2050. It is estimated that the cumulative amount of waste solar panels generated in 2022 is about 148 thousand tonnes and is projected to increase to 1.7 million tonnes by 2050. Based on that, sound management solutions towards a circular economy have been proposed to properly manage waste solar panels in Viet Nam.

Keywords: waste solar panel, waste estimation, waste photovoltaic panel management.

Classification numbers: 3.3.2, 3.8.3

1. INTRODUCTION

Solar energy technology refers to the technology that involves capturing and directly converting solar light energy (radiant energy) into electrical energy based on the photovoltaic (PV) effect of PV cells. In an age where sustainable energy sources are imperative for combating climate change, solar energy technology has emerged as a sustainable power source due to its capability to exploit the abundant (and hence considered as renewable) energy source from the sun to meet the increasingly growing global energy demand without generating greenhouse gases during its operational process [1].

In 2017, the global installed solar power capacity exceeded 400 GW, reaching parity with other energy production technologies for the first time. According to the International Renewable Energy Agency, solar power capacity is projected to reach 4,500 GW by the year 2050 [1]. In Viet Nam, solar power investment has experienced a surge in recent years [2]. Particularly since 2019, Viet Nam has become the leading country in solar power adoption in ASEAN [3]. By the end of 2020, the total installed capacity of solar photovoltaics reached about 16,500 MW, which far exceeded the initial 2020 target of 850 MW set by the Vietnamese Government in 2016 [4].

However, alongside the socio-economic and energy security benefits, the rapid growth of the solar industry brings with it a pressing concern: the management of end-of-life solar PV panels [6]. Environmental scientists and energy experts have raised concerns about potential environmental impacts associated with obsolete solar panels. A solar PV panel consists of six components, which are a metal frame, tempered glass, two layers of ethylene vinyl acetate [7] encapsulating the PV cells [6], a back sheet, and a conjunction box. PV panels hence contain both hazardous (e.g., As, Hg, Cr, Ni, etc.) and valuable components (e.g., Si, Al, Cu, etc.) [8, 9]. Therefore, with the recent global and domestic solar energy boom, there is an emerging need to establish a sound management system for waste solar panels to not only avoid their harmful effect on the environment but also recover and conserve their valuable resources.

In that context, countries with substantial solar energy utilization are actively seeking for solutions and policies to manage waste solar panels. To achieve this, identifying waste sources, estimating, and forecasting waste generation, understanding the basic characteristics of the waste flow, and assessing waste management practices are of utmost importance. Worldwide, different studies have been conducted at national, regional, and global scales to estimate the generation of waste solar panels and seize appropriate solutions for waste solar panel management. Some examples are studies for India [10], Jordan [11], Bangladesh [12], Australia [13], China [14], USA [15], Europe [16], and global [6].

In Viet Nam, the major attention is on improving solar power potential and optimizing solar panel efficiency; attention to the slowly but surely increasing PV waste problem is still limited [6]. Moreover, no statistical data on the amount of obsolete solar panels is available. Estimation of waste solar panels has just been preliminary conducted in some recent studies such as research by the Institute of Energy and UNDP [2], or research by GIZ [17]. However, in most of the existing studies on waste PV panels, a rough estimation is made based on secondary data about the situation in other countries or the global scenario. There are no studies based on survey data to model PV lifespan and waste estimation.

Therefore, this study has two purposes: i) to estimate the waste solar panels generated in Viet Nam during the period 2030 - 2050. Survey data are aggregated to model PV panel lifespan and waste estimation, ii) to assess the characteristics of the flow of waste solar panels, the current status of waste solar panel management in Viet Nam, and to propose sound management solutions to manage waste solar panels.

2. MATERIALS AND METHODS

2.1. Survey and data collection

To estimate the waste solar panel generation in Viet Nam from 2009 to 2050, information and data were retrieved from various sources, including both primary and secondary data sources.

