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Towards Photovoltaic Module Waste Management in the Philippines: Review of Strategies and Regulatory Framework

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Abstract *- The drastic increase in solar energy dependency would yield a tremendous amount of waste worldwide, and sustainably managing the emerging PV waste prevents potential environmental impacts and harm to humanity. This paper presents a systematic review of literature to identify strategies for PV module waste management and an internet-based assessment of PV module waste regulations in the Philippines. The systematic review utilized four key phrases to identify relevant articles. The title and abstract of the resulting articles from 2012 to 2022 were screened based on selection criteria and relevance, and 54 articles were selected. In addition, an internet-based assessment was conducted to determine the regulations of PV module waste in the country. Several key themes were also discussed that include waste assessment, global regulatory framework and policies, and end-of-life management encompassing monitoring, collection, recycling, and supply chain for recovered secondary materials. In addition, strategies for the various stages of the life cycle of PV modules were presented in the review. The identified waste management strategies include carefully designed PV modules to withstand breakage, utilization of recovered secondary materials, correct installation procedures, regular PV waste assessment and monitoring, efficient collection and fast classification of PV module waste, and sustainable recycling and recovery methods and technologies. Furthermore, the assessment shows that there is no specific regulation in the country that deals with PV module waste. Policies for PV module waste monitoring, take-back scheme, and subsidization should be explored. Indeed, PV module waste management strategies and regulations in the Philippines are critical to managing emerging waste effectively.*

Keywords: photovoltaic module, waste management, strategies, regulations, framework, circular economy

I. INTRODUCTION

In response to the threat posed by global warming and climate change, it has been the global consensus to reduce carbon footprint towards the concept of sustainable development. One way to curb the effects of global warming and climate change is the utilization, production, and consumption of energy from renewable resources [1]. The fundamental renewable energy resource that has immense potential to help sustain electricity generation is solar energy. However, the drastic increase in the solar energy dependency would yield the creation of a tremendous amount of waste worldwide, and there is a need to sustainably manage emerging waste to prevent potential environmental impacts and harm to humanity [2].

Due to the abrupt increase in population worldwide [3], there will be a corresponding increase in energy consumption since anthropogenic activities such as livelihood, transportation, and leisure heavily depend on electricity. The utilization of fossil fuels for energy production receives criticism since it produces substantial greenhouse gases (GHGs). Cleaner and greener energy production through the utilization of renewable energy sources were explored in recent studies. One advantage of increasing renewable energy in the energy mix is that it can help decrease global warming by around two to four degrees by 2100. However, there have been concerns about the worldwide displacement phenomenon resulting from the production and utilization of technologies harvesting renewable resources, which needs to be carefully understood by all stakeholders [4].

Photovoltaic (PV) technology as a form of solar energy harvesting technology is currently the most mature [5], most viable commercially, reliable, and sustainable electricity generator. In addition, solar PV technology is cheap, safe, efficient, and environment-friendly [6]–[8]. The global forecasted solar energy capacity by 2050 is around 4500 gigawatts which will generate about 60-78 megatons of PV module waste [9] based on a global probability-based forecasting model. Appropriate PV module waste management is critical to prevent further degradation of the environment and detrimental effects on the health of society.

The current state of the literature has given little attention to the end-of-life management (EOL) of PV module waste, and there is a need for continuous review of PV waste management in light of new knowledge [10]. Studies reviewed several recycling methods and techniques for PV waste, focusing on dismantling and retrieving materials [11], significant impacts of the EOL of PV module waste focusing on the entire life cycle [12], various barriers, drivers, and enablers of PV systems and battery waste management [13], understanding the trend of EOL treatment procedures for PV modules [14], solar PV research, and potential risks and regulatory approaches [15]. Based on the assessment using Focus Group Discussion, SWOT analysis, and readiness assessment, Bergado determined that the country still needs to be ready to deal with PV module waste and recommended establishing recycling facilities to manage emerging PV waste [16]. There is still a lack of information regarding comprehensive waste management strategies to guide policymakers, researchers, and stakeholders in the Philippines and improvement approaches of regulatory frameworks in the country.

This paper presents a review of related literature on PV module waste management that utilizes a systematic review (SR) approach for identifying strategies available in the literature and internet-based assessment of regulatory frameworks in the Philippine setting. The review focuses on i.) examining global sustainable PV module waste management strategies at the various phases of PV module life cycle and ii.) assessment of national and local regulations for PV module waste in the Philippine context. The central question of the systematic review is: What are the sustainable waste management strategies towards the circularity of the entire life cycle of PV modules? Indeed, the successful adoption of the identified comprehensive waste management strategies can help policymakers, researchers, and all stakeholders become knowledgeable and employ effective and efficient PV module waste management in the country. In addition, the assessment of regulations can aid in creating regulatory and policy frameworks for sustainable PV module waste management toward resource sustainability and circularity in the country. Furthermore, the findings of the study will greatly help with research and development in the country.

II. METHODOLOGY

The study utilized SR methodology proposed by Denyer and Tranfield to address clear and specific research questions [17]. SR methodology provides practitioners, researchers, and policymakers with empirical and research-based evidence from the existing body of knowledge through gathering, analyzing, and synthesizing scientific contributions. Table 1 presents the detailed steps of the SR methodology.

