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SPECIAL ISSUE: Eco-friendly sustainable management
CASE STUDY

Adoption and implementation of extended producer responsibility for sustainable management of end-of-life solar photovoltaic panels

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ABSTRACT

BACKGROUND AND OBJECTIVES: Extended producer responsibility has been a policy tool for managing solar photovoltaic waste in European Union countries for approximately a decade. Furthermore, EPR has been widely used in many countries for electronic waste and other forms of waste management. Several studies have recommended this tool to sustainably manage solar photovoltaic waste in countries transitioning to large-scale solar energy usage. Nevertheless, implementing a policy tool varies depending on numerous factors, particularly context differences in developed and developing countries. The research on adopting and implementing this tool for solar photovoltaic waste management is limited in developing countries. Bangladesh requires appropriate regulations to manage the impending waste, which will soon encounter substantial end-of-life solar photovoltaic panel volumes. Therefore, this study investigated the adoption and implementation of the extended producer responsibility policy tool within the context of Bangladesh.
METHODS: A comprehensive literature review was conducted to identify the enabling and challenging factors influencing the implementation of this tool. Subsequently, a Likert Scale-based questionnaire incorporating the enabling and challenging factors was framed. A survey targeting stakeholders in the solar photovoltaic sector was then performed. Data analysis involved univariate and bivariate analyses, and Bangladesh was selected as a representative developing country for this study.
FINDINGS: The results revealed that stakeholders in the solar PV industry significantly emphasized (mean > 3) all enabling factors associated with extended producer responsibility for adoption in their country to manage end-of-life photovoltaic panels. This observation signified the importance of adopting and implementing extended producer responsibility to manage the impending disposal of end-of-life solar photovoltaic panels. Among the enabling factors, the public expense reduction (mean = 3.97), user acceptance (mean = 3.89), eco-design encouragement (mean = 4.02), and the local recycling facility with secondary material market establishments (mean = 3.89) emerged as the most crucial factors. The solar photovoltaic waste-specific regulations (mean = 3.72), the absence of a pre-established collection network (mean = 4.20), and weak institutional capacity (mean = 4.03) were identified as challenging factors requiring special attention during this tool adoption. The inter-item correlation matrix analysis for enabling and challenging factors also demonstrated high significance. Moreover, Cronbach's alpha for enabling and challenging factors were 0.885 and 0.749, respectively. This outcome suggested a good and acceptable internal consistency level among the factors.
CONCLUSION: Adopting extended producer responsibility was essential in developing countries to ensure the sustainable management of end-of-life solar photovoltaic panels. Nonetheless, successful implementation required addressing specific domestic concerns, such as the absence of a pre-existing waste take-back system and weak institutional capacity. Regulators should also proactively take measures to leverage enabling factors, including gaining users' acceptance, reducing costs, and potentially tapping into secondary material markets. Consequently, this study can assist in formulating appropriate regulations regarding the sustainable management of hazardous end-of-life solar photovoltaic panels. The findings can be utilized in Bangladesh and other countries encountering similar challenges, contributing to environmental preservation and eco-friendly development.

