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Multi-levels of photovoltaic waste management: A holistic framework

Sajjad Mahmoudi [a], Nazmul Huda [a, *], Masud Behnia [b]

[a] School of Engineering, 44 Waterloo Road (44 WR), Macquarie University, NSW, 2109, Australia
[b] Macquarie Graduate School of Management, Macquarie University, North Ryde, NSW, 2109, Australia

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ABSTRACT

With the unprecedented global growth of Photovoltaic (PV) panels installation at the annual growth rate of 25–30%, their appropriate End-of-Life (EoL) management gets into focus. The major gap is currently a strategic pathway that facilitates internationally closed-loop supply chain (CLSC) leading to a circular economy from the management point of views. This paper introduces a universal framework for sustainable management of about 5000 GW PV products by 2050 and illuminates the different boundaries and elements that influence the circular economy. There is a minimum of 24 types of substances embedded in PV waste flow which are classified into 6 categories. The research findings estimate 60–80 million tons (MT) of PV waste by 2050 which entails proactive strategy for EoL treatment. Latest update of WEEE Directive in 2019 enforces 85% recovery and 80% preparation for recycling of PV panels. If an environmentally friendly treatment pathway could be achieved and the recovery rate and purity level meet the market demand, there is strong potential for a circular economy, but it needs proper marginalization at the management levels. This study indicated that the PV panels' sustainability should be broken down into three principal levels comprising product and component (Macroscopic), material (Mesoscopic), substances (Microscopic). In each level, the associated parties were introduced, and critical elements were discussed. The parties at the macroscopic level mostly consider the projection of the waste, awareness, and marketing of the recovered materials. While the environmental impacts, treatment pathway and its standard are covered by the associated parties at the mesoscopic level. The micro-management more concerns the monitoring of the purity level and transparent movement of the recovered materials and substances into the new industry and new market and highlights further consideration on the regulation at the international and national levels in this case.

1. Introduction and PV waste management proposal

To be able to answer the questions what legislation and incentives need to be in place to make the recycling of PV panels viable and what would be a potential framework towards PV panels circular economy, the proper understanding of the PV market, as well as the opportunities and threats in the short and long term, is required. In the following sub-sections, 1.1–1.7 the overall status of PV modules is elucidated in terms of global PV deployment, PV waste generation, PV waste management in terms of policy and regulations, latest research findings, and the current major gaps are outlined and aims and significance of this research are expressed. Thereafter, the overall formwork and classification of EoL PV panels as one of the key aspects towards the circular economy of EoL PV panels is proposed and the PV waste management roadmap is illuminated.

1.1. Up-to-date worldwide PV deployment background

Global solar panel capacity has grown significantly in recent years leading to a cumulative capacity of 227 GW by 2015 (IEA-PVPS, 2017), and 303 GW (GW) by 2016 (IEA-PVPS, 2016), then erected to more than 480 GW in 2018 (IRENA, 2019), predicted to rocket to 700 GW in 2020 (Woodmac, 2016) and reach 1720 GW by 2030, and 4675 GW by 2050 (IRENA: Stephanie Weckend, 2016; Komoto and Lee, 2018). Solar panels as types of clean and green products would not be completely environmentally-friendly without considering proper disposal pathway and holistic treatment strategy at the end of their operational life (REC-Group, 2018). Given the fact that the use of renewable energy products and in particular PV panels are broadening significantly, the erecting and

* Corresponding author.
E-mail address: nazmul.huda@mq.edu.au (N. Huda).

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mandating of the suitable policy and regulation for the discarded PV module is inevitable by every PV consumer country.

1.2. Global cumulative PV waste generation

Solar photovoltaic panels have been designed to generate clean and renewable energy for about 25–30 years; however, there is no such a constant lifetime to be expected and the panels will gradually enter to the waste stream either at the early stage of their lifetime or a regular lifetime. This is due to damage during the transportation and installation stages, initial failures after start-up operations, technical and physical failures during operation caused by severe environmental conditions, and unexpected external factors including natural disasters (Komoto and Lee, 2018). It is anticipated that the significant PV deployment in overall results in a considerable number of modules to be entered into the waste stream in the coming years (see Fig. 1).

Globally, the number of panels which reach to the end of functional life is increasing so that the worldwide cumulative PV panel waste was estimated to be to 43500 tons by 2016, with a considerable surge to 1.7 or 8 million tons (early-loss scenario vs regular-loss scenario projection) by 2030, remarkably escalating to even higher, amounting to 60 or 80 million tons (early-loss scenario vs regular-loss scenario projection)in 2050 (IRENA: Stephanie Weckend, 2016). The development of an early supporting framework can facilitate the comprehensive end-of-life policies and management of PV panels.

1.3. Latest worldwide policy and regulation

This section of the manuscript will review some of the prominent policy and regulations presently being employed for EoL PV management across the globe. In the literature, there is a range of policy and regulations either suggested or enacted for the EoL management of PV module which should be appropriately adapted based on the conditions of PV consumer countries.

Directive 2012/19/EU was established by the European Union. This regulation is mostly for the reduction of the amount of waste that goes to disposal through the proper collection and treatment method and prevents illegal exportation of the waste (Paiano, 2015). A wide range of restrictions and regulations has been established for limiting using hazardous materials in electrical and electronic equipment (Li et al., 2015). Also, the Basel Convention was enacted in 1999 on liability and compensation of damage resulting from transboundary movements of hazardous wastes and their Disposal (Ogunseitan, 2013).

Table 1 provides the revolutionary progress of regulatory scheme on collection and recovery targets of Waste Electrical and Electronic Equipment (WEEE). As can be seen, the original directive was initially regulated in 2002 with an annual collection target of 4 kg per inhabitant concerning the annual recovery and recycling targets of 75% and 65%. Subsequently, four revisions were published and in the latest one it is asking for the annual recycling rate of 85%, and recovery rates of 80% of the total annual WEEE.

In addition to the WEEE Directive, Europe, and some major PV user countries such as United Kingdom, Germany, Czech Republic, Korea, Japan, China and the U.S. state of California have revised their WEEE regulations for appropriate treatment of their obsolete PV panels. The main regulations and contributions for the EoL PV panel sector employed by them can be seen in Table 2.

1.4. Latest findings on PV waste management

(Hocine and Samira, 2019) pinpointed that EoL PV panel assessment should not be based on a fixed life cycle (approximately 25 years) because the economic benefits of the panel according to its energy generation could vary from one region to another one. In fact, an aging evolution scheme can be more realistic so that a panel with no economic profitability at one region is moved to another region such as a remote area for supplying electricity for pumping or rural lighting and still meets the economic profitability requirement since the electricity supply costs vary in a different region.

The current status of solar panel waste recycling, recycling technology, environmental protection, waste management, recycling policies and the economic aspects of recycling was evaluated by (Chowdhury et al., 2020). Their findings showed that the vast majority of the countries are extending the duties of the PV materials' manufacturers in terms of PV waste management either for disposal or reuse. However, there are not enough indications on policies that can be carried out globally to handle the PV waste and limit the environmental burden at the global level. Further improvements in the economic viability, practicality, high recovery rate and environmental performance are required.

(Farrell et al., 2020) investigated the routes in the recycling of EoL c-Si PV panels and provided insights on the technical challenges and opportunities towards a circular economy. It was outlined that among various recycling methodologies of mechanical,

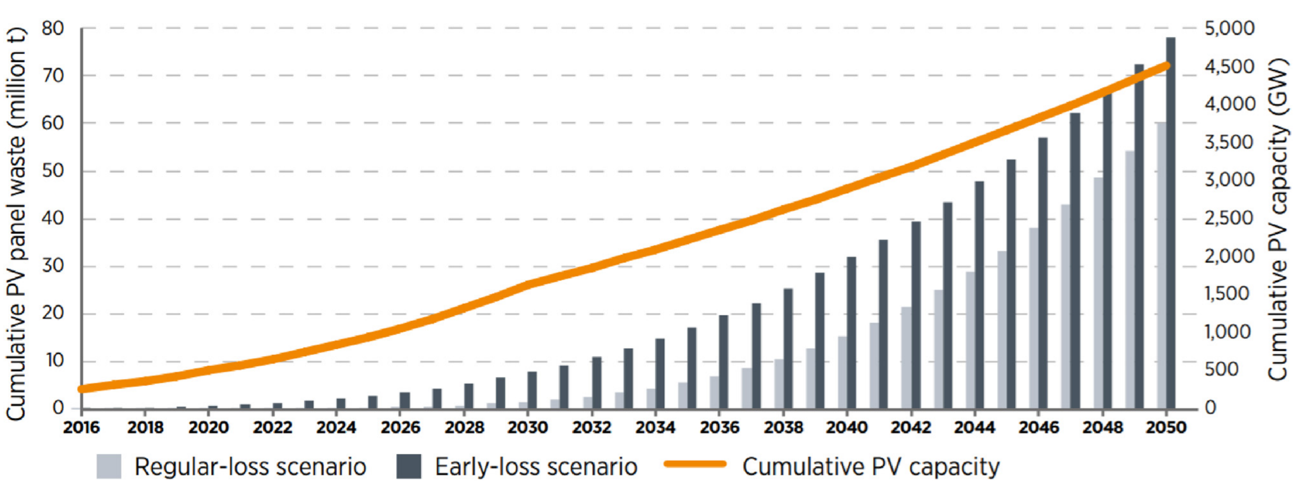

Fig. 1. Estimation of Global EoL PV waste (million t) generation (Weckend et al., 2016).

Table 1
The WEEE Directive regulatory scheme on collection and recovery targets (data summarized from (IRENA: Stephanie Weckend, 2016; Komoto and Lee, 2018).

Type	Date	Annual collection target	Annual recycling/recovery targets
Original WEEE Directive	2002/96/EC	4kg/inhabitant	75% recovery, 65% recycling
Revised WEEE Directive up to 2016	2002/19/EU	4kg/inhabitant	Start with the 75% recovery, 65% recycling, 5% increase after 3 years
Revised WEEE Directive from 2016 to 2918	2002/19/EU	45% (by mass) of all equipment put on the market	80% recovery and 70% prepaid for reuse and recycled
Revised WEEE Directive from 2018 and beyond	2002/19/EU	65% (by mass) of all equipment put on the market*	80% recovered and 75% prepared for reuse and recycled
Revised WEEE Directive from 2019 and thereafter	2002/19/EU	–	85% recovered and 80% prepared for recycled

Table 2
International contributions for the management of EoL PV module (data was collected from the review paper (Komoto and Lee, 2018; Sica et al., 2017)).