Primary data on the types of solar panels in use, obsolescence rates, and the status of the usage, disposal, and management of obsolete solar panels was collected from the surveys at 3 solar panel manufacturing plants, 15 solar power plants, and 22 roof power systems (at both household and farm scale) with different capacities in the North, Central, and South of Viet Nam in 2022.

Secondary data was retrieved from official datasets such as data and information from the National Power Development Plan for the period 2011 - 2020 with a view to 2030 (referred to as PDP7), National Electricity Development Plan for 2021 - 2030, with a vision to 2050 (PDP8) [5], statistical data from the Ministry of Industry and Trade, technical data from main solar panel manufacturers, national and international scientific papers and reports. These data were then evaluated based on several criteria, such as data source, data reliability, data continuity (i.e., continuous, or intermittent data), and the representativeness and update of the data.

2.2. Estimation of the waste PV panel generation in Viet Nam

In this study, a life cycle approach is applied to thoroughly investigate the potential sources of waste PV panel generation. Accordingly, PV panel waste might be generated in all main phases of PV panels' life cycle, including PV panel manufacturing, transportation, installation, use, and end-of-life management. However, domestic production only accounts for about 10 % of the total PV consumption in Viet Nam, the rest is imported from different countries, mostly from China. Moreover, surveys at PV manufacturers show that the amount of PV waste at PV manufacturing plants is trivial, and the waste is easily collected and managed by the manufacturers. Therefore, PV manufacturing is assumed to contribute insignificantly to the amount of waste PV panels generated in Viet Nam and thus not covered in this study. The waste estimation model therefore only covers the waste amount from the other phases.

The first PV panels were installed in Vietnam in 2009 and significant PV installation occurred in the period 2019 - 2020. With an average lifetime of 25 - 30 years, the first significant waste PV panel generation due to regular loss will be expected in 2045 - 2050. Therefore, this study aims to estimate the waste PV panels from 2009 to 2022 and project the waste amount in the period 2023 - 2050.

More specifically, the following calculation pathway is applied.

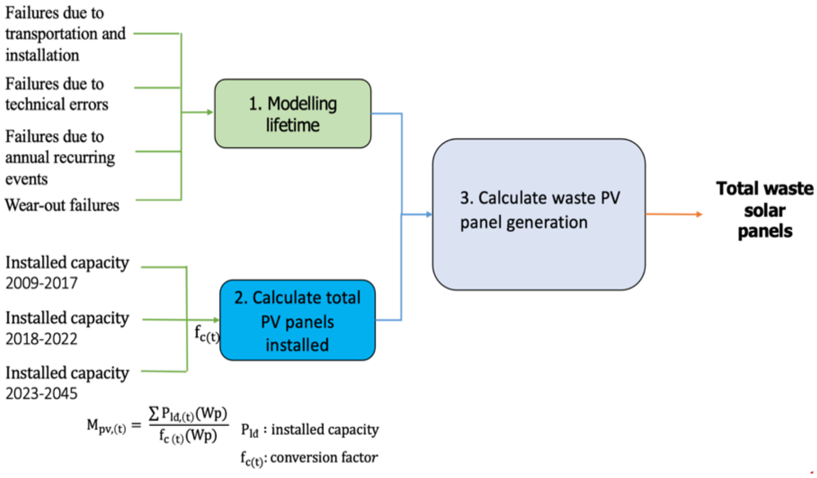

Figure 1. Calculation pathway for waste PV panels.

2.2.1. Calculating the quantity of PV panels in use

Since no statistical data on the amount of installed PV panels is available, the total volume of PV panels (in mass units) installed and projected to be used in the future is obtained based on the annual installed PV capacity and a conversion factor which is defined as the average ratio of PV capacity per mass unit (MW/t).

$$M_{pv,(t)} = \frac{\sum P_{ld,(t)}(W_p)}{f_{c(t)}(W_p)} \tag{1}$$

in which: $P_{ld(t)}$ (W_p): installed capacity of PV panels with capacity W_p (MW); $f_{c(t)}$ (W_p): conversion factor of PV panels with capacity W_p(MW/t)

To calculate the conversion factor, technical characterization data of PV panel was retrieved from leading PV panel providers. Based on that, the conversion factor for historical year (from 2007 to 2022) was defined for each year by averaging the weight and the nominal power of the most used PV panels. Additionally, market surveys show that improvements of PV technology in material savings and energy efficiency enhancement make PV panels more powerful and lighter over time. To model this trend, the obtained results of conversion factors were then used to model the change of conversion factors over time using the least-square fitting method. The trend was then assumed to remain in the future and used to project the conversion factor from 2023 to 2050.