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INTRODUCTION

Renewable energy (RE) is an essential alternative to fossil fuels in achieving a net-zero emissions target (Obobisa, 2022; Moghadam and Samimi, 2022), which is pivotal in mitigating catastrophic natural disasters driven by anthropogenic climate change to achieve sustainable development (Dincer, 2000; Fawzy *et al.*, 2020). This motivation, coupled with the recent significant drop in panel cost and enabling government policies, has caused a tremendous upsurge in solar photovoltaic (PV) installations in recent years. A study reported a 46 percent (%) compound annual growth rate since 2000 (IRENA, 2019). Meanwhile, the average useful lifespan of solar PV panels ranges from 20 to 30 years (Faircloth *et al.*, 2019). Conversely, this exponential growth in solar PV systems has generated an impending challenge: the responsible retrieval and recycling of millions of metric tons of end-of-life (EOL) solar panels (Yu and Tong, 2021). A study by IRENA and IEA-PVPS (2016) reported that the world could accumulate 1.7 to 8 million tons and 60 to 70 million tons of waste panels by 2030 and 2050, respectively. Alternatively, addressing environmental challenges is imperative to generate green and clean energy from solar PV panels (Nasri *et al.*, 2023). Nonetheless, improper management of EOL panels leads to substantial resource losses and severe environmental damage, pollution, and public health hazards (Li *et al.*, 2021; Drobyazko *et al.*, 2021; Ramli *et al.*, 2022). The demand for materials to manufacture new panels is also steadily rising. A dependence reduction on environmentally polluting and emission-causing primary sources can be highly achieved from 2035 onwards if the recycling of EOL panels is effectively established (Kusch and Alsheyab, 2017). Despite the positive environmental load impact, the economic viability of recycling remains unfavorable. Therefore, policies ensuring producer responsibility are vital throughout the PV industry, including EOL panels (Tao and Yu, 2015). The primary reason for failing to achieve collection and recycling targets for solar PV waste is the inadequate suitable regulations for bulk panel disposal in landfills (Oteng *et al.*, 2022). A study by Li *et al.* (2021) in China emphasized the need for governments and industries to establish appropriate regulations and guidelines, outlining the responsibilities and obligations of concerned stakeholders. Another study by Kim and Park (2018) in South Korea highlighted the importance of implementing an appropriate system for monitoring, collecting, and storing PV waste. Regulations that demonstrate fixed recovery rate targets and compel manufacturers to retrieve EOL products are essential to address this issue (Salim *et al.*, 2019). Hence, extended producer responsibility (EPR) is a suitable option, and its novel operational measures increase sustainability in the PV sector (Cai *et al.*, 2019). The EPR is an environmental policy approach extending a producer's responsibility for a product throughout its life cycle, including the post-consumer stage (OECD, 2001). These producers include manufacturers, importers, distributors, and retailers (Kusch and Alsheyab, 2017). The EPR consists of two characteristic components as 1) Transferring either physical or economic responsibility (or both) from municipal bodies to manufacturers; 2) Allocating incentives for manufacturers to integrate environmental considerations into product designs (Rubio *et al.*, 2019). The EPR establishes a compliance mechanism for producers in collecting and recycling EOL panels. Numerous EPR objectives ensure sustainability and eco-friendly development, such as waste reduction, resource conservation, high recycling rates, waste diversion from landfills, and promoting eco-friendly product design (Majewsky *et al.*, 2021; Samimi and Safari, 2022). Particularly, European Union (EU) countries have been at the forefront of EOL solar PV panel management by applying EPR tools under the Waste Electrical and Electronic Equipment (WEEE) Directive since 2014 (Kusch and Alsheyab, 2017). These minimum targets have been set for take-back, recycling, and recovery of EOL panels based on the EU WEEE Directive, which are 60, 80, and 85%, respectively (Granata *et al.*, 2022). In the contexts of China (Yu and Tong, 2021), India (Jain *et al.*, 2022), Australia (Majewski *et al.*, 2023), and the United States of America (USA) (McElligott, 2020), the EPR implementation or similar policy tools for the sustainable management of growing EOL solar PV panel volumes has been recommended. The EPR implementation differs significantly due to social, economic, and technological differences. For example, Nigeria introduced EPR in its Electronic and Electrical Sector in 2013 to manage electronic waste (e-waste). In contrast, only 3% of importers of non-reusable WEEE had registered with the relevant regulatory authority by 2017, which produced insufficient funds for EOL management (Nnorom and Odeyingbo, 2020). Although the EPR model prevents the development and growth of the solar energy sector, its mandatory nature of whole life cycle responsibility for products imposes additional costs on manufacturers (McElligott, 2020). A suitable regulation is required considering the internal realities of each country (Jain *et al.,* 2022). Consequently, the viable use of EPR requires examination for sustainable EOL solar panel management in developing countries aiming to install large-scale PV systems. Previous studies focused on various solar PV waste aspects, including volume estimation (Domínguez and Geyer, 2017), environmental impact analysis (Maani *et al.,* 2020), life-cycle analysis (Latunussa *et al.*, 2016), and economic feasibility analysis of recycling (D'Adamo *et al.*, 2017). Stakeholder participation is important for resolving solar PV waste (Sharma *et al.,* 2023), while stakeholder consultation has been long employed in waste management and environmental policy formulation (Kujala *et al.*, 2022). Sustainable waste management necessitates the participation and consultation of all the relevant stakeholders within the respective sector (Joseph, 2006). Otherwise, environmental policies can fail if stakeholders do not accept them (Gregory and Wellman, 2001). Therefore, recognizing stakeholders' perspectives through regulatory measures is vital when addressing the solar PV waste issue. Bangladesh was selected for this study as a representative developing country case in adopting solar PV technology using data from 2003 (Hussain *et al.,* 2013). Considering that the first solar panel batch is expected to reach EOL soon, inadequate regulations can cause the EOL panels to either be in landfills or handled by the informal sector. Both options are unsustainable and harmful to this densely populated and land-scarce country. Conversely, regulation introduction ensures the large recovery of valuable materials, such as aluminum, copper, silicon, and glass. Some studies (Tasnim *et al.,* 2022) have suggested appropriate policy formulations for the sustainable management of solar PV waste. Thus, the present study bridged the existing knowledge gap by assessing the solar PV industry stakeholders' perspectives on adopting and implementing EPR in Bangladesh. The results were related to identifying enabling factors (EFs) and challenging factors (CFs) regarding e-waste, solar PV waste, and other solid waste management. The following research questions were addressed: 1) What are the EFs and CFs concerning EPR implementation for e-waste, solar PV waste, and other solid waste management in different country contexts? 2) What are the major EFs and CFs in adopting and implementing EPR (stakeholders' viewpoints in the solar PV industry) for sustainable management of EOL solar PV panels in Bangladesh?