Country	Regulations and Contributions in EoL PV module management
United Kingdom	- Registration of all produced and imported PV panels - Putting obligations for all manufacturers for providing critical data of the panels
Germany	- Updating their regulation for the end-of-life treatment of PV modules - Considering heavy fines for offenders - Obligations for registering of imported and manufactured PV panels into or in Germany
Czech Republic	- Asked Retina as a photovoltaic waste processor for rehabilitation and recycling management of their PV panels - WEEELABEX is an organization situated in Czech is also involved in a project aimed at developing standards and monitoring of waste-processing companies as well as collecting, storing, processing, and recycling of WEEE
Japan	- Developing recycling technologies - Developing a local company working on recovery technologies - Obligation enacted by environment ministry asks the PV panel manufacturer to look after the recycling aspects of panels. - NPC company accepted a joint venture for recycling of PV panels with Hamada Company as an industrial waste-processing - Shell oil company officially connected with the EOIO (European photovoltaic international organization) - A roadmap was promoted by METI and MOE that endorses the laws and regulations of the design and R&D of the low-cost technologies required for the optimal and environmentally friendly dismantling, transportation, and treatment of the discarded PV panels
USA	- California developed a proposal for control and supervise the processing of EoL PV components - Recycling and reducing landfill disposal of hazardous substances have been supported by the department of toxic substances control. - First Solar as the American silicon film panel producer has planned for recycling and reusing of PV panels by the establishment of companies in the U.S., Germany and Malaysia. - Only general waste regulations are applied for the collection and recycling of end-of-life PV modules in the whole United states excepts California and Washington - the state renewable energy system tax and the necessity of takeback and recycling program for end-of-life PV modules was implemented in Washington by Senate Bill 5939 - commitment for the manufacturers to prepare product stewardship plans that describe how they will finance the takeback and recycling program and provide for takeback of PV modules at locations within the state. - Stewardship developed by the Washington State Department of Ecology states that manufacturers who sell solar units in the state of Washington after July 1, 2017, are responsible for financing and providing a recycling program for their units. - Manufacturers who do not provide a recycling program cannot sell solar modules after January 1, 2021. - The U.S. Solar Energy Industries Association (SEIA) has maintained a corporate social responsibility committee that reviews developments related to PV recycling and announced the launch of a National PV Recycling Program in September 2016.
China	- CESRI (Chinese environmental science research institute) investigate on the environmental management of EoL PV panels - exploration has started in terms of technology development, recycling and safe disposal - no specific regulations for the discarded PV panels - the necessity of special laws and regulations aiming at providing a high recycling rate of first and second PV generations has been targeted - Cost-effective and optimum energy usage and the proper financial frameworks were proposed
Europe	- Transposed the PV requirements into national law - All producers that put PV panels on the market in the European Union need to either operate their take-back and recycling systems or join the producer compliance schemes. - European R&D initiatives are developing recycling technologies to reduce the expenses of treatment - Enhancing the awareness regarding the value of recovered secondary raw materials to enhance the potential revenue streams by recycling of EoL PV materials. - The European Commission also asked the European Committee for Electro-Technical Standardization (CENELEC) to develop specific PV treatment standards for different fractions of the module the waste stream to support a high-value recycling approach - Developing a standard and technical specification containing (Part 1 and Part 2) for PV module collection and treatment in terms of administrative, organizational, and technical requirements for waste photovoltaic panels. - Also, the standard for monitoring, sampling, and reporting and storage requirements were provided in the standard.
Korea	- No regulations governing the EoL stage of the photovoltaic panel in Korea. - The registration and reporting of end-of-life PV panels was mandated by the Ministry of Trade, Industry and Energy (MOTIE) to update the existing regulations - Promotion of R&D protocol for the development of recycling facility to reclaim of unbroken wafers with a capacity of 730 tons/year - Aiming at the foundation of a PV recycling centre in Korea in the near future - There is also the Non-R&D projects lead by the local government and six non-profit organizations supporting: - the technology, process, and facilities for the recycling of c-Si and thin-film Si PV module - Establishing a system for the declaration, collection, and transportation EoL PV module

chemical, and thermal recycling and recovery of materials embedded in the EoL c-Si panel, pyrolysis offers the most effective potential in order to the optimum recovery of material and energy in the c-Si panels especially for removing polymeric material in the form of the EVA encapsulant and majority of the PV backsheet. It can also provide energy which can aid the delamination of further panels and positively affect the economic feasibility of the recycling process leading to a circular economy.

As a proactive measurement, the cost-benefit analysis of PV waste recycling and its feasibility assessment are being grown by receiving the scholars' attention in recent years (Liu et al., 2020). Performed the cost-benefit assessment of PV panels in China and highlighted that the treatment of waste generated in 2020–2034 is viable and estimation showed that the unit net benefit is 0.57 USD/KW with the NPV and BCR of 21.14 million USD and 1.023 respectively. The sale benefits of recovered PV materials is the most sensitive factor affecting the project's economy which also confirmed by other studies (Faircloth et al., 2019; Lee et al., 2018). The environmental impacts and economic benefits of domestics PV waste recycling were also investigated in Thailand by (Faircloth et al., 2019) and Australia by (Mahmoudi et al., 2020a). The former research showed that although the cost to recycle could be as little as $0.03 per kg by applying discounted cash flow (DCF), there is no economic profitability on PV recycling yet unless the PV waste flows are increased, and the initial investment costs are decreased. The latter research, on the other hand, indicated that the domestic full treatment of annually 20 Kilotons PV panels is feasible and meet the environmental sustainability and circular economy metrics.

The treatment of discarded PV modules is inevitable and entails a holistic, and systematic approach for the management of discarded PV modules. At this stage, the guidelines and recycling infrastructure are being developed globally and there is a decentralized focus in this case while solving PV waste management as an upcoming global problem entails a unanimous and integrated framework. Nonetheless, there are still many countries which are far behind without a concrete regulation system for EoL PV products (Mahmoudi et al., 2019a; Tao and Yu, 2015).

According to the current literature, it is realized that the current gap is the lack of an overall framework outlining proactive metrics and boundaries in policy and management of EoL Solar PV panels across the world. In fact, the scholars addressed some of the aspects of PV waste management fragmentally and mostly provided the technical proof and evidence on PV waste recyclability in terms of treatment methodology and economic feasibility; however, there is no research presenting the connection and link between each segment of PV panel sustainability and providing a universal framework helping the industry and decision-makers to visualize the roadmap in this matter. The proposed framework in this paper is a critical step for the evolution of the circular economy in the PV industry.

1.5. Aims and significance of this paper

This study intends to address the following questions. 1) What are the current and future PV deployment projections and estimated waste distribution of the PV panels up to 2050? 2)What are the latest action plans and regulations at the global level to handle the PV waste? 3) What is the overall framework of sustainable PV waste management leading to a circular economy? 4) What are the major elements and steps need to be considered on this framework? 5) What is the priority of these levels to achieve sustainability in this sector? The significance of this article is twofold. First, this research provides a clear vision and classified information on the status of PV waste management at the global scale and highlights the latest findings related to managerial aspects. Second, this research attempts to establish a universal management framework to achieve a circular economy in the PV industry and attempts to illuminate the gaps and establish a foundation.

1.6. The essence of developing various regulatory and management levels

Photovoltaic waste contains different types of materials including valuable resources as well as toxic materials (;(Chowdhury et al., 2020; Mahmoudi et al., 2020b) which can be a matter of concern. Thus (Ardente et al., 2019), evaluated the resource-efficient recovery of critical and precious metals in c-Si panels and revealed high-quality recycled materials can minimize the environmental burdens and leads to significant benefits (Salim et al., 2020). Explored the complexities around managing the end-of-life (EoL) residential solar photovoltaic (PV) through a participatory system thinking approach and urged proper regulation for the PV product and material recovery rates to avoid valuable and hazardous materials be disposed of in the landfill, stockpiled or illegally dumped (Savvilotidou et al., 2017). Performed the toxicity assessment and feasible recycling of the 2nd generation of the PV panels through an optimized chemical treatment and raised the recycling challenges of critical metals in thin-film modules.

Conducted a comparative LCA of CdTe and Si panels and highlighted the importance of the process of the recovering of raw materials, a reduction of energy demand and emissions of materials that would increase the potential environmental impacts and human health risks by improper and informal recycling or being discharged in landfills. On the other hand (Sica et al., 2017; Tao and Yu, 2015), discussed that the appropriate treatment and formal recycling leads to an affirmative influence on the environment, the sustainability of natural resources, economic viability, closed-loop supply chain and circular economy.

Despite this, the process of recycling and recovery of discarded PV panels through mechanical dismantling, thermal and chemical separation can still generate and release toxic to the environment as all recovered materials are not 100% recycled yet (Awasthi et al., 2016; Wu et al., 2016). The hazard remained in the valuable recovered substances can enter into completely new products and put the public and environment under exposure to risk factors (Zeng et al., 2017), and cause environmental and health problems (Cucchiella et al., 2015). Also, inappropriate treatment may cause public concerns about the environmental burden and health risks of the EoL PV modules which can create barriers to the market penetration (Fthenakis, 2000) as well as changing the belief of the user to no more consider it as the green product.

1.7. How the EoL PV wastes should be classified?

To effectively solve the global concern about the significant photovoltaic waste generation in the world, a systematic approach which observantly classifies the discarded PV waste based on various factors is imperative. In the course of waste management, the material flow of the EoL PV panel starts with the obsolete PV panel and can potentially end up with the completely new products through desired treatment. To achieve optimal outcome form PV waste treatment, a pivotal classification of PV panels waste needs to be taken into consideration. To this end, the material flow of EoL PV panels can be broken down into four categories including product, component, material and substance Fig. 2.