The annual installed PV capacity was retrieved from different sources, i.e. statistical data on renewable capacity in 2022 from IRENA [4], national statistics from the Ministry of Industry and Trade, and data/information from PDP7. Projected data on solar energy from 2023 to 2050 was aggregated from PDP8 for the period 2021 - 2030 with a vision towards 2050.

2.2.2. Modeling the lifespan of solar panels

Determining the lifespan of PV panels is one of the crucial steps in estimating the amount of waste PV panels. In this study, the lifespan of a PV panel is defined as the service lifetime, which is calculated from the time it is put into use until it is no longer functional [18].

Research on the lifespan of PV panels has shown that the lifespan distribution can follow different statistical distributions (such as Normal, Gaussian, Lognormal, and Weibull) [19]. Among these, the Weibull distribution has been proven to be the best-fit distribution for modeling the lifespan of PV panels [19]. Therefore, the Weibull distribution was used in this study to represent the lifespan of PV panels in Viet Nam.

The Weibull function is presented as follows, with the shape parameter α(t) and the scale parameter β(t) being defined as time-varying values.

$$L^{(p)}_{(t,t_n)} = \frac{\alpha_{(t)}}{\beta_{(t)}}(t_n - t)^{\alpha_{(t)}-1} e^{-\left[\frac{t_n - t}{\beta_{(t)}}\right]^{\alpha_{(t)}}} \tag{2}$$

in which: t_n is the historical year and t is the evaluation year; $L^{(p)}_{(t,t_n)}$: PV panels' lifespan, representing the obsolete rate of PV panels over time.

However, due to data limitations, the variation of solar panel lifespan over time was not considered in this study. This means that the values of α(t) and β(t) remain constant during the evaluation period.

Solar panels have only been introduced into Viet Nam since 2009, and there is no publicly available data on the lifetime of PV panels. Moreover, surveys at solar power plants show that there are two primary reasons for the decommissioning of PV panels, that is, power decrease, and damage and technical failures. Therefore, to model the PV panel lifespan, obsolescence rate related to the transportation, installation, infant failures, and part of midlife failures were also defined based on the survey data. Since no actual data on wear-out failures has been available so far, this data was referenced from the available research, i.e. the studies of IRENA and IEA-PVPS [6].

2.2.3. Estimation and projection of the waste PV panel generation

In this study, the waste estimation model with a stock-based approach was applied. Its mathematical expressions are as follows.

$$W(t) = N_{pv,(t)} \times L^{(p)}_{(t,t_n)} \quad (3)$$

in which: $N_{pv,(t)}$: quantity of PV panels installed; $L^{(p)}_{(t,t_n)}$: PV panel lifespan.

The model was employed to estimate the waste solar panels generated from 2009 to 2022 and to project the waste amount from 2023 to 2050. The projected PV panel installation capacity obtained in Subsection 2.2.1 and the solar panels' lifespan obtained in Subsection 2.2.2 were used as inputs for the model assuming that the panel lifespan remained unchanged within the studied period.