Table 1. SR methodology summary

SR Phase		Steps and Description
Phase 1	Research questions formulation	Determine sustainable PV module waste management strategies to explore approaches towards circularity at the various phases of PV module life cycle
Phase 2	Locate studies	Data Types: Journal articles, thesis manuscripts, and conference proceedings Time frame: 2012-2022
Phase 3	Selection and evaluation	Define search strings: "solar pv module waste" AND "management", "solar pv waste" AND "management", "Photovoltaic waste" AND "management", "end-of-life management" AND "solar PV" Include articles: Photovoltaic Module Waste Management System
Phase 4	Synthesis and Analysis	Define review protocol Code and data extraction
Phase 5	Report the findings	Descriptive analysis of the article database

The researchers have identified four key phrases that include: i.)“solar PV module waste” AND “management,” ii.) “solar PV waste” AND “management,” iii.) “photovoltaic waste” AND “management,” and iv.) “end-of-life management” AND “solar PV” were searched through accessible open databases. There are 54 journal articles, thesis manuscripts, and conference proceedings selected from 1,623 resulting articles after the screening, and relevant details of the paper were stored in an Excel file. The title and abstract of the resulting articles from the databases were screened based on selection criteria and relevance. The study considered literature from 2012 to 2022. Figure 1 shows the flow diagram of the SR.

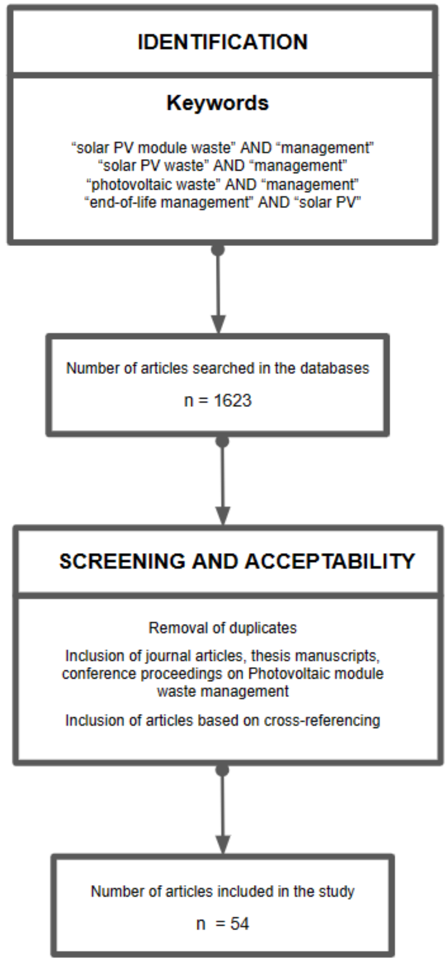

Figure 1. Systematic review flow diagram

In addition, an internet-based assessment was carried out following the study of Saplala-Yaptenco [18] to identify national laws and regulations that deal with PV module waste. An internet search through Google advanced search was conducted using the keyword phrase "PV module waste management" in the Philippine region.

III. RESULTS AND DISCUSSION

The discussion will follow several themes that have been identified in the study that include: 1) structure and composition of PV modules, 2) PV waste assessment, 3) global PV waste management regulatory and policy framework, and 4) EOL management of PV module waste: transport, collection, recycling techniques and technologies, and supply chain for recovered materials, 5) strategies for PV module waste management, 6) Philippine energy profile and development plan, and 7) regulatory framework for PV module waste management in the Philippines. The findings of the study need to be presented forthwith to all stakeholders in the country. However, there is a need to conduct future studies that may use interviews and focus group discussions to determine the appropriate prioritization and roadmap of the proposed strategies and regulations based on the state of PV module waste management in the country.

3.1 Structure and Composition of PV Modules

Alexandre Edmond Becquerel first demonstrated the photovoltaic effect phenomenon in 1839[19], which caused scientists and researchers to explore various photoresponsive materials. Gupta et al. presented three types of solar PV cells, namely: wafer-based silicon, thin-film, and new emerging technologies [20]. In contrast, the paper of Ghosh and Yadav presents five types of PV technologies, namely: crystalline silicon, single-junction Gallium Arsenide, thin film, multi-junction cells, and emerging technologies [21]. It is clear that solar PV modules are classified depending on their composition and structure.

The market for PV modules is rapidly evolving. The majority of PV modules in 2014 were crystalline PVs, with a 90% market share percentage. By 2050, the share of thin-film PVs will increase to 44.1%, which is close to the 44.8% share of crystalline PVs. It could be identified that emerging PV technologies' market share is increasing. The composition of PV modules includes several metals that can be potentially recovered, such as base metals that include iron, nickel, copper, aluminum, silver, and critical substances like tellurium, manganese, and gallium. They may also contain hazardous metals like cadmium, lead, and selenium [22].