The term *product* is the combination of various assembled components and separate parts with economic value and specific application which is priced by market and has a regular lifetime before discarding. The term *component* is basically the different

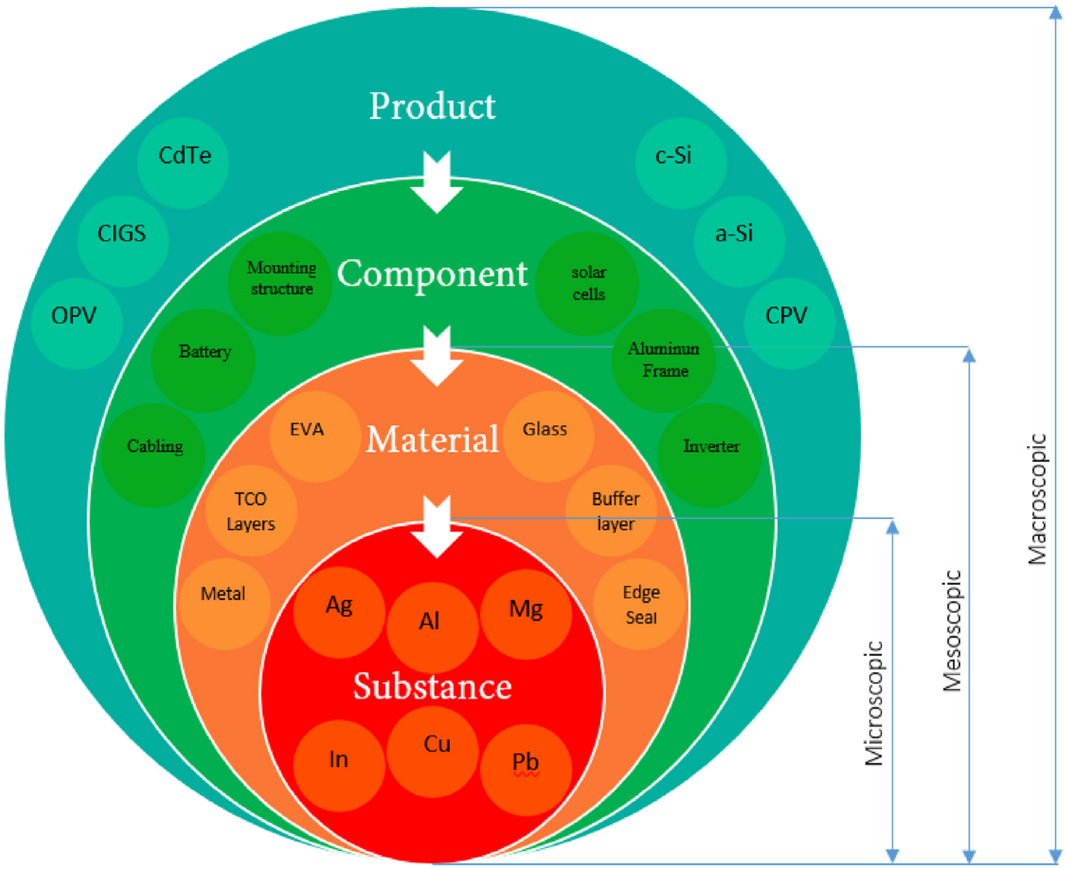

Fig. 2. PV waste classification to three levels of macroscopic, mesoscopic, and microscopic management.

parts embodied in a product and consists of different materials. The term *material* is the mixture of different substances which provide a specific function for a component and *substance* as the principal composition is defined as a mater with the uniform unit (Zeng et al., 2017).

With regards of this classification, different types of decommissioned PV modules such as c-Si, CdTe, CIGS is product; mounting structure, cabling, inverter, transformer, solar cells, frame, back sheet, strips are typical components dismantled from EoL PV waste; metal, plastic, steel, glass, laminate encapsulate (EVA), Edge Seal, (Absorber, TCO and buffer layers) is regarded as the material of PV waste flow; and further copper, gold, silver, indium, nickel and cadmium are substances.

To put it in another way, product/component, material, and substance of EoL PV waste can also be categorized into macroscopic, mesoscopic, and microscopic levels. On the whole, the different levels of management are required in terms of regulation and policy if the sustainability of the solar photovoltaic panel is desired.

2. Macroscopic management of EoL PV panels

The sustainability and viability of the EoL PV panels management program require careful attention to the multiple factors. These factors are many but mainly limited to the PV waste projection, reverse logistics network design, developing proper treatment facilities and infrastructures, training of the workforces, awareness regarding the environmental burdens, and economic viability and profitability for the parties and the investors, and finally marketing of the secondary materials and substances in local and international markets.

2.1. PV waste management at the product and component level

The step one is called “Macroscopic” management which focuses on the EoL PV waste stream at the product and component level. The importance of monitoring decommissioned PV panel at the product and component level is more helpful for the reduction of the extra environmental burden that could be imposed by disregarded treatment method while either the product or some of the components of the panel are still reusable with just some minor services. In addition to the true sustainability sourcing of material and manufacturing, the full track of PV panels in terms of product, component, material and substances throughout their lifecycle from cradle to grave is one of the prominent steps towards sustainability (Mahmoudi et al., 2020a). Also, a very critical monitoring step which was unintentionally overlooked by policymakers starts exactly after the disposal stage (Dias et al., 2019).

The natural progression of PV technology has led to the production of the higher versions of the panels with more affordability and better functionality and lower environmental issues across the life cycle of the panel. It can potentially increase the probability of early replacement of the new version of the panel with the older one in addition to the regular decommissioning of the panel. Here, the authors strongly believe that the foundation of a global organization via either Federation of PV producing countries or OECD countries or United Nations that could track the PV waste flow at different treatment steps is imperative. The detailed structure of such an organization requires further exploration which is out of the scope of this article. If a broad monitoring system and proper obligation are ratified for all imported and manufactured photovoltaic modules into or in every PV user country, these panels can be carefully tracked and be collected as soon as it is discarded by the end-user.

This organization can mandate a registration procedure for all discarded PV panel based on the producer, brand, serial number and all necessary identification factors so that it could be addressed whenever is needed. A robust tracking system plus considering heavy fines for lawbreakers would potentially avoid any transboundary movement of the waste as well as the illegal recycling which may cause serious environmental and health risks in both short and long term.

2.2. The commitment of active parties

To effectively manage the EoL PV panels, a responsible management legislative that can mandate the commitments of all parties is necessary. Under such a management legislative, the principal reference is supposed to be a global organization that has authority and power to compel all parties to systematically share and report information required for the management of EoL PV waste. Through the systematic data collection, the organization can vividly visualize the global PV waste generation trend and its status at various scales and assign proper commitment for the target parties. To this aim, all parties need to be a valid member of the organization by making an official account of their business at any level which is dealing with the panels either at the selling of the panel or the disposal or treatment process of the panel.

There are several parties who are involved at the macroscopic level including insurance companies, PV producers, installers, home builders, and PV owners. The reason why a couple of parties are supposed to report the status of the panel at this level is to make sure the panel has been properly registered and traced at the early stage of its operation by the organization. All the parties at this level of management are responsible to inform any issues which are caused the panel being discarded and before delivering to the parties related to the mesoscopic scales. The major parties for all management levels are depicted in Fig. 3. The scenario is implemented by reporting of necessary data shared by corresponding parties at each level to the local government. It is followed by government verification after visual and careful inspection and finally will be published after the confirmation of the appointed organization globally. So, the lawbreakers will be penalized by heavy fines if the organization is identified at any time even in future. The role and effective cooperation of the other parties at the mesoscopic and microscopic levels are addressed in sections 4 and 5 of this manuscript.

2.3. Potential opportunities and threats in EoL PV waste

As shown in Fig. 4, the EoL PV panel contains a different category of materials and substances including precious metals, base and special materials, hazardous metals, critical substances, and other metals and materials. When it comes to volume, it can be considered as a very interesting source of the commodity. The volume of PV waste is one of the key factors which can play a critical role in the viability and sustainability of treatment toward circular economy and consumption. As discussed earlier in the introduction section, PV deployment had an astonishing growth since last decades leading to an incredible amount of EoL PV products gradually. The recent review paper by (Sica et al., 2017), underlined that the raw materials technically recoverable (at a rate of 65–70% by mass) from the global cumulative volume of PV panel waste (at least 1.7 million tonnes by 2030) based on the regular loss scenario, could yield a value up to € 540 million by 2030. Another report by (IRENA: Stephanie Weckend, 2016) disclosed that potential value creation of 60–80 million tons of EoL PV panel generated up to 2050 is expected to surge to over US$ 15 billion by applying the same regular-loss scenario. It can also prevent tremendous environmental burdens caused by the production of the panel.

However, improper treatment strategy including a weak monitoring system, transboundary movement of the PV waste flow, low recovery rate, defective reverse logistics networks would cause a serious challenge and big loss such as resource depletion, environmental burdens and health and human risks. There are many recycling and recovery methodologies and procedures which have been addressed by the scholars; however, none of them could still lead to the desired output and meet the limitation ratified for the environmental burdens yet. Fig. 5 shows the overall issues with the current PV treatment procedures adopted from the latest review papers published by (Chowdhury et al., 2020; Xu et al., 2018). The major processes employed in this case are quite diverse. For instance, the physical disintegration, thermal treatment, radiotherapy, nitric acid dissolution, and Ultrasonic irradiation are considered under the category of delamination technology. Also, there are a variety of processes such as dry and wet mechanical process, etching, vacuum blasting, surfactant chemistry, leaching, flotation as the material separation technology. However, the category of material purification technology and procedures in pyrometallurgical (pyrolysis), hydrometallurgical (acid leaching) and biotechnological technologies (microbial leaching) have been less explored. The purification level in all of these processes are not well capable yet for a high purity level of the PV waste materials and they mostly lead to certain levels of emissions (Awasthi et al., 2016) and releasing harmful and toxic gases (Keiichi Komoto, 2018), health risk issues (Huang et al., 2016; Zeng et al., 2016), and high energy consumption (Chowdhury et al., 2020).

2.4. Forecasting of future PV waste generation

The reliable prediction of the total amount, concentration or material composition, and value of reclaimable material of future PV waste streams has a critical impact on the economic viability of the treatment program and by decreasing the potential risks of investment on the treatment of EoL PV panels. It also can be a major incentive for the investors and also policymakers for enacting directive and legislations. Thereafter, the policymakers and investors would have a clearer result to take a better step toward successful treatment and sustainability with lower environmental burdens and higher profitability.