3. RESULTS AND DISCUSSION

3.1. Cumulative solar PV capacity and the quantity of PV panels in use

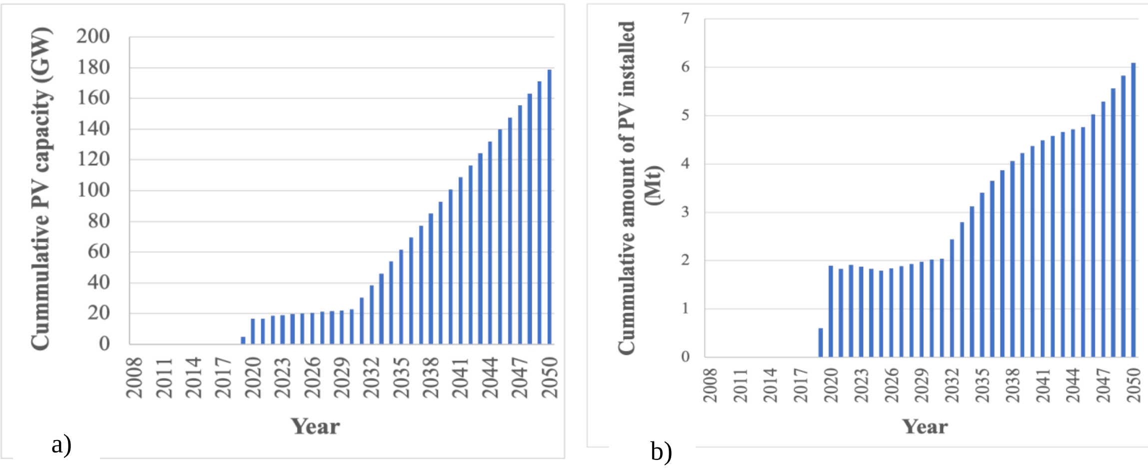

Figure 2. Cumulative PV capacity (a) and total quantity of PV panels in use in Viet Nam (b).

Overall, statistical data on the PV panel capacity shows a remarkable development of solar energy in Viet Nam as the result of several mechanisms and incentives to promote solar energy. The implementation of modified PDP7 and incentive mechanisms for promoting solar energy (e.g., Decision No. 11/2017/QD-TTg dated April 11, 2017, and Decision No. 13/2020/QD-TTg dated April 6, 2020 by the Prime Minister) have led to a significant surge in the overall adoption of renewable energy and specifically solar energy in Viet Nam (Figure 2). As a result, the quantity of PV panels put in use has increased since 2009. Figure 2 presents the result of the cumulative PV capacity (Figure 2a) and the total amount of PV panels installed in Viet Nam from 2009 to 2050 (Figure 2b).

The results show that before 2018, the number of solar panels put in use in Viet Nam was limited. From 2009 to 2017, PV systems were installed at a small scale with the total capacity below 10 MW (Figure 2a), equivalent to about 30 thousand panels in use (Figure 2b). The situation has changed since the end of 2017 because the Government implemented important policies to promote investment in renewable energy, including solar power. The total installed capacity has reached 105 MW, equivalent to about 318 thousand panels or 13 thousand tonnes of panels used. The first large scale solar power plant in Viet Nam, TTC Phong Dien 1, located in Dien Loc commune, Phong Dien district, Thua Thien Hue province, started operating in October 2018, after six months of construction. It has a total capacity of 35 MW.

The solar power boom occurred in 2019 - 2020 with a total installed capacity of 4,994 MW and 16,661 MW in 2019 and 2020, respectively, far exceeding the expected figure of 1,000 MW by 2020 according to PDP7. Most projects were concentrated in the central and southern regions where solar radiation is higher than in other areas [2]. The operating capacity of grid-connected solar power increased by approximately 9,000 MW [2]. Additional to large-scale projects (including ground-mounted solar and floating solar projects), rooftop solar power also experienced a significant growth. By the end of 2019, the installed capacity of rooftop solar nationwide was only 272 MW and reached 7,780 MW by the end of 2020 [2]. It is estimated that by 2021, around 130 large-scale solar energy projects were operated in Viet Nam [2]. This hence led to a significant increase in the total amount of PV panels put in use. In 2019, the total amount of PV panels used was about 599 thousand tonnes and tripled to 1,898 thousand tonnes in 2020.