It is also important to track and understand PV product flows. However, material flow analysis has been less explored in recent studies. Mahmoudi et al. conducted material flow analysis in Australia towards appropriate recycling plans, policies, and regulations [6]. In addition, Mahmoudi et al. conducted further assessments of decommissioned PV modules in OECD countries [23]. They have estimated the material composition for PV module waste in 2058 for OECD countries presented in Figure 2. The estimated PV module waste mainly consists of glass, aluminum, steel, ethylene vinyl acetate (EVA), nickel, copper, silicon, iron, and magnesium, having percent composition of 68.10%, 13.99%, 7.98%, 5.94%, 1.317%, 0.908%, 0.680%,0.503%, and 0.4405%, respectively. The main substances have high recycling yields except for nickel and magnesium, which need to be improved by further studies.

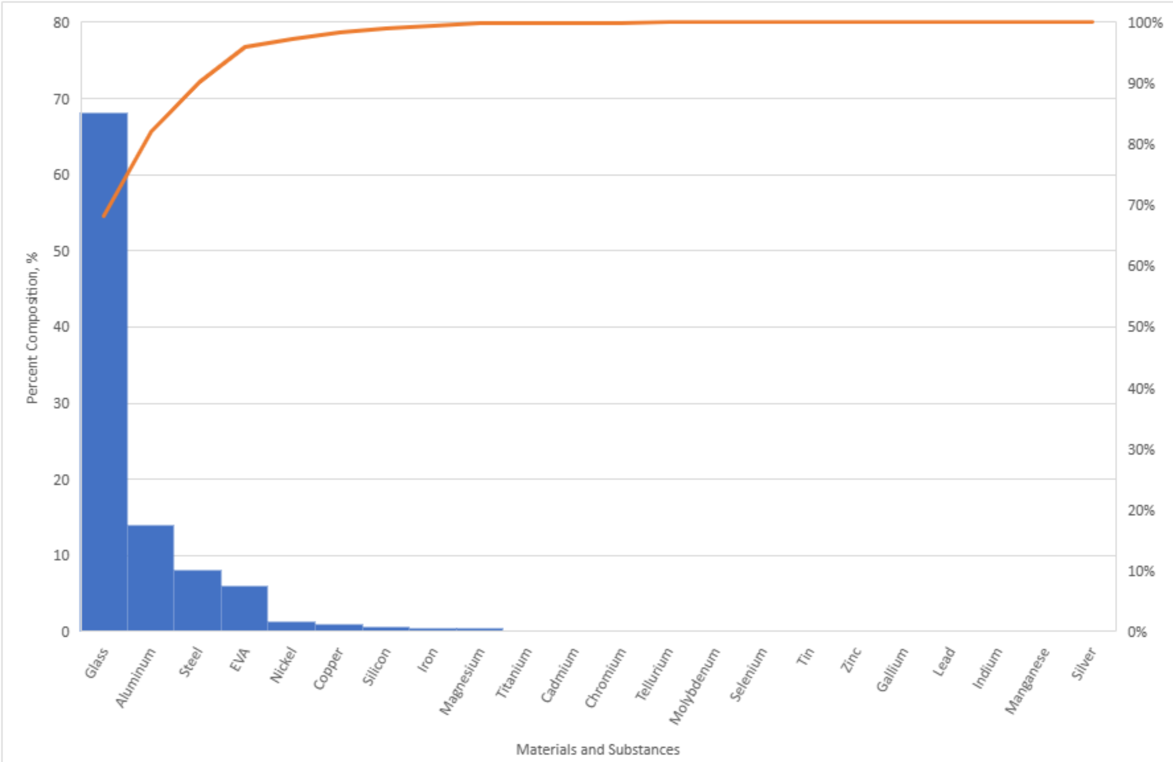

Figure 2. Material inventory for projected PV module waste of OECD countries. *Source: Mahmoudi et al.[23]*

3.2 PV Waste Assessment

Several studies that conducted PV waste assessments in specific countries showed an increasing volume of PV waste worldwide. The study by Domínguez et al. estimated that there will be around 6.6 million metric tons (Mt) of PV modules in the USA from 2030 to 2060, considering 30 years of average module lifetime, and further presented the projected recovery of metallic content of PV waste [24]. In Mexico, the estimated amount of 0.7 Mt of PV module waste will be produced by 2045, considering 30 years of average module lifetime [25]. In another study, Italy will generate an estimated amount of 8.2 Mt of PV module waste in 2050, considering 25 years of average module life [26]. Mahmoudi et al. projected an estimated volume of around 1-8 Mt of PV module waste in Australia by 2060 under different scenarios [27]. Furthermore, the study by Santos and Alonso-García presented the PV module waste estimate for Spain, Germany, Turkey, UK, Ukraine, and France [28]. Bergado projected around 962, 000 tons of utility-scale PV module waste in the Philippines by 2050 [16]. The summary of PV waste assessment is shown in Table 2. In addition, projecting the material content of PV modules is critical in understanding the amount of recovered secondary materials from recycling [24]–[27].

Mahmoudi et al. utilized the Weibull function under various scenarios to forecast the estimated volume of PV waste compared to the other works that use a linear function [27], making it suitable for understanding the projection of the emerging waste. Furthermore, according to Mahmoudi et al., the economic feasibility of recycling initiatives and facilities heavily relies on forecasting the volume of PV module waste based on three types of failures: early, constant accidental, and wear-out [29].