Better insights on the reliability of PV waste projection, lower loss and more economic profit would be expected. Reliability and quality of EoL PV waste projection as a critical factor must be carefully assessed by the authorities in a sense that the probability of PV waste generation through both the wear and technological obsolescence of the first photovoltaic panel placed on the market and the early and constant failures of recently sold products are considered in the waste projection (Peeters et al., 2017). By considering the three-level of failures depicted in Fig. 6, the PV waste streams can be forecasted with higher precision. This waste projection strategy can be effective to identify whether a PV panel would return for repair or reuse, remanufacturing or recycling, and recovery.

2.5. Economic feasibility assessment

The decision markers main role would be to create the economic climate for profitable PV treatment through enacting suitable

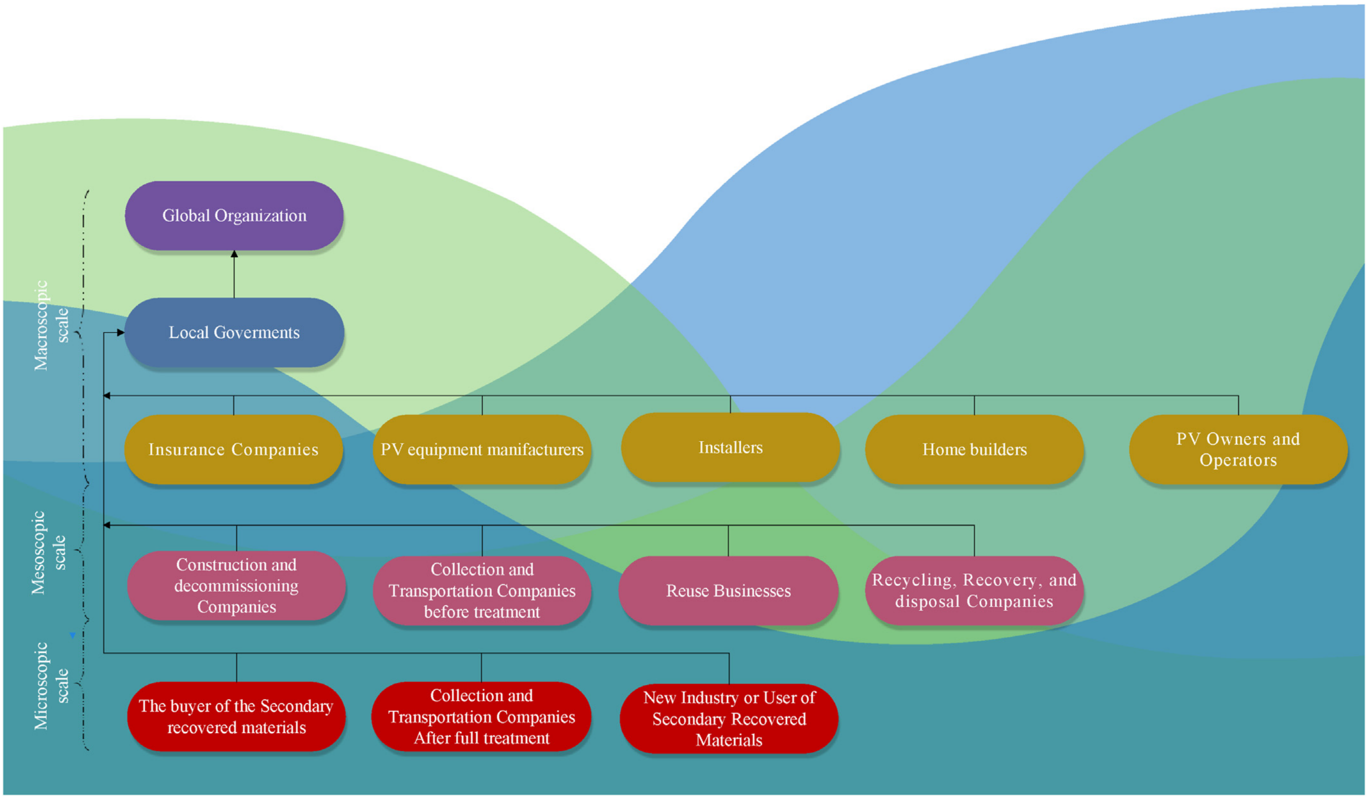

Fig. 3. The perspective of photovoltaic (PV) waste management including all major parties.

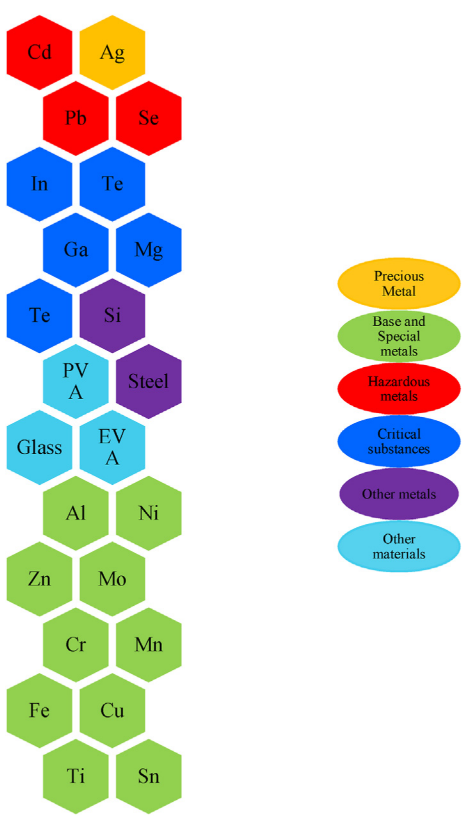

Fig. 4. The material inventory of the PV waste stream for c-Si, a-Si. CIGS, CdTe panels.

regulations, making financial incentives for investors to get involved, R&D support program, etc. It means that the short- and long-term profitability of the business should overweigh the total cost as time-limited as possible reducing the escalation of probable risks and loss.

The economic feasibility of the treatment program of EoL PV panels hinges on the geographic concentration of the discarded panel, the proximity of PV wastes to the appropriate recycling facilities, and on their content of valuable materials (Fthenakis, 2000). The annual amount of the PV waste generation (at least 20,000 tons/year for a recycling plant), purity rate of the recovered materials, and attractive price and proper marketing strategy can play as the influential factors. Besides, because of global high demand of the raw materials, the scarcity of the original material and substances which in turn determine the market price of raw materials can act as a stimulator and motivation factors for successful and promising revenue stream of the secondary materials extracted from EoL PV panels. Last but not least, an international ban on landfilling, and enacting global policy and regulation on proper recycling strategy and creating an incentive for the private sector such a tax exemption and low-interest-rate loan can potentially make this business more successful and sustainable. The assessment of the viability of the EoL PV treatment program should be taken into account at the macroscopic level of management to avoid the potential risks of failure in the early stage. The common method, in this case, is the Discounted cash flow (DCF) method estimating the net present value (NPV) and the discount payback time (DPBT) as two influential economic indicators. These indicators consider an incremental approach to calculate cash inflows and outflows in a business. The financial indexes employed DCF method for economic profitability assessment of the PV waste flows are (Bortolini et al., 2013) who studied a multi-parameter analysis

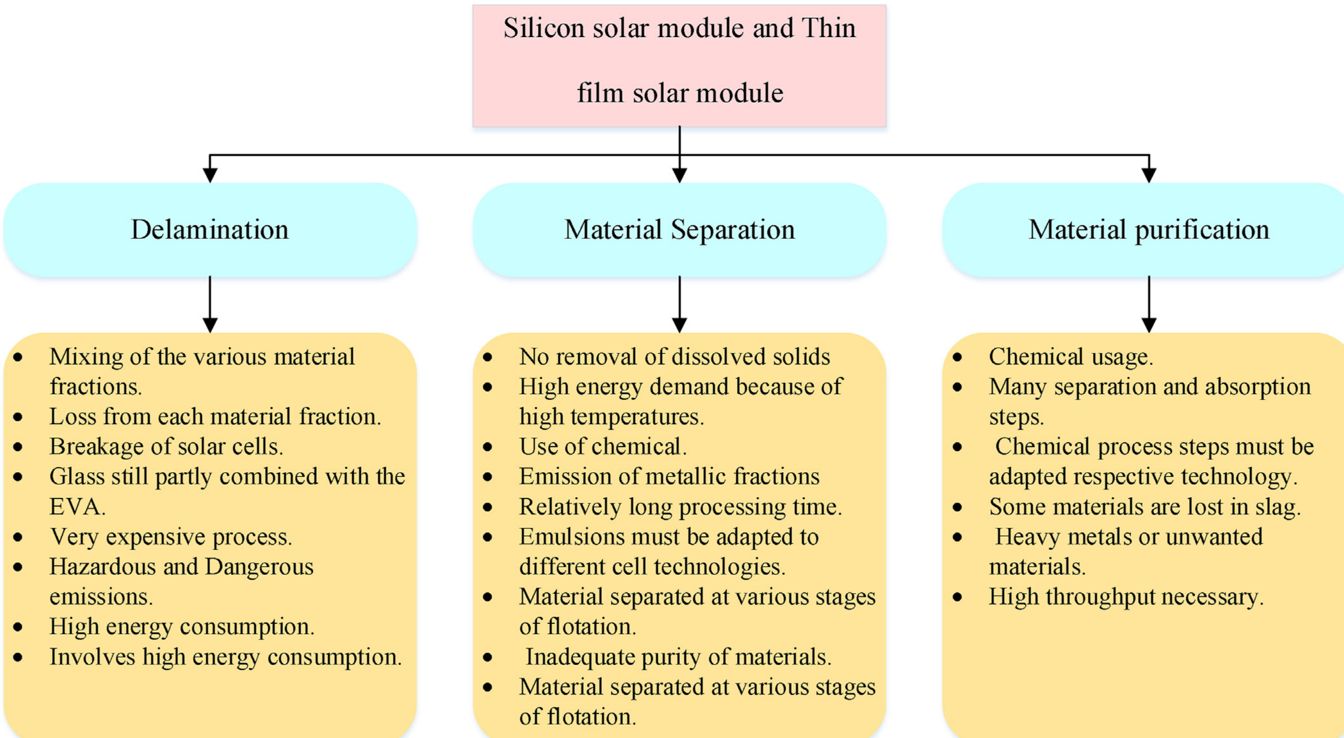

Fig. 5. Downsides of available recycling procedures for silicon and thin-film based PV modules adapted form (Chowdhury et al., 2020; Xu et al., 2018).