An extensive literature review identified the EFs and CFs related to EPR implementation in various contexts. These factors were included in a survey questionnaire for further investigation. A univariate analysis method was adopted to evaluate the demographic profiles of the respondents. The mean and standard deviation (SD) were calculated to assess the central tendency of the factors. Subsequently, Cronbach's alpha (α) determined the internal consistency of the factors as a group. Bivariate analysis was also utilized to ascertain the significance factor levels in a group, such as the inter-item correlation matrix. A noteworthy aspect of this study was identifying the major EFs and CFs to EPR implementation for the sustainable management of EOL solar PV panels in a developing country. The results of this data-driven study involving the solar PV industry stakeholders offer valuable insights into countries with similar challenges. This finding can formulate effective regulations and contribute to the existing body of literature. Meanwhile, this study was performed in Bangladesh between 2022 and 2023.

MATERIALS AND METHODS

A two-stage approach was employed to achieve the objectives of this study. Firstly, an extensive literature review was conducted to identify important EFs and CFs associated with the EPR implementation in e-waste, solid waste, and solar PV waste management across various contexts. Subsequently, a survey was performed using a questionnaire incorporating the factors to evaluate the stakeholders' perspectives within the solar energy industry in Bangladesh. Fig. 1 illustrates the methodology applied in this study.

Study area

Bangladesh has been actively installing distributed and utility-scale solar PV panels. As of the first quarter of 2022, the country had an installed capacity of 416 MW of solar PV. This value had surged to 960 MW by June 2023 (SREDA, 2023). Furthermore, an additional 1448.37 MW of electricity from 24 utility-scale solar