Table 2. Summary of PV waste assessment

Estimated PV waste, million metric tons	Estimated year	Region	Types of PV Waste Considered	Average Module life, years	Reference
6.6	2060	USA	PV modules, inverters, transformers, mounting structure, cables, and trackers	30	Domínguez & Geyer [24]
1.2	2045	Mexico	PV modules, inverters, transformers, mounting structure, cables, and trackers	30	Domínguez & Geyer [25]
8.2	2050	Italy	PV modules only	25	Paiano [26]
8	2060	Australia	PV modules only	30	Mahmoudi et al. [27]
0.75	2050	Spain	PV modules only	30	Santos & Alonso-García [28]
4.3	2050	Germany	PV modules only	30	Santos & Alonso-García [28]
1.8	2050	France	PV modules only	30	Santos & Alonso-García [28]
1.5	2050	UK	PV modules only	30	Santos & Alonso-García [28]
0.4	2050	Turkey	PV modules only	30	Santos & Alonso-García [28]
0.3	2050	Ukraine	PV modules only	30	Santos & Alonso-García [28]
1.8	2050	India	PV modules only	25	Rathore et al.[3]
0.962	2050	Philippines	PV modules only	25	Bergado [16]

3.3 PV Waste Global Regulatory and Policy Frameworks

Several countries lack specific policies in dealing with PV waste and PV module waste. This section presents several studies examining various global regulatory and policy frameworks. The study by Jain et al. identified the regulatory approach of PV waste management and the associated principles for USA, Japan, China, Korea, and selected European Union countries, including the UK, Italy, and Germany [5]. The study by Rathore et al. discussed the regulatory framework of Czech Republic [3], andSharma et al. examined the regulations in Switzerland, Norway, and India [7]. It has been observed that EU countries follow the WEEE directive that utilizes the popular extended producer responsibility (EPR) principle. PV module manufacturers are mandated to deal with the waste associated with their products regardless of their location. In addition, EPR warrants involvement from producers to take part in sustainable development. In the Philippines, RA 11898, or the EPR, lays out the framework for EPR. However, the current law focuses on plastic pollution and must be extended to various types of waste like e-waste that include PV module waste.

Other works focused on developing frameworks to improve PV waste management. To address the EOL management of PV module waste in India, Sheoran et al. proposed a policy framework, which is a straightforward approach based on the EPR principle that provides a scheme to monitor and regulate the recycling of PV waste [30]. In addition, Jain et al. developed a more holistic national-level policy framework, which defines PV waste management guidelines to address the social, financial, and technical factors adequately [5]. The study of Weiner et al. suggested an improvement in the e-waste management in Brazil to include PV module waste in the category of special waste and recommended that proper monitoring of the collection and waste recycling of PV module waste is essential [31]. In addition, Mahmoudi et al. suggested understanding EOL management of PV modules in multi-levels, namely: macroscopic, mesoscopic, and microscopic [29]. Furthermore, the review of Bajagain et al. pointed out that understanding the fundamental processes of EOL management of PV waste and existing regulatory approaches can help policymakers craft suitable and appropriate PV module waste management [15]. The presented frameworks can guide policymakers and stakeholders in dealing with emerging PV waste.

Some studies have extensively emphasized the crucial role of circular economy (CE) and EPR in EOL PV module waste management. CE promotes waste minimization and resource sustainability. Jain et al. argued that EPR provides circularity in dealing with PV waste [5]. In addition, Balaji and Hiremath suggested integrating the CE principle in dealing with PV module waste [32] and identified that recycling and recovery require significant financial investments [33]. Mahmoudi et al. argued that a recycling initiative and a suitable regulatory framework would promote a CE [6]. Furthermore, Mathur et al. proposed that an Industrial Park utilizing the Life Cycle Symbiosis principle following a CE approach can help prevent the potential direct disposal of PV module waste in landfills and recover valuable secondary materials [34]. Recycling and recovery of materials are vital components of the CE approach, however, the cost of establishing recycling and recovery facilities remains to be a challenge. Policymakers can utilize the proposed framework of Ndzibah et al. to address financial concerns in recycling PV module waste [4]. The authors argued that EOL management of PV waste would produce value creation [4, 35], such as the generation of jobs, specialized logistics, creation of new businesses, and opportunity for business of recovered secondary material, but the participation of environmentally aware public and private entities is critical. The utilization of CE approach highly promotes sustainable development, environmental protection, and resource sustainability.

A unified circular economy framework for PV waste management is presented in Figure 3, where elements from the Philippine setting and culture in managing solid waste [36] are joined with the end-of-life management scheme created for solar PV waste. The proposed framework incorporates sustainability pillar elements: the economic viability component encompasses business opportunities, job and value creation, local and foreign investments, social acceptability components include public-private partnerships, policies and regulations, education and awareness, and research development of PV module waste, and environmental protection that focuses on waste material valorization, diversion from landfill and unregulated dumping. The proposed framework provides the foundation for establishing appropriate and effective waste management strategies and regulatory frameworks by aligning the standards and best practices of industry, government, academia, and other stakeholders.