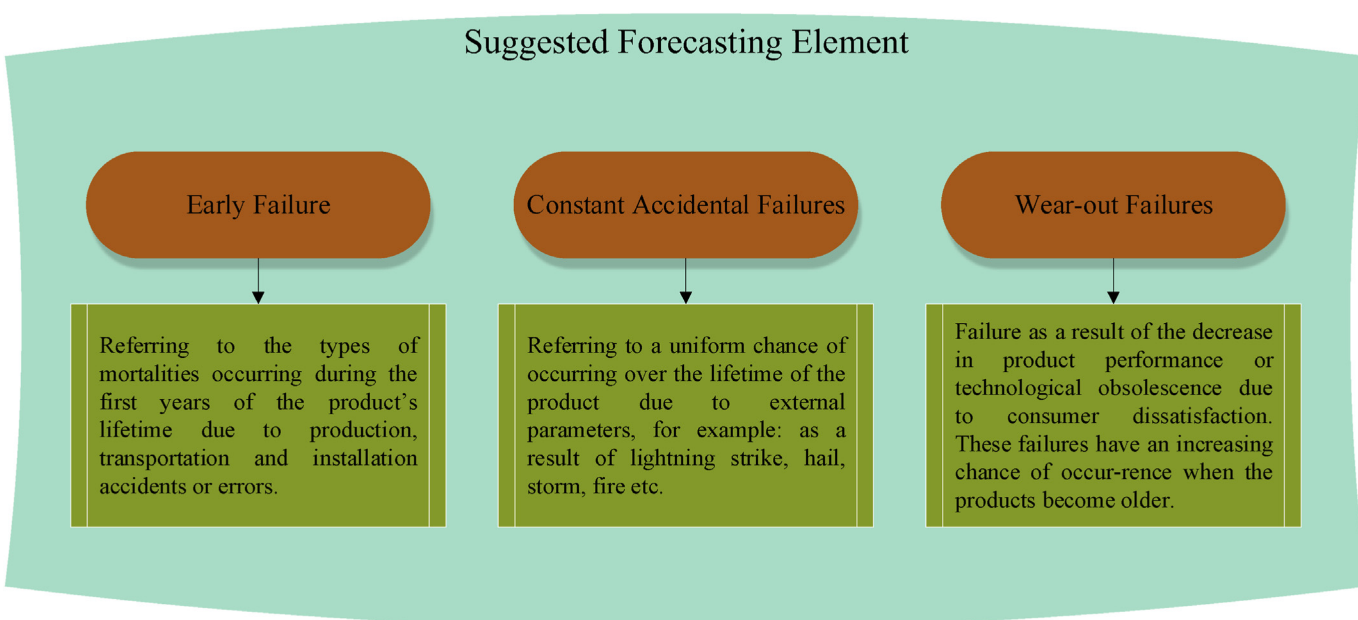

Fig. 6. The EoL PV waste strategy applying early failure, constant accidental failure and wear-out failure factors.

for the technical and economic assessment of photovoltaic systems in the main European Union countries (Cucchiella et al., 2015), evaluated the potential revenues coming from the recovery of 14 e-products including PV panels on the base of current and future disposed volumes in Europe (D'Adamo et al., 2017), investigated the financial feasibility of the recycling processes of crystalline silicon PV module, and (Tudisca et al., 2013) evaluated the economic convenience of PV systems on farm buildings for Italian feed-in schemes.

2.6. Awareness and marketing

A cleaner and more sustainable world require a more extensive awareness about the opportunities and threats of EoL PV waste flow leading to the reduction of this unregulated waste. The awareness component (Fig. 7) including health hazards, disposal

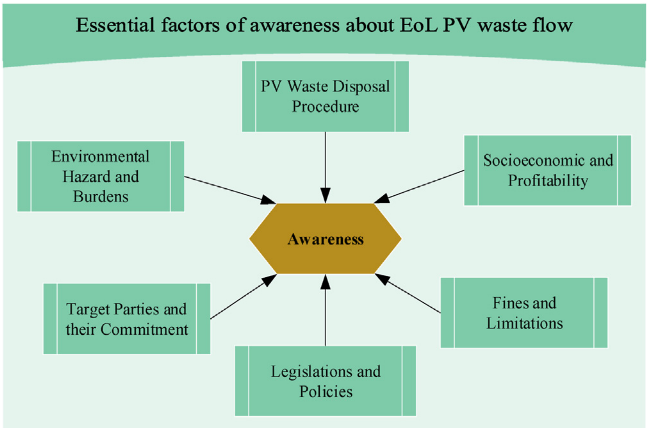

Fig. 7. Influential factors for effective awareness and insights about EoL photovoltaic wastes.

practices, environmental burdens of improper disposal and treatment strategy, awareness towards legislative policies, the value of the recovery of embedded material and substances in the PV waste flow, growing the people insights about sustainability and the gaps in PV products as a green product at their end-of-life stage can considerably support the better management of the EoL PV panels in the mesoscopic and microscopic levels of management. Since achieving behavioural changes in all parties is a critical matter, enhancing the level of awareness in the various aspects depicted in Fig. 7 may help us to effectively deal with this crucial E-waste.

The authors of this manuscript would suggest that the main player for increasing the level of awareness about EoL PV wastes can be a global organization and the local governments of every PV consumer countries employing various potential elements and tools for educating the target audiences depicted in Fig. 8. The overall strategy of education can be designed by the organization, and the customized program may be defined by the governments

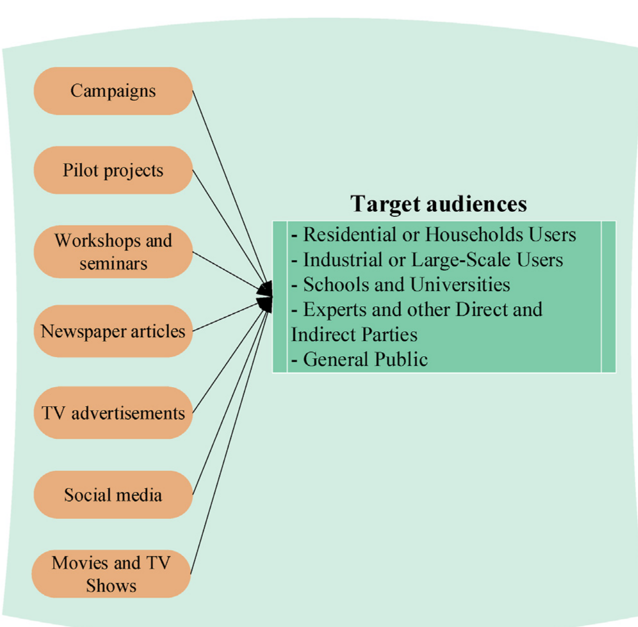

Fig. 8. A general framework to create awareness for target audiences of EoL PV waste management.

and relevant authorities to enhance the effectiveness of the education. Some of the insightful surveys tested to measure the awareness of WEEE are a survey-based analysis of public environmental awareness and performance on household electrical and electronic equipment in Ningbo, China by (Huang et al., 2006), a novel collection model tested by (Solé et al., 2012) in Catalonia (Spain) to foster the separate collection and recycling of electrical and electronic toys, with the participation of selected primary and secondary schools, as well as waste collection points and municipalities, survey-based analyses by (Sun et al., 2015) with 1874 valid participants evaluating the consumer behaviour and perspectives concerning spent household battery collection and recycling in China.

Along with awareness as an important component, considering influential marketing programs (see Fig. 9) and supportive policies are necessary to empower the associated parties for better trading of secondary material extracted through recovery and recycling. To this end, a clear understanding of the role and opportunities for secondary raw materials of EoL PV waste as part of the implementation of the Circular Economy Action Plan (CEAP) is needed. To achieve a successful marketing outcome, the initial step is to reduce the current marketing barriers such as the absence of quality standards for recovered PV materials, difficulties related to the trading of secondary raw materials (Ratner et al., 2020), and concerns about the presence of chemicals in recycled materials owing to low purity rate (Chowdhury et al., 2020; Zeng et al., 2017).

2.7. Reverse logistics

Reverse logistics (RL) network is known as the conceptual framework, mathematical programming, and computational algorithms employed for decision-making to find the most effective and economically efficient networks for design, operation, and control of the reverse flow of the EoL or discarded product (Yu and Solvang, 2016). RL covering the collection, sorting, transportation and storage of product, components, parts, materials, substances at any stage of the end of the life treatment process. Collection and transportation process has a critical effect on sustainability and minimizing of environmental issues. The profitability of a reverse logistics network is a paramount concern and is always coupled with either maximizing overall profits or minimizing costs (Demirel et al., 2016).

Present global markets of the photovoltaic panels are dominated by residential (roof-top), industrial sites, and utility applications. The distribution of these facilities is quite heterogeneous depend on the demand and the extent of each country. The collection and transportation of these waste inside of each country present a challenge. Also, when it comes to the global scale this challenge becomes more complicate and requires a holistic RL network design to effectively determine how to deal with the reverse flow of the PV waste at both country level and global level with lowest environmental impact and costs. The estimated cumulative waste volumes of EoL PV panels by country in ton (Fig. 10) indicates that the profitability of some countries may not meet the minimum annual PV waste generation required to assure the economic feasibility of the treatment. To avoid any problem for such countries, the creation of a convention to provide an opportunity for countries with lower PV waste flow to join the potential countries. These countries can contribute in EoL PV waste program of each other with the aim of reducing environmental burdens and making mutual interests by capturing the remaining values of EoL PV panels and bring them back to supply chain trough shared treatment program.