The fast acceleration of solar power has resulted in a change in the solar power plan. According to PDP8, a deceleration in the growth rate of solar power might be witnessed within 2021 - 2030. However, the total capacity of solar power is expected to increase by an additional 4,100 MW by 2030. In the period 2031 - 2050, solar power capacity is expected to have another surge similar to the one experienced in 2019 and reach 168,594 - 189,294 MW by 2050.

3.2. Lifetime of PV panel

The lifetime developed in this study averaged 26 years, 4 years shorter than the average lifetime of 30 years defined for both the regular loss and early loss scenarios in the work of IRENA and IEA-PVPS [6] and the previous work of the Institute of Energy and UNDP [2] or GIZ [17]. This variability might be explained by the difference in degradation analysis and modeling failure rate of the PV panel.

In the work of IRENA and IEA-PVPS [6], both scenarios employed the most common assumption of a 30-year average panel lifetime and a maximum lifetime of 40 years; hence the scale factor $\beta(t)$ was fixed and only the shape factor $\alpha(t)$ was adjusted based on the inventory data. The other above-mentioned studies of the Institute of Energy and UNDP [2] and GIZ [17] employed the lifespan of IRENA and IEA-PVPS [6].

In this study, the shape and scale factors of lifetime distribution were calculated by regression analysis between data points from the literature and data from surveys on causes and frequency of early panel replacement. In general, early panel replacement is caused by failures in three phases: the infant, midlife, and wear-out failures. The infant failures occur at the commencements up to four years after installation; whereas, the midlife failures occur after five to seven years of installation and the wear-out failures occur from 12 years of installation to the end-of-life [20]. Since most of PV panels have been installed in Viet Nam since 2018, available data only covers infant failures, a part of the midlife failures, and does not cover wear-out failures. Therefore, the obtained lifespan distribution only covers the infant and part of midlife failures. The survey results show that loose frame, glass breakage, failures in J-box, cell-interconnection, and delamination are the most significant infant failures. They are mainly damages in transportation and installation (failure rate of 0.01 - 0.1 %) as a result of poor planning, incompetent mounting work, and bad support constructions. The most frequently observed midlife failures are related to the degradation of the anti-reflective coating of the glass, glass breakage, failures in diode, delamination, and cracked cell isolation. They are caused by both natural and manmade factors. The most common natural factors are environmental stresses such as wind load, temperature changes, heavy rain, or lightning strikes. The most common manmade factors are external impacts caused by people shooting birds, poor maintenance, and processing, leading to a failure rate of 0.01 - 0.4 %.

3.3. Estimation and projection of waste PV panel generation

The results of waste PV panel estimation show a continuous growth of waste PV panels in Viet Nam. Figure 3 presents the amount of waste PV panels generated annually in Viet Nam from 2009 till 2050 (the bar graph) and the total PV installation capacity (the line graph), and Figure 4 presents the accumulative waste PV panels generation within the study period.

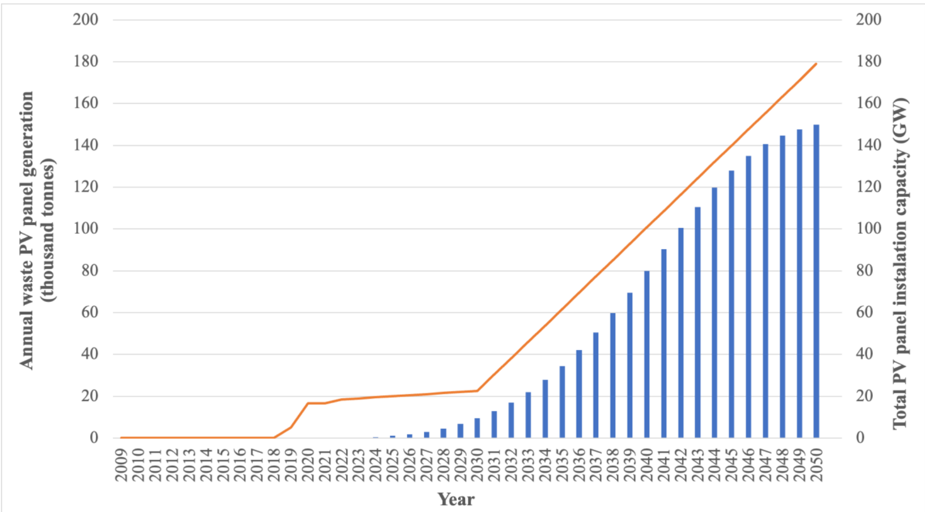

Figure 3. The annual waste PV panels generated in Viet Nam (blue bar) and the total PV installation capacity (the yellow line) within 2009 - 2050.