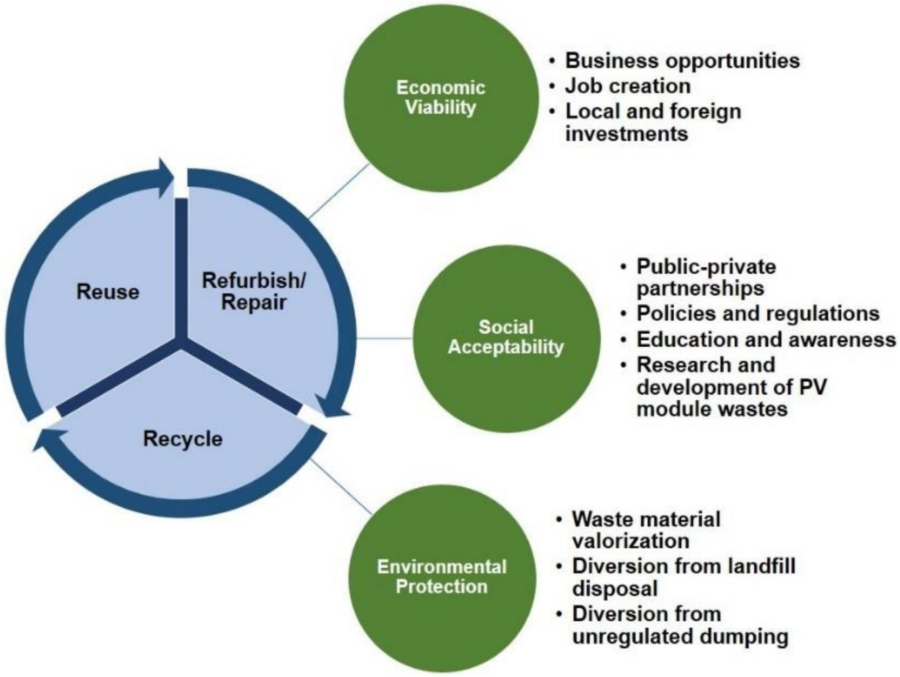

Figure 3. CE framework incorporating sustainability pillars (economy, social, and environmental). *Original work of the authors based from the study of Ndzibah et al.[4] and Lunag et al.[36]*

3.4 EOL Management of PV Module Waste

This section presents the existing and recommended EOL management of PV module waste based on the literature review. A summary of the key findings of studies for EOL of PV module waste is presented in Table 3.

3.4.1 Ecotoxicity, Environmental Impacts, and Degradation of PV Module Waste

Potential ecotoxicity and human health risks of PV module waste's material leaching in landfills were investigated by Nain and Kumar and identified possible exposure scenarios from leachates [37]. It is vital that the direct disposal of PV waste to landfills should be prevented due to their detrimental effects on nearby communities and ecosystems.

A further study by Nain and Kumar has identified several reasons for the failure and degradation of PV modules: defective modules in production, breakage during transportation, breakage during installation and operation, and environmental and human damage [38]. In addition, Mahmoudi et al. presented three PV module failure factors: early failure, constant accidental failure, and wear-out failure [29]. Furthermore, Chowdhury et al. argued that poor design causes PV module failure [8]. Understanding the cause of failure is critical in potentially decreasing the early disposal of PV module waste.

3.4.2 PV Module Waste Transport, Collection, Recycling Methods and Technologies, and Supply Chain

According to Goe and Gaustad, due to limited scope and data insufficiency, precursory literature suggested that recycling has a higher significant environmental impact than disposal in landfills [39]. On the other hand, the latest studies contradict these findings due to the leaching of hazardous materials from landfills and the ecotoxicity of PV modules [40].

Energy consumption and emissions are significant from the recycling and collection of PV waste. The transport, landfilling, and recycling of PV waste have an estimated emission of 7 to 252 g CO2 eq/ kWh, and roughly 28-47 % of the emissions of EOL management of PV waste come from transportation [41], which makes it an essential factor in the sustainability of EOL management [42].

Several approaches were developed to optimize the collection and transport of PV waste. A framework was proposed to determine the ideal locations of recycling facilities using a mathematical model considering economic performance [43-44]. In addition, a mathematical approach utilizing mixed-input linear programming was used to optimally locate recycling and collection networks [45]. Lu explored a GIS-based approach to optimally locate recycling facilities for PV waste management [46]. There are a limited number of studies for transportation optimization of PV module waste [10], and optimization of reverse logistics should be incorporated in policies [47].

Some studies recommended creating a labeling system that will contain information about the composition and structure of PV modules to sort the waste at the processing facilities quickly. Protopapa et al. explored the vibrational spectroscopy approach for PV module waste to automate sorting at processing facilities in the absence of waste labeling schemes [49]. Furthermore, the study by Ardente et al. pointed out that the information on the composition of the PV module waste is critical to improving recycling efficiency [50].

There are several studies that explored recycling methods and technologies. Macalova et al. reviewed the trends in PV module recycling, which focused on the process of mechanical and thermal recycling [51]. Aravelli et al. identified the core recycling processes for respective types of PV modules and developed a smart recycling technology using a Programmable Logic Controller [52]. Majewski et al. focused on regulations and product stewardship in PV recycling [53]. In addition, it was found out that pyrolysis as a recycling method maximizes the recovery potential of c-Si PV modules [54]. Furthermore, it is essential to note that as recycling efficiency increases, the energy payback time decreases[55].