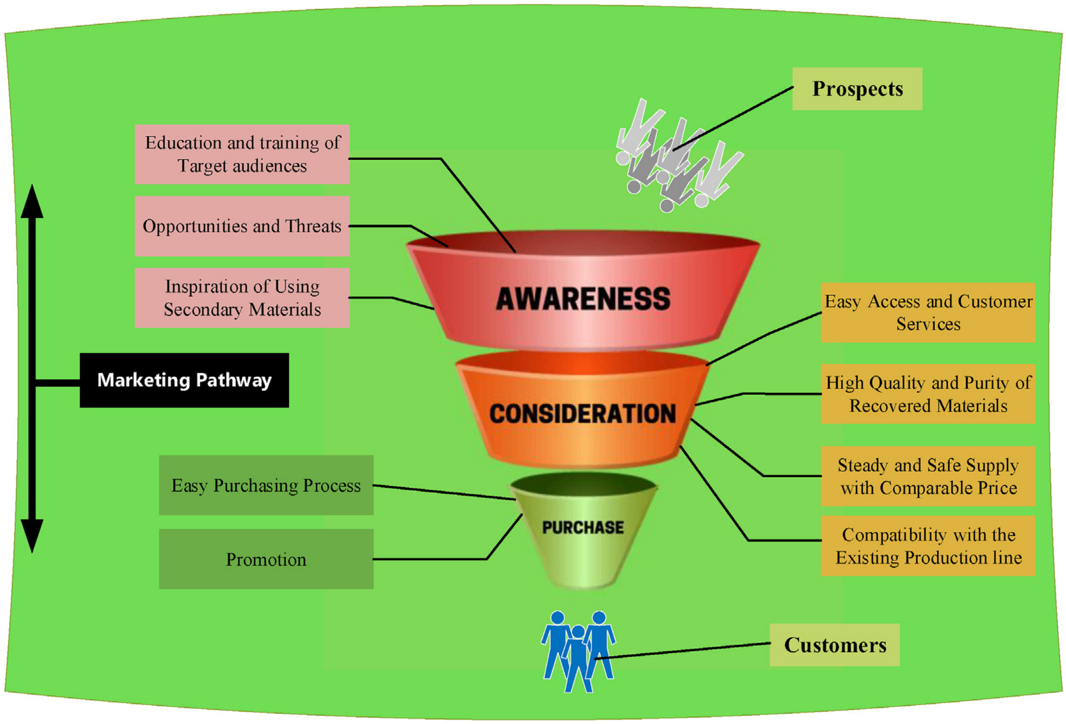

Fig. 9. Marketing Pathway for successful selling of Secondary Materials.

3. Mesoscopic management of EoL PV panels

As part of EoL PV waste management strategy, the mesoscopic management level aims to carefully look at how the recovery of embedded materials in the waste flow can effectively avoid the resource losses and meet the environmental protection targets through material compatibility analysis, life cycle assessment (LCA), and material flow analysis (MFA), (Khan, 2020).

3.1. PV waste management at the material level

Aiming at a closed-loop supply chain, Fig. 11 demonstrates the valuable resources existing in the PV waste flow which can be reclaimed by appropriate treatment strategy. A various EoL PV panel recycling methods are being commercialized; however, the process efficiency, economic feasibility (Deng et al., 2019), recycling and recovery rates, and environmental performance (avoided/imposed burdens) are under development and need to be improved as highlighted by many studies. For example (Contreras-Lisperguer et al., 2020), pinpointed that the design and development of a fully recyclable and reusable PV panel are very essential. The current design lacks the easy disassembly and material recovery standard and causes a variety of issues (Herceg et al., 2020). Evaluated the impact of recycling PV panels on electricity production's footprint, and (Farrell et al., 2020) outlined that pyrolysis offers the best potential for the optimum recovery of material and energy for the c-Si modules.

There are four major target parties at this level who are suggested to be responsible to report clear and accurate information (the standard of the report is enacted by the global organization) to the local governments including construction and decommissioning companies, collection and transportation companies, reuse business, and finally recycling, recovery and disposal companies. The essence of continuous confirmation of the status of the discarded panel at this level is to avoid any chance for the unofficial recyclers, transboundary movement of the PV waste, and to make sure that the panels are fully tracked. Thereafter, the panels will be delivered to the official recycling, recovery and disposal companies as the main parties who are seriously in charged with multiple directives and rules. Then, these parties need to meet the limitations of the environmental impact for the treatment process as well as purity of the recovered materials before and after treatment up to the full recovery of the materials embedded in the panels and the disposal of the residues after treatment.

3.2. Material compatibility analysis

In the treatment of EoL PV panels, there are a number of processes (see Fig. 12) such as dismantling, crushing and shredding as the mechanical treatment, and using various solvents for acid leaching, etching, neutralization, and purification in the chemical treatment and heating the PV sandwich and the other plastic materials by incineration for thermal treatment. If these processes, for instance, the types of solvent and solvent ratio, etching or leaching time are not selected carefully, there is a possibility of creating a certain level of damage in the recovered materials such as impurity, low performance, and health issues as well as releasing harmful and toxic gases (Klugmann-Radziemska and Kuczyńska-Łażewska, 2020). Assessed the compatibility of recovered semiconductor silicon wafer material in the production of the photovoltaic production. The results confirmed 58% total environmental impact reduction and 42% mitigation in Global Warming Potential (GWP) and greenhouse gas emissions of photovoltaic production compare to the primary production stage (Zeng et al., 2017). Discussed that even formal recycling would not the dissipation of the Hazardous substances into new products especially in new lower-grade products and proper regulation are still lagging behind. There is also the possibility of serious environmental impact follows from inappropriate and incompatibility of the chemical and thermal treatment methods on the target materials embedded in the PV

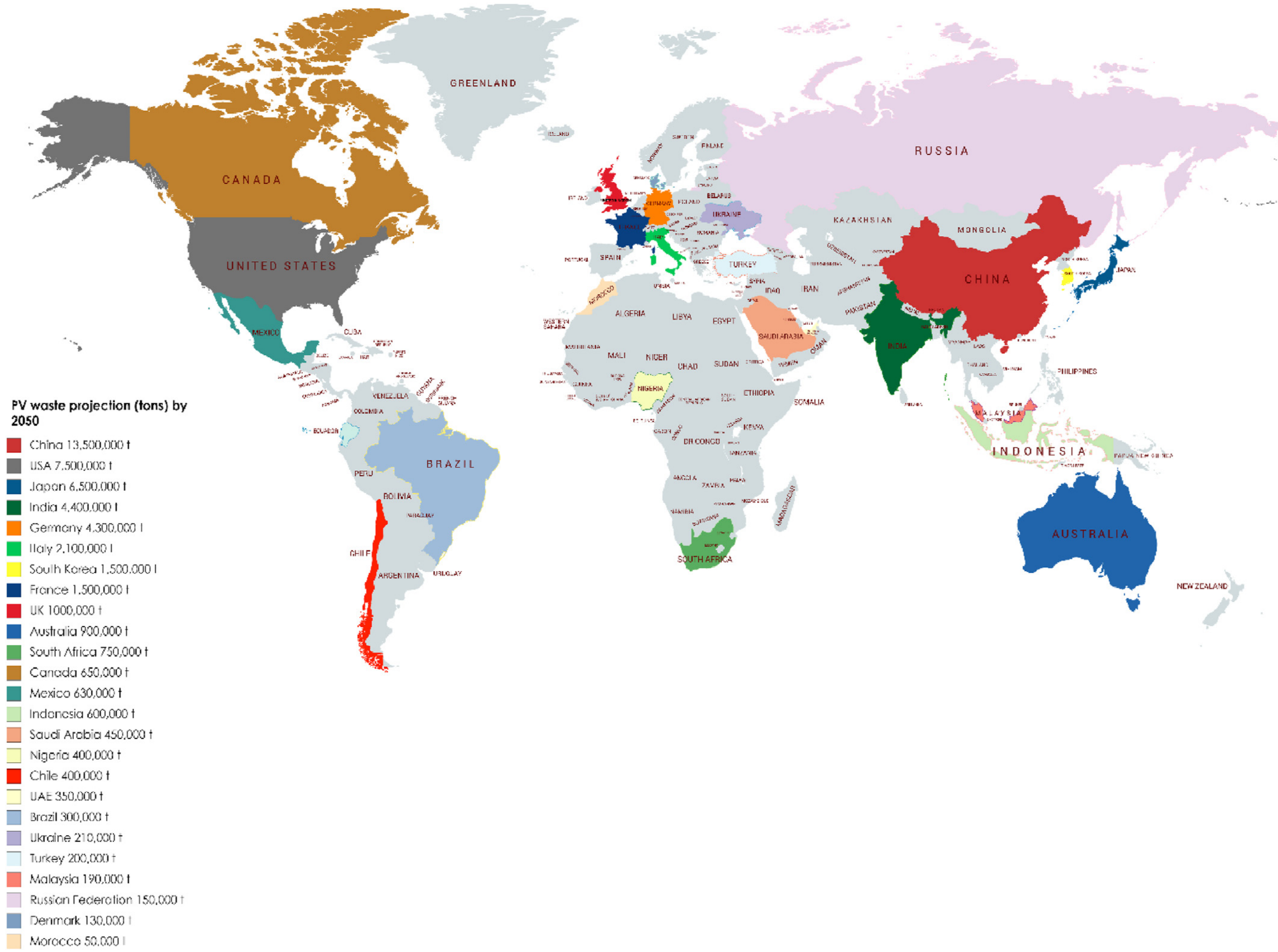

Fig. 10. The distribution of the cumulative global PV waste generation by 2050 based on regular loss scenario (the map was adopted using the data provided in (IRENA: Stephanie Weckend, 2016)).

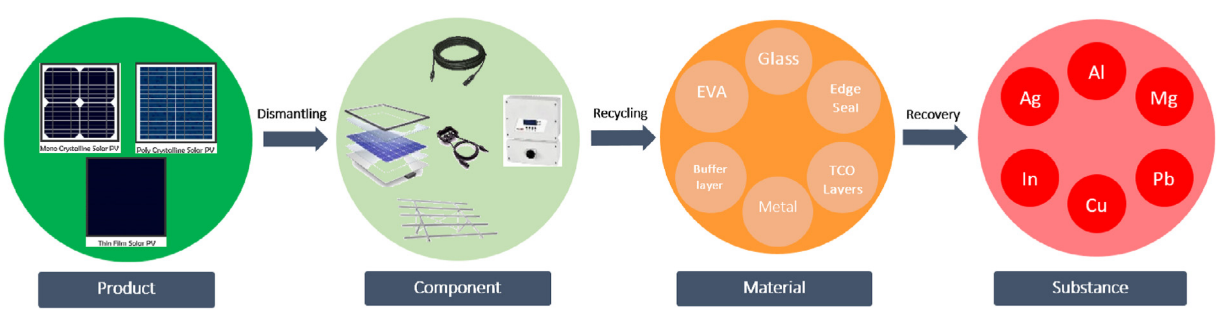

Fig. 11. EoL PV waste treatment levels comprising product, component, material, and substance.

waste flow resulting considerable loss of materials during the treatment (Khan and Asiri, 2019). Then, these losses will be scattered in the environment with harmful effects and health problems. Thus, applying the compatibility rules is necessary to enhance the recycling yields effectively.