At the beginning of the period, the amount of waste was negligible due to the small amount of PV panels in use and the low infant failure rate. In 2019 - 2020, when solar power boomed, the annual amount of waste PV panels was estimated to reach 4 - 8 thousand tonnes, constituting the accumulative amount of about 20 thousand tonnes of PV waste generated by the end of 2020 (Figure 4). Then the annual amount of waste continued to increase with a compound annual growth rate (CAGR) of about 7 %, reaching nearly 99 tonnes by the end of 2022.

Although the PV installation capacity is expected to increase slowly from 2023 to 2030, the amount of waste PV panels is expected to increase faster than in the previous period with a CAGR of about 10 %. From 2030 to 2045, both PV installation capacity and annual waste PV panels are projected to sharply increase. The waste PV panels are expected to grow from 9 thousand tonnes in 2030 to 128 tonnes in 2045. The cumulative PV waste is therefore expected to grow 36 times, from 28 thousand tonnes to 992 thousand tonnes during 2030 - 2045. The growth of waste PV generation is predicted to slow down from 2045 to 2050 as a result of the slow increase in the amount of PV panel installation in the previous period from 2019 to 2030. It is estimated that 150 thousand tonnes of obsolete PV panels will be disposed of in 2050, contributing to the accumulative amount of 1.7 million tonnes of waste PV panels generated by then.

Figure 4 displays the cumulative amount of waste PV panel generation. This calculation utilizes the lifespan distribution obtained in our study, as well as the lifespan distributions for early loss and regular loss scenarios modeled in the IRENA and IEA-PVPS study [6]. The results indicate that, with an average lifespan of 26 years, the cumulative amount of waste PV panels, based on our derived lifespan, falls within the range of waste amounts calculated in the early loss and regular loss scenarios in the IRENA and IEA-PVPS study [6]. Particularly, the cumulative amount of waste PV panels generated in 2022 of this study was about 148 thousand tonnes, about five times higher than the amount of waste in the regular loss scenario and 55 times lower than the waste amount in the early loss scenario. The amount of waste PV panels will gradually increase in all considered scenarios, reaching approximately 1.9, 1.7, and nearly 1.5 million tonnes in the early loss scenario, this study scenario, and the regular loss scenario, respectively.