Other works looked into the economic feasibility of PV waste recycling. According to Liu et al., the potential of PV waste recycling in China is low, and a strategy to boost the economic value of recycling PV module waste is to establish fiscal policy and improve the recycling strategy [56]. Cuchiella et al. agreed that recycling PV module waste has high economic losses and suggested that bigger plants will have better economic benefits [40]. In addition, the study of Prabhu et al. presented a net loss for recycling PV modules, and government subsidy was identified to be necessary to ensure a break-even point [57]. Markert et al. determined that the net economic benefit of recycling c-Si PV modules using a novel process called the ‘Full Recovery End-of-Life Photovoltaic’ (FRELP) method is $1.19/m^2 [58]. FRELP is a high-efficiency recycling process for c-si PV modules with key processes that include: transport, unloading, disassembly, cable treatment, incineration, disassembly, glass separation and refinement, cutting, sieving, acid leaching, filtration, electrolysis, neutralization, and filter press. In addition, an estimated revenue rate of 28% was identified with the simulation of Lim et al. for PV module waste recycling, having a payback time of less than a year with government subsidization [59]. Ganesan and Valderrama mentioned that high-value and decentralized mobile PV recycling are the top sustainable management approaches [60].

Furthermore, a supply chain for recovered substances in PV module waste recycling must be established. The study of Mahmoudi et al. suggested that proactive policies must be established to ensure that there will be a healthy supply chain of the recovered secondary materials from recycling to promote value creation [23]. In addition, Kim and Jeong proposed two mathematical models to help manufacturers with the supply chain of PV module waste management [61]. In addition, Gautam et al. developed a supply chain using the circular economy approach in dealing with PV module waste [62]. Moreover, Ansanelli et al. suggested a supply chain where secondary materials recovered from PV module recycling can be utilized in the production of new PV modules [63].

Table 3. Summary of studies on EOL management

Authors	EOL Section	Key Findings
Guo & Kluse [44]	Transport and Collection	Proposed a recycling network incorporating location, route optimization, EIA and cost analysis, and trade-off analysis
Guo & Kluse [43]	Transport and Collection	Proposed a mathematical model to locate geographical locations of PV recycling facilities using capital, operation, and transport costs.
Lu [46]	Transport and Collection	Optimally located recycling facilities using a GIS-based approach. A greater number of recycling facilities will lower the distance and impact of transport.
Yu & Tong [45]	Transport and Collection	Simulated two scenarios in establishing a reverse logistic network for decommissioned PV modules using mixed-integer linear programming
Protopapa et al. [49]	Waste identification	Proposed optical methods in identifying various PV module components and recommended labeling schemes using RFID or QR code for faster identification.
Ardente et al. [50]	Recycling Method	Life-cycle analysis was conducted to assess the resource efficiency of a novel process called FRELP with baseline scenarios. The study further found that thermal treatments are vital to achieving high efficiency.
Macalova et al. [51]	Recycling Methods and Technologies	The study discussed thermal, mechanical, and chemical recycling methods.
Aravelli et al. [52]	Recycling Methods and Technologies	This study presented an efficient smart recycling technology that uses Supervisory Control and Data Acquisition and Programmable Logic Controller.
Rathore et al. [3]	Recycling Methods and Technologies	Consolidated recycling methods that include physical separation, chemical treatment, and thermal treatment for recycling. The life cycle assessment of technologies in recycling was further presented.
Xu et al. [11]	Recycling Methods and Technologies	Discussed PV module recycling techniques that include component repair, module separation, and materials and substances extraction.
Chowdhury et al. [8]	Recycling Methods and Technologies	The study presented existing recycling processes like physical separation, thermal treatment, and chemical treatment. In addition, silicon and thin film PV module recycling processes were discussed.

3.5 Strategies for PV Module Waste Management

The recommended and existing strategies for PV module waste management were presented in the previous subsection based on the literature review. The information from the review were used to create comprehensive waste management strategies considering the life cycle of PV modules. With the observed rapid adoption of PV technology in the country for both residential and utility-scale, there is a need to prepare for the emerging PV waste. The proposed PV module waste strategies in this section adhere to UN Sustainable Development Goals and should be presented forthwith to policymakers for possible inclusion in policymaking, researchers to help solve challenges in the effectiveness and efficiency of the waste management, and other stakeholders, such as PV module producers, developers, and consumers.

The management of PV module waste is critical to promote the circularity of resources and prevent direct disposal of PV modules to landfill that poses health risks to nearby communities. A sustainability framework for PV Module Waste Management is presented in Figure 4 based on the proposed unified CE framework. The framework also puts strong emphasis at the crucial role of transport throughout the life-cycle of PV modules. Waste management strategies for PV modules at the production, installation, and decommissioning phase are discussed in the succeeding sections.