3.3. Life cycle assessment EoL PV waste

To keep the energy security and climate change mitigation achieved by utilizing PV panel, LCA as a robust methodology can be used to evaluate and quantify environmental impacts of the treatment and disposal steps of EoL PV panel product. There are a number of scenarios such as reuse, recycling, recovery of the materials and substances which can be assessed based on the ISO14040 and 14044 standards (ISO14040, 2006; ISO14044, 2006) as general guidance to perform LCA (Gerbinet et al., 2014). The sustainable closed-loop life cycle pathway of PV panels demonstrated in Fig. 13. Through the proposed pathway, the resource depletion would be potentially minimized. Nonetheless, the burdens follow from the production stage and the end-of-life

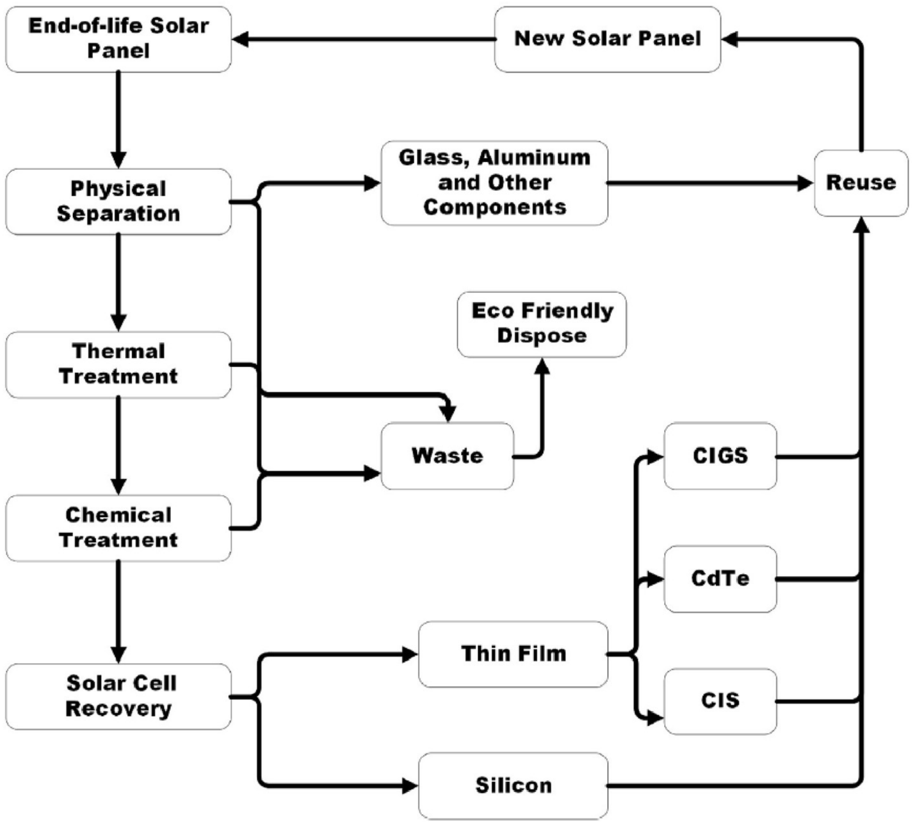

Fig. 12. Solar PV recycling processes for various PV generation and technologies (Chowdhury et al., 2020; Kang et al., 2012; Klugmann-Radziemska and Ostrowski, 2010).

treatment stage highly rely on mesoscopic and microscopic management.

LCA technique of EoL PV panel compiles and examines the inputs and outputs of materials and energy associated with the operational processes of the treatment pathway, and provide critical interpretation to the public sector, stakeholders and manufacturers with a possible recommendation for improvements and sustainability (Curran, 2015; Lunardi et al., 2018). With this in mind, it is worth noting that sometimes the treatment process works perfectly up to a certain step, for instance, the recovery of materials; however, achieving pure substances which can make much higher economic values need further treatment with serious environmental burdens and cost. In such difficult and multi-influential factors situations, interpretation of the result when decision-making must be carried out for such complicated e-waste is not easy at all. Multi-Criteria Decision Analysis (MCA) can be suggested as a facilitator for decision making which is discussed in section 4.5.

3.4. Material flow analysis of EoL PV waste

(Kwak et al., 2020) discussed that EoL solar panels with complex material structure can be potentially a source of environmental pollution and hazard but (Mahmoudi et al., 2019b) investigated that it also potentially offers a valuable resource recovery leading to considerable economic benefits and environmental protection through proper treatment. The treatment of the panels requires the active role of multi-parties in the reverse supply chain, evaluation and identification of the material flow in the whole PV waste management pathways (D'Adamo et al., 2017). Toward circular economy, closed-loop supply chain and sustainability, Material flow analysis (MFA) as an attractive decision support tool can be considered to manage the complex waste stream (Islam and Huda, 2019; Kiddee et al., 2013). According to the common definition of MFA provided by (Brunner and Rechberger, 2016), "MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material". One of the common and user-friendly software applied in this case is called "STAN" that supports performing material flow analysis (MFA). There are a variety of MFA and supplementary methods such as Dynamic SFA and MFA, Static MFA, Input-output MFA, substance-flow analysis (SFA), covering agent-based model, sales-stock-lifespan model, population mass balance, logistic model, lifespan distribution, distribution delay and time-step method, mass-balance model, time-step and consumption and use etc. Which are widely employed by researchers.

In resource, waste and environmental management of EoL PV panels, MFA is capable to quantify EoL PV panel mass flows in a system (PV Waste generated in a region, country, continent, and worldwide) during a defined period. According to the MFA principle which follows the law of conservation of mass, the material flows of PV waste is evaluated through comparing the inflows into an MFA system and the outflows plus changes during transformation (Sajid et al., 2019). The balance of the system is assessed by considering the defined boundaries and uncertainties.

3.5. Multicriteria analysis (MCA)

Growing EoL PV panel can provide business and jobs opportunities, value creation resulting in new economic avenues. In the course of selecting the optimum method for the treatment of such a

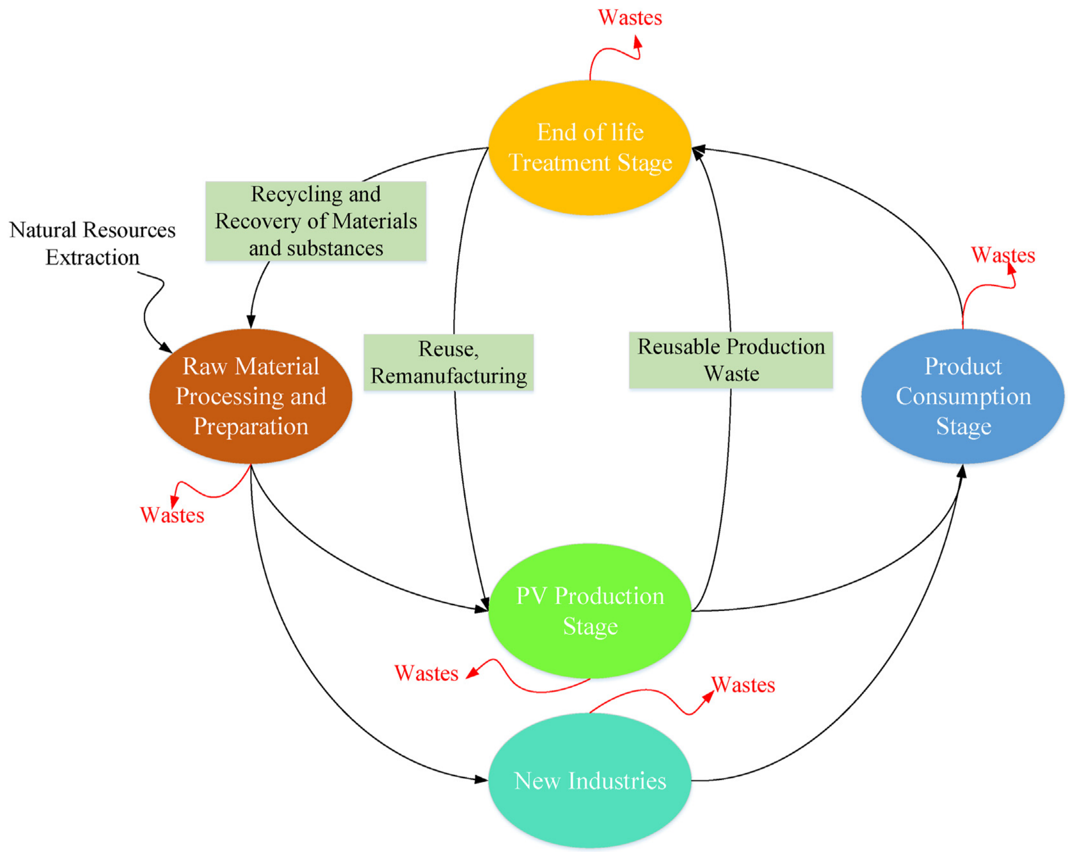

Fig. 13. Modified sustainable pathway of PV panel life cycle adapted from (Tao and Yu, 2015).

complicated waste flow, the utilizing of multicriteria analysis (MCA) has been suggested and utilized by the scholars (Khan and Kabir, 2020). Performed the sustainability assessment of common waste-to-energy generation technologies using MCA (Milutinović et al., 2014). Evaluated the sustainability of waste management with energy recovery using MCA and found that sustainable scenario is recycling inorganic and composting organic waste (Rani et al., 2020). Utilized the multi-criteria decision-making (MCDM) under the fuzzy atmosphere to evaluate the sustainability planning of an E-Waste recycling job selection problem. MCA is a decision-making tool developed for complex problems concerning multiple and often conflicting criteria, and objectives like EoL PV waste panel. MCA for PV waste management can act as an optimizer by focusing on the minimization of the environmental impact through maximum energy recovery, lowest materials and substances loss caused by treatment and landfilling and creating maximum value creation through appropriate marketing strategies. It will be achieved by the weighting of various factors mainly related to the technical feasibility aspects of the treatment scenarios, and the intersection of economic, environmental, and social elements. The 'weighting' step; hence, can act as a useful arm to aid in better decision making leading to the desired trade-off. To this end, a variety of scenarios are considered and through various tools and weighting of the influential factors the compromised decision can be adopted. The overall decision-making concept is depicted in Fig. 14 visualizing. MCA empower us to close to the intersection leading to sustainability by weighting the influential factors. Whatever the weighting factors are adjusted in the sense that the output is placed at a certain distance far from the centre the effectiveness of a particular factor surges in return for sacrificing of sustainability. Hence, MCA can be considered as a powerful tool to move toward sustainable management of EoL PV panels.