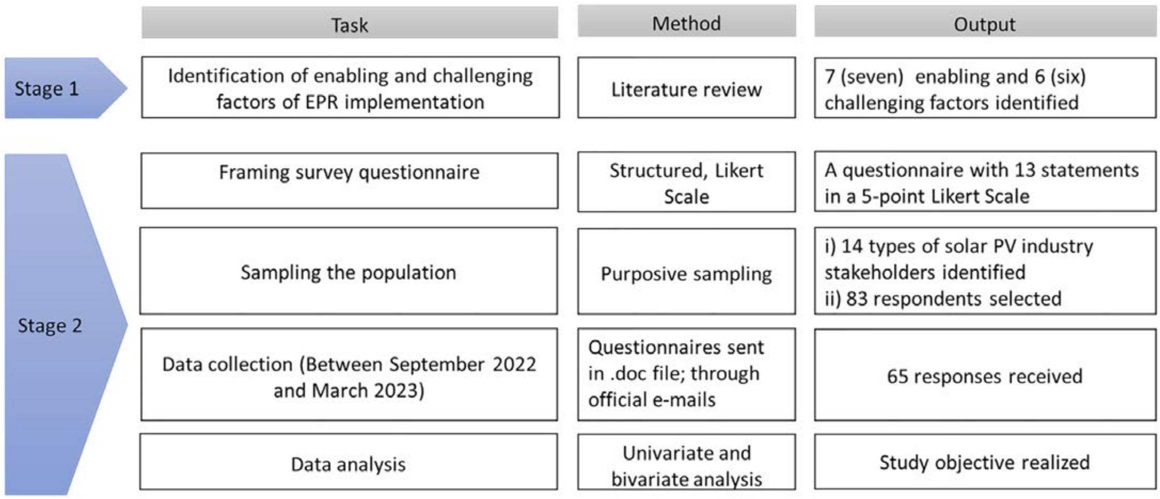

Fig. 1: Methodology applied the current study

projects has been forecasted to be integrated into the grid by 2025 (SREDA, 2022a). In addition to utility-scale installations, Bangladesh has been at the forefront of distributed solar PV adoption since 2003. The country boasts over 6 million solar home systems (SHSs), making it the largest SHS installer globally (Cabraal *et al.*, 2021). The recently drafted National Solar Energy Roadmap predicts 6.0, 20.0, and 30.0 GW of electricity production by 2041 in business-as-usual, medium, and high-case scenarios, respectively (Chowdhury, 2020). This roadmap has been drafted to increase the RE share in the national electricity generation. The country is poised to encounter a substantial EOL solar panel influx soon. Distributed solar PV systems and utility-scale plants have been scattered throughout the country, including solar irrigation pumps, rooftop solar systems, solar streetlights, and SHSs. Thus, this study encompassed stakeholders (users, implementers, distributors, and generators for solar PVs) and local government bodies responsible for waste management, e-waste recyclers, and regulators. These stakeholders were drawn from seven out of eight divisions of the country. Fig. 2 presents the study area of the survey respondents.

Factors affecting EPR implementation

One significant advantage of applying EPR is its potential for higher collection and recycling rates (OECD, 2014; Kosior and Crescenzi, 2020). For example, a waste package study in Portugal and Spain discovered increased recycling rates due to EPR (Rubio *et al.*, 2019). This benefit is particularly valuable for waste management in countries lacking physical and financial capacity or both (Tojo *et al.*, 2001). The EPR motivates related parties to incorporate materials more efficiently into their products while extending the lifespan of the products (Khawaja *et al.*, 2021). EPR holds producers responsible for the physical and financial aspects of products at their EOL (Atasu and Subramanian, 2012), producing high user acceptance. Moreover, this policy in increasing collection and recycling rates (Kosior and Crescenzi, 2020) will likely promote local recycling efforts and secondary material markets. Nevertheless, the socio-economic and technological barriers in developing countries pose challenges to deploying EPR for managing e-waste and other solid waste (Johannes *et al.*, 2021; Maphosa and Maphosa, 2022; Le Dinh *et al.*, 2022). In EU countries, the EPR tool has been effectively used for managing e-waste (Faibil *et al.*, 2022) before its application in managing EOL solar PV panels. Countries at the initial stage of solar PV recycling challenges can benefit from learning lessons and experiences with framing regulations and guidelines from EU countries (Sharma *et al.*, 2019). The requirement to shift administrative, financial, and physical responsibilities from government or local government entities to producers, manufacturers, wholesalers, or distributors (Monier *et al.*, 2014)