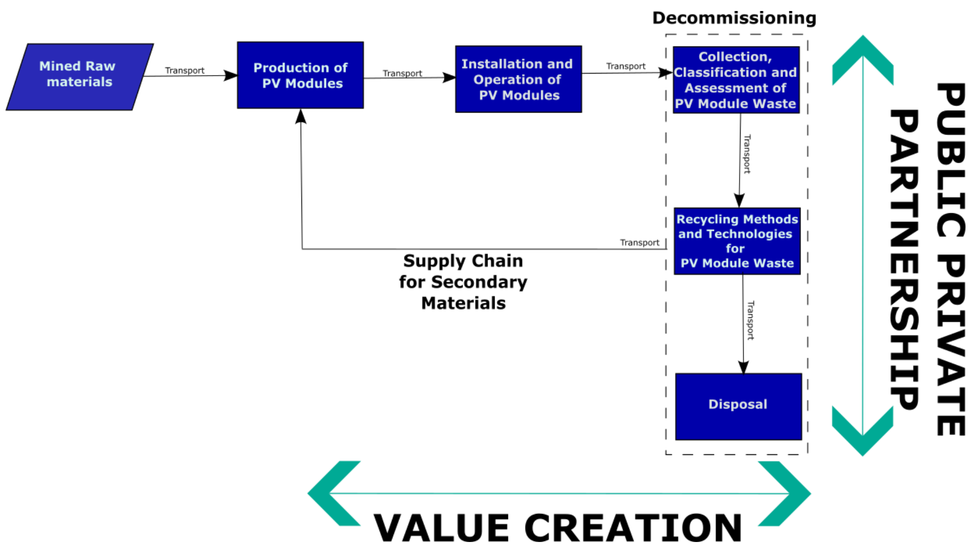

Figure 4. Proposed sustainability framework for PV module waste management. *Original work of the authors.*

3.5.1 Waste Management Strategies in the Production Phase of PV Modules

Raw materials should be extracted and mined sustainably to support the production and manufacturing of PV modules. The production of PV modules should adopt manufacturing methods, techniques, and technologies so that producers can maximize the use of resources, minimize energy consumption, and significant environmental impacts. In addition, the utilization of recovered secondary materials such as metals ensures resource sustainability in the country. Furthermore, PV Modules should be carefully designed to withstand breakage during transport and weather resistant in operation.

3.5.2 Waste Management Strategies in the Installation and Operation Phase of PV Modules

Correct installation procedures should be followed to prevent early wear-out failure. There is a need for careful planning and ensuring proper construction of mounts and supports of PV modules. Furthermore, appropriate monitoring of the state and performance of the PV system and regular maintenance should be complied with by solar energy system developers.

3.5.3 Waste Management Strategies in the EOL Phase of PV Modules

The waste management strategies in the decommissioning of PV modules should include i.) regular PV waste assessment and waste management practices monitoring, ii.) efficient collection and fast classification of the type of the PV module, and iii.) utilization of sustainable recycling and recovery methods and technologies.

Regular waste assessment and monitoring of the current state of PV module waste management and policies in the country should be conducted to identify the barriers and enablers of PV module waste management, improve the management practices, and recommend the most suitable regulatory and policy framework approaches.

Optimizing the location of recycling facilities and collection networks and route optimization can ensure efficient collection. In addition, the type and composition of the collected PV module waste should be identified quickly using a labeling system or vibrational spectroscopy to automate sorting.

The utilization of smart technologies to minimize cost, optimized energy use, and increase the efficiency of PV module recycling and recovery can be one strategy to make PV module waste management sustainable. Furthermore, optimized processes, such as mechanical, chemical, and thermal recycling, should be explored and used in recycling facilities. Understanding the nexus of cost, energy, and recovery efficiency is critical to the sustainability of PV module waste management.

Waste or by-products from recycling and recovery should be stored and disposed of securely to prevent leaching. Recycling should also be able to recover secondary materials with low levels of impurities. Furthermore, a healthy supply chain should support the utilization of recovered secondary materials from recycling by producers. It is important to note that transportation will play a significant role in reducing environmental impact in the environment.

3.6 Philippine Energy Profile and Development Plan

Understanding the energy profile in the Philippines plays a vital role in assessing the impact of renewable energy, particularly solar energy. The rising economic status of the country entailed a drastic increase in power demand, tapping mainly from fossil fuels at 76% of the total energy mix and the remaining composed of renewable, such as hydro power, wind, and solar [64]. While an estimated 316 million metric tons of coal are considered recoverable in the Philippines, the energy reliance on this source might not be beneficial in the long term due to its adverse effect on the environment and climate change [65]. In addition, the Department of Energy, which actively promotes clean energy transition for decarbonization and lower GHG emissions, identified a clean energy scenario under the Philippine Energy Plan 2020-2040 aims to increase the solar PV capacity by around 45 gigawatts [66]. Thus, alternative energy sources are to be considered for eliminating or at least reducing the usage of non-renewable sources and steering towards renewable sources.

In an energy assessment report by ADB, the potential solar capacity in the Philippines is estimated to have an average global horizontal irradiance of 5.1 kWh/ m2-day [67]. Furthermore, it is projected to increase to 3.5% of the total energy mix in a clean energy scenario, a big leap from its 0.20% counterpart in a business-as-usual setting. With efforts to transition to a low-carbon economy, the Philippines have the opportunity to optimize the utilization of its solar energy potential. The formation of RA 9513 has given light to the search for alternative and relatively clean energy, particularly for the energy sector companies. Based on the National Renewable Energy Program (NREP) projections, the Philippine government aims to increase around 16 GW of installed capacity for renewable sources, including solar energy [64].