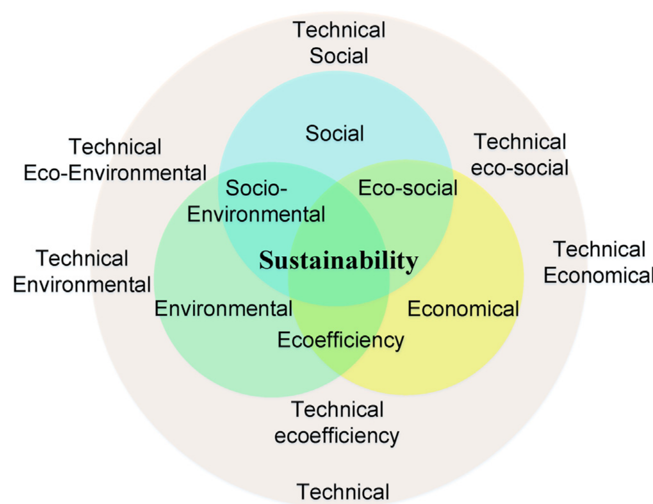

Fig. 14. Suggested decision-making criteria for EoL PV waste management.

4. Microscopic management of EoL PV panel

In the microscopic level of management, the focus is on the effective handling of the waste after recovery into to the much deeper level of treatment associated with the recovery of the substances contains in the PV waste flow. At this level, the recovered materials are may be considered for further treatment through serious MCA to check the technical possibility as well as the overall percentage of social, environmental, and economic profitability of the further treatment.

4.1. Monitoring of the recovered PV materials and substances

The essence of the monitoring system at the microscopic level will be at the highest level since the fact that the severity and challenges of EoL PV waste management are much higher than the previous stages. The reason is that the recovered materials and substances are going to back to the market for the sake of circular economy and environmental sustainability. It means that recovered materials and substances can be utilized either in the same production process or a completely new industry for completely new products. Poor monitoring system means that the recovered materials and substances with low purity level containing a certain level of toxic and other harmful germs and materials can be moved and scattered throughout the market.

It should be a serious warning for the authorities and policymakers as the public at different levels with vulnerable immune systems are on the direct exposure of health risk and danger. It would a catastrophic problem if no monitoring system exists at this level. The findings of the recent research on the potential market and application of the recovered materials and substances extracted through the treatment of the EoL PV panel which can be considered as a confirmation of this early-mid stage warning (see Fig. 15).

4.2. Restriction on secondary materials supply chain

The major parties at this level are supposed to be at least three including the transportation companies who collect and transfer the secondary materials and substances from the plant to the next party, the third person companies who sell the materials in the market, and the end-user referring to the industries who consume these materials and substances in the production of new products (microscopic level in Fig. 3). The main commitment of the plant is to provide a certificate that confirms the purity level of the secondary materials and substances meet the regulations mandated by the global organization. This confirmation letter will be delivered to the local government and other parties. After this, the rest of the partners should also update the status of those materials and substances at each step up to the end-user level. This cycle will be continued to make a closed-loop supply chain and confirm sustainability.

5. Future directions

PV waste will inevitably become a serious challenge for the governments within the next decade, and the overall framework introduced in this paper is just an intuitive that suggests how to face this problem. However, it needs further investigation at each management level. For example, the reverse logistics network design, economic viability assessment, awareness and marketing of the secondary materials and substances have not been addressed comprehensively since it is out of the scope of this paper. Also, further work on PV waste recycling method that is safe for the environment and the recovered secondary raw materials that meets the market demand is required. Another future study direction is the development of a monitoring system worldwide that is capable to track the PV panel throughout its lifecycle at all levels to achieve sustainability and circular economy. The authors hope that future research could prove the necessity of the introduced framework practically and solve this global challenge appropriately by performing research on the details of the action plan for the central organization, local governments, and the major parties.

6. Conclusion

This paper has given an account of the management of the EoL PV products as one of the fastest-growing waste globally with the estimated flow of about 60–80 million tons by 2050. An articulate framework was introduced into macro, meso, and micro-levels of management and some important initiatives supporting the proactive management of EoL PV modules were explored. The in-depth exploration of the current efforts on the PV waste management revealed that there is a lack of holistic managerial framework approaching the PV waste flow in terms of product and component, material, and substances altogether. At the moment, Europe has the most contribution to all three management levels to achieve a circular economy in the PV industry. The other pioneer countries or region such as United Kingdom, Germany, Czech Republic, Korea, Japan, China, and the U.S. state of California have just revised their WEEE regulations to add PV waste into the current regulation program, but it is yet to achieve a functional perspective and appropriate action plan. In practice, a holistic framework is required to shed light on the various angles of the sustainability in the PV industry. Twelve prominent parties alongside the local

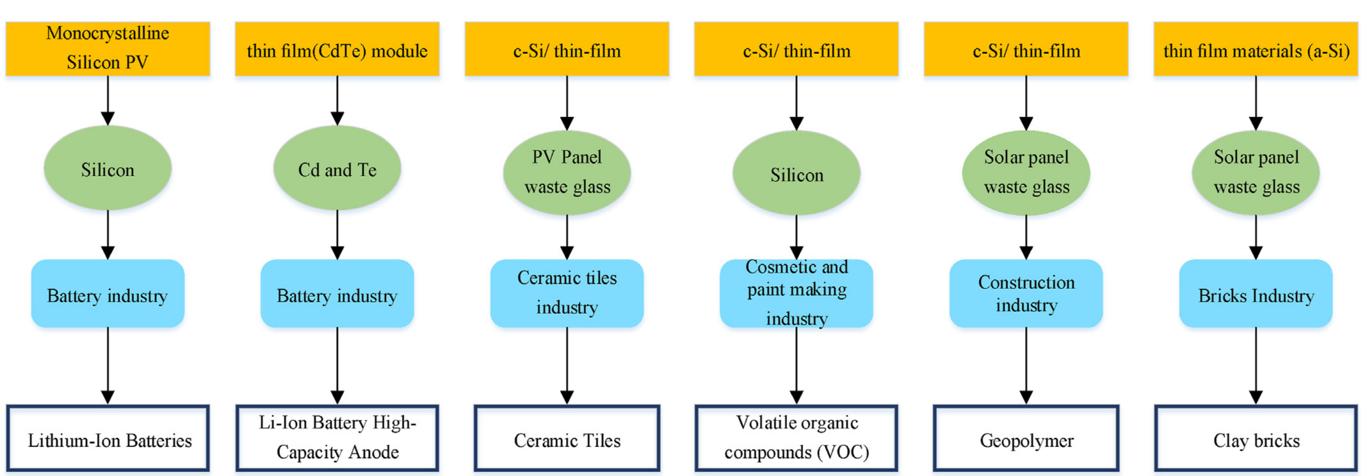

Fig. 15. The recent discovered application of the second recovered materials from EoL PV panels in the new industries adopted from (Mahmoudi et al., 2020a).

governments of each PV consumer and producer country were introduced and the functionality of each was discussed in different levels. In macro-level, a central organization at the global level with the close cooperation of local governments is required to ensure the sustainability program is well implemented and the expected outcomes are achieved as well. To address the social and cultural dimension of sustainability, six influential factors were discussed in meso-level to enhance the awareness of the target audiences including public and enterprises on EoL PV wastes opportunities and threats, and the essential marketing metrics leading to consideration and purchase of recovered secondary materials. Current findings showed that PV recycled materials have the potential to be employed in the same industry or other industries such as buttery industry, construction industry, ceramic tiles industry. To avoid the transboundary movement of the PV waste and ensuring of safe delivery of the recovered materials into either same or new industries, a universal monitoring system was introduced in micro-level that provides a real-time update on the status of the PV waste. Future research should take the detailed executive action plan and directive for the central organization and the comprehensive directive in terms of regulation and policies for local governments with a clear direction to address the essential metrics discussed in this paper to achieve circular economy of EoL PV panel.

CRediT authorship contribution statement

Sajjad Mahmoudi: Conceptualization, Methodology, Software, Data curation, Writing - original draft. **Nazmul Huda:** Supervision, Validation, Writing - review & editing. **Masud Behnia:** Supervision.

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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Nomenclature

c-Si	Crystalline silicon
WEEE	Waste Electrical and Electronic Equipment
RL	Reverse logistics
GW	Gigawatt
IRENA	International Renewable Energy Agency
IEA	International Energy Agency
PV	Photovoltaic
EOIO	European photovoltaic international organization
MCA	Multicriteria Analysis
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
OPV	Organic Photovoltaics
OECD	Organization for Economic Co-operation and Development
NPV	Net Present Value
CEAP	Circular Economy Action Plan
LCA	Life Cycle Assessment
MCA	Multi-Criteria Decision Analysis
METI	Ministry of Economy, Trade and Industry
MOE	Ministry of the Environment
R&D	Research and Development
SEIA	Solar Energy Industries Association
CESRI	Chinese environmental science research institute
CENELEC	European Committee for Electro-technical Standardization
MOTIE	Ministry of Trade, Industry and Energy
MFA	Material Flow Analysis
EoL	End of Life
EVA	Ethylene-vinyl acetate
a-Si	Amorphous silicon
CPV	Concentrator photovoltaics
DPBT	Discount Payback Time
DCF	Discounted Cash Flow
RL	Reverse Logistics
MFA	Material Flow Analysis
SFA	Substance-Flow Analysis

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