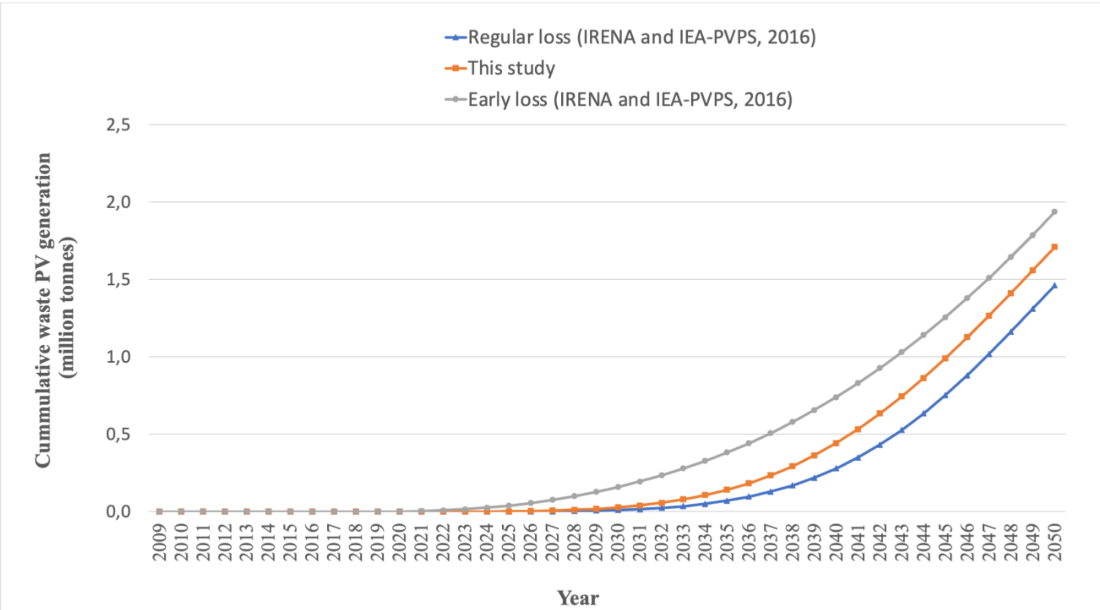

Figure 4. The cumulative waste PV generation in Viet Nam from 2009 to 2050.

The obtained results on PV panel installation capacity and waste PV panel generation in Viet Nam during 2016 - 2045 show a good correlation with the respective results for global during the same period in the study of IRENA and IEA-PVPS [6].

3.4. Orientation of waste PV management

The authors' previous study on the composition of the most popular PV panels (Monosrystalline silicon PV) showed that the dominant Si-based PV panels consist of five major components, in which tempered glass is the main component, accounting for 61 - 63 % total weight of the PV panels, followed by aluminum frame (11 - 13 %), junction box, electric wires (10 - 13 %), encapsulation foils [7] (6 - 8 %), back sheet (polyvinyl fluoride (PVF) and thermoplastic Elastomer (TPE)(approximately 3 %), and stringed solar cells (3 - 4 %) [8]. Furthermore, 80 % of the total weight of crystalline silicon (c-Si) based PV is composed of glass and aluminum, while the rest is shared by lead, copper, and tin [8]. This indicates the potential for recycling these valuable resources and promoting a circular economic model.

Substance analysis of 16 hazardous compositions (i.e., Sb, As, Ba, Ag, Be, Cd, Pb, Co, Zn, Mo, Ni, Se, Tl, Hg, Cr, and V) in PV panels reveals that their content is below the permissible standard of QCVN 07:2009/BTNMT by a magnitude of 5 (in case of Pb) to thousands of times [8]. It, therefore, can be concluded that the popular PV panel waste is not hazardous and should be managed as ordinary solid waste. Moreover, it should be recognized as a potential source of secondary materials. Therefore, to deal with the prodigiously rising PV panel waste, a sound management system based on a circular economy approach is proposed, in which the following aspects should be considered.

- **Clearly classifying waste PV panels in legislation**

In Viet Nam waste from solar panels is classified into the group of waste from electrical and electronic equipment as industrial waste that needs to be controlled. This means that waste solar panels need to be analyzed to determine whether they are hazardous waste or not.

According to the survey results at solar power plants, all defective and damaged solar PV panels are stored in the temporary storage area that is designed in compliance with Circular 02/2022/TT-BTNMT for storing hazardous waste. The plants retain this waste type and wait for specific instructions from the relevant authorities or return it to the suppliers when the storage amount is substantial. Therefore, the clear classification of PV panel waste as ordinary industrial solid waste will help guide the plants to properly store and treat PV panel waste.

- **Applying extended producer responsibility (EPR) for waste PV panel management**

According to Appendix 22, Decree 08/2022/NĐ-CP, solar panels are classified into Group Đ for electrical and electronic appliances, with a mandatory recycling rate denoted as 3 % of total put-into-market (POM) volume. Article 77 of the Decree regulates the responsibility for collecting and recycling waste solar panels for importers/manufacturers, which takes effect from 2025. Considering that in this case, waste solar panels from households (rooftop solar power systems) also need to be treated according to this regulation.