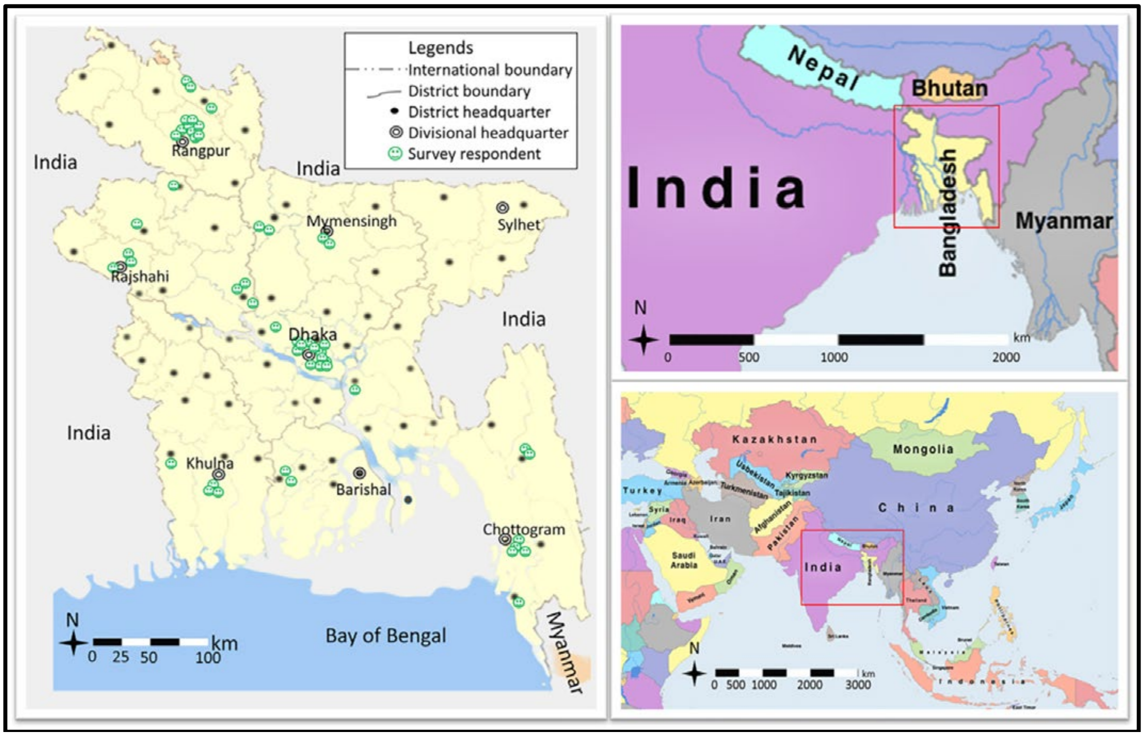

Fig. 2: Geographic location of the study survey area in Bangladesh

reduces public waste management expenses (Kosior and Crescenzi, 2020). Alongside the EFs expediting EPR, several CFs hinder its implementation. A study by Nnorom and Osibanjo (2008) on poor EPR implementations in developing countries identified insufficient legislation addressing e-waste as a fundamental issue. Meanwhile, Akenji *et al.* (2011) described that developing Asian countries encounter added complexities in e-waste management due to the prevalence of a strong informal waste sector. Unlike industrialized economies with effective waste management infrastructure, developing nations rely primarily on an informal sector employing traditional e-waste recycling methods, such as hammering and open-air burning (Gui, 2020). This informal sector involved in collecting, transporting, recovering, and disposing of e-waste hinders the effective EPR implementation (Jain *et al.*, 2022). A successful EPR implementation also necessitates a pre-established collection system due to its knowledge and expertise in expediting efficient EPR implementation (Tojo *et al.*, 2001). Developing countries often lack proper waste collection infrastructure (Gautam *et al.*, 2022; Santos and Alonso-García, 2018) and have demonstrated a lack of initiation and implementation of EPR policy (Zheng *et al.*, 2017). Furthermore, the compliance of EPR policies for waste collection and recycling imposes additional expenses on manufacturers, which are eventually passed on to end-users (Monier *et al.*, 2014). A study by Kojima *et al.* (2009) in China and Thailand revealed that producers over-reported the collected waste to receive more government support. Moreover, several concerns require continuous and vigilant monitoring, including free-riding, fair competition, illegal landfilling, and waste exports. In some instances, regulators lack the enforcement mechanisms necessary and capabilities to ensure compliance (OECD, 2014). Developing countries in Asia have encountered challenges in constructing adequate institutions and administrative capacity to effectively address the e-waste issue (Akenji *et al.*, 2011). Remarkably, recycling targets under WEEE Directives are met without recovering silver and other valuable materials considered scarce in solar panels (Ganesan and Valderrama, 2022). This situation prioritizes collection and recovery targets over full recycling. The studies above have outlined five key EPR advantages and two important factors promoting EPR adoption in EOL solar PV panels. Additionally, six CFs have been identified. These enablers and challenges of EPR implementation from different studies were used as items to frame the questionnaire for the survey in the study.

Sampling technique, population, and sample size