In conjunction with increasing renewable energy in the energy mix profile of the Philippines, the supply and demand for PV module materials must be well-defined. A significant increase in the demand for critical metals, such as indium, gallium, tellurium, and cadmium, will be expected due to the rise in solar power utilization. In addition, raw metallic materials will not be sustainable in the future if we constantly use virgin materials for production. Thus secondary materials pose a solution to this problem, granted that proper metal management in the form of material flow is imposed [67]. Another area to be looked upon is efficiency. In 2018, Philippine RA No. 11285, known as the Energy Efficiency and Conservation Act, was enacted to establish energy sufficiency and stability, mitigate the high prices of fuels, and support the economic and social development goals, among others through environmental protection. This can be properly administered by ensuring the quality of the material for the PV module being used. As future research, this area gives a good starting point for further development to give justification for secondary materials to be mixed in PV module production. Furthermore, this will involve more opportunities to prove the right amount or mix of secondary materials that will give comparable or better energy from solar-based products.

In addition to the Philippine government's effort in supporting low carbon transition, solar energy also has the advantage of supplying power to remote areas. This kind of scenario is common and scattered across the country, in rural and agricultural plots of land. Supplying energy from fossil fuel sources, such as diesel, will cost significantly higher distribution costs in far-flung areas, as compared to those near the supply. Strategic locations and installations must also be considered so that solar farms may be optimized for remote areas that have limited access to power.

3.7 Regulatory Framework for PV Module Waste in the Philippines

PV module waste is hazardous waste that contains several toxic substances, such as cadmium, selenium, and other heavy metals [16], and requires attention. Regulatory frameworks should be established to deal with PV modules installed in the country that are prone to breakages contributing to the rapid increase of emerging PV waste. The Philippines is ranked fifth among countries most affected by extreme weather events and other natural calamities, such as typhoons, floods, rising sea levels, and earthquakes, to name a few. This may be attributed to its geographic location within the typhoon belt and Pacific Ring of Fire [68]. With this, frequent exposure to such natural disasters may entail losses and damages to properties and infrastructure, thus affecting delays in productivity and, consequently increase in waste. In relation to structural damage, PV modules are no exception to this because of their delicate, brittle nature. In fact, PV module breakage is a common theme even in its transport [37].

In the Philippines, PV module waste is subjected to the DOE Department Circular No. 2021-06-0018, commonly referred to as the Solar Code, which complies with RA 9003 and RA 6969 [47]. PV module waste can be classified as special waste under RA 9003 or waste electrical and electrical waste (WEEE) under RA 6969. The Ecological and Waste Management Act of 2000 or RA 9003, lays out the incentives and mechanisms for the management of solid waste that ensures the conservation, utilization, and recovery of resources, while the Toxic Substances and Hazardous and Nuclear Wastes Control Act of 1990 or RA 6969, deals with the management of toxic and hazardous waste, including nuclear waste.

The inclusion of solar energy systems in the development plan of the nation, technological advancement, and economic growth [69] are key enablers in the increasing adoption of PV systems in the country. There is really need to establish recycling facilities to deal with emerging PV module waste. Recycling facilities for PV module waste follow DAO 2013-22, which is the IRR of RA 6969 that expedites the procedures for handling toxic substances and toxic waste. Waste generators, transporters, and treaters are key actors in the management of hazardous waste and toxic substances guided by the procedural manual implemented by the Department of Environment Natural Resources - Environmental Management Bureau.

There are no specific national regulations created to deal with PV waste and PV module waste in the country. Furthermore, the 10-year solid waste management plan of municipalities has not yet incorporated strategies to manage PV waste [16]. These two crucial observations support the conclusion that the country is not yet ready to deal with emerging PV module waste. Indeed, there is a need to formulate regulatory frameworks and policies and adopt suitable strategies that deal with PV module waste. The composition, waste assessment, and management strategies to address PV module waste should be included in the regulatory framework. Furthermore, policies in terms of monitoring the PV waste in the country, take-back schemes, and funding and subsidization can be explored.

IV. CONCLUSION

In this work, the authors have investigated PV module waste management in the Philippine setting, where there is scarce discussion in the literature, and presented key waste management strategies and frameworks. The increasing volume of PV module waste must be managed effectively to achieve sustainability and prevent environmental harm and degradation through integrated frameworks. This paper identified waste management strategies on the various stages of the life-cycle of PV module waste based on a systematic review of literature. It also assessed the existing regulations of PV module waste management in the Philippines. It has been found out that the country is not yet ready to deal with PV module waste due to the lack of specific regulations and standard waste management strategies. The collaboration of all stakeholders, PV module waste assessment, robust design of PV modules, the establishment of an optimized recycling network, utilization of efficient recycling technologies, healthy supply chain of recovered secondary materials, and practical regulatory frameworks and approaches are vital elements towards PV module waste management. This work can help researchers and policymakers create practical and effective approaches and policies to manage emerging PV module waste.

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