Since there is no recycler available for recycling the waste PV in Viet Nam, manufacturers or importers can only choose to contribute to the Vietnam Environmental Protection Fund (VEPF) —The financial contribution is determined based on the weight of products and the recycling cost norm to recycle a unit of waste PV. However, there is no technology available for waste PV panel recycling in Vietnam, it is impossible to estimate the recycling cost norm. Moreover, the existing collection system is not intended for waste solar panels due to their size, and the complexity of dismantling, especially the rooftop system. Lastly, until now no laws or policies are available to support the treatment and recycling of this type of waste, making it less attractive to any investors.

- **Developing proper PV panel waste recycling technology**

Among the six main components of the PV panels, the PV cell layer is a notably complex part that contains numerous recyclable materials. In contrast, the other are relatively uniform in terms of composition. Thus, an appropriate recycling system for waste PV panels consists of two main stages: dismantling, sorting, and precious metal recovery.

The first stage involves conventional mechanical dismantling and thermal-assisted mechanical disassembly. Firstly, hand tools are used in conjunction with disassembly equipment to remove the metal frames, junction boxes, and electrical wires, which can be recycled directly. The next step involves mechanical disassembly with thermal assistance. The PV panels are thermally treated on both sides at temperatures ranging from 200 to 300 °C. Due to the properties of non-crystalline materials, the EVA layers melt, and the viscosity decreases as the temperature rises. This allows for easy separation of the glass layers, the back sheet, and the PV cells. For toughened glass sheets that remain intact, they can be reused as greenhouse materials for agricultural purposes. All the components that are no longer intact can be shattered, crushed, or ground into pieces for alternative construction materials. As for the back sheets, they can be recycled into plastic or repurposed for other uses. Regarding the group of PV cell materials, since they still contain precious metals (e.g., silver), recycling occurs in the second stage.

The second stage is the precious metals recovery from PV cells. Two methods are suitable to apply in the Vietnamese context. The first method is smelting PV in a furnace. The silver is melted first at 962 ^{o}C and separated for refining, while silicon will be melted at over 1.400 ^{o}C [21, 22, 23] and then ground into building material. The second method is the leaching process. PV cells are ground to a size of less than 1 mm and then subjected to leaching using a leaching agent, typically nitric acid. The leaching solution is then recovered for silver [24, 25]. The remaining residue is primarily composed of silicon, while the recovered glass can be reused as a substitute for construction materials.

4. CONCLUSIONS

In this study, the life cycle approach and waste generation model are applied to estimate the amount of waste PV panels generated in Viet Nam. Surveys at solar panel manufacturing plants, solar power plants, and rooftop systems have been conducted to gather data and information on the type and the amount of solar panels in use and the failure rate of solar panels during manufacturing, transportation, installation, and use. The obtained results indicated that the average lifespan of solar panels in Viet Nam is 26 years. Moreover, the total PV panel installation capacity in 2020 is estimated to be 16,661 MW. It is then expected to increase by 4,100 MW by 2030 and reach 168,594 - 189,294 MW by 2050. This hence led to a surge in the total amount of PV panels put in use and the waste PV panel generation. More specifically, the amount of waste solar panels generated in 2022 is about 148 thousand tonnes and is projected to increase to 1.7 million tonnes by 2050. Based on the composition analysis, it can be concluded that waste solar panels should be categorized as ordinary solid waste and managed using a proper take-back system. The application of EPR for waste solar panels and the development of appropriate recycling technology are also key solutions for a sound management system towards a circular economy strategy. In more detail, a recycling scheme including two main stages is proposed, which are dismantling and categorization, and precious metal recovery.

This study is one of the first attempts to enhance the estimation of waste solar panels in Viet Nam based on primary data on the current situation of solar panel use. However, data limitations still hinder the obtained results. To improve the assessment results, it is important to improve the quantity and the quality of the input data. Consequently, it is vital to upgrade the existing data inventory system, broaden consumer surveys, extend the modeling based on the survey data for the whole lifespan of waste solar panels, and establish a monitoring system for the waste flow. This monitoring system will facilitate cross-referencing with modeled and calculated results.

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Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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