The solar PV sector involves numerous users and various stakeholders. Considering the EPR study based on stakeholders' consultation is a relatively complex issue, a conservative approach was adopted, particularly the purposive sampling technique. The identification and selection of the sample (stakeholders) relied on two primary sources: a study conducted by Kunz *et al.* (2014) and the stakeholder list provided by the Sustainable and Renewable Energy Development Authority (SREDA). This authority oversees expansion, regulation, monitoring, and data preservation regarding RE (including solar PV) in Bangladesh. Kunz *et al.* (2014) identified 12 stakeholder types in the EPR implementation. Alternatively, SREDA categorized stakeholders into 13 groups: government organizations (GOs), development partners, non-government organizations (NGOs) or non-government companies (NGCs), RE associations, research institutes, testing laboratories, financing organizations for RE programs, exporters, importers, suppliers, with local manufacturers of RE products or appliances, RE program/project owner/shareholder/implementer/investor in operational expenditure (OPEX) [excluding engineering, procurement, with construction (EPC) companies], and EPC companies. As of August 2022, the SREDA listed a total of 228 stakeholders. These stakeholders were categorized into 13 groups of 33, 4, 188, 3, 6, 5, 97, 8, 45, 49, 11, 147, and 176 members, respectively (SREDA, 2022b). Nonetheless, the stakeholders' roles revealed overlapping roles. For example, six members were listed under the research institute category and five in the testing laboratory category among the 33 GOs. The remaining 188 stakeholders across eight types were NGOs and companies, excluding the 33 GOs, four development partners, and three RE associations (a total 40). Only 65 were reported to have roles within the other eight stakeholder types. Given the diverse stakeholder types involved in solar PV expansion and EPR implementation, a modified section of 14 stakeholder types was included in this survey. Notably, SHS users were excluded from the present study for convenience. Instead, it focused on the organizations and institutions installing and implementing SHSs. In addition, certain stakeholder types were not included, such as development partners, producer responsibility organizations (PROs), communities, and the illegal informal sector. Consequently, the initial sample consisted of 83 stakeholders, with 65 respondents from the 14 selected stakeholder categories participating in the survey. The outcome yielded a response rate of 78.31%.

The questionnaire

The survey questionnaire comprised two parts: the first part gathered the demographic profile of the respondents. In contrast, the second part presented 13 EFs and CFs discussed in the introduction as statements. These statements were formulated using EPR experiences in e-waste and other waste management as proxies to frame the questionnaire of this study. Respondents were asked to rate their comments using a 5-point Likert Scale, where 1 represented 'least important' and 5 defined 'extremely important' for EFs (7 items) and CFs (6 items). Generally, the use of the Likert Scale waste management surveys is well-recognized. For example, Esmaeilizadeh *et al.* (2020) employed a 5-point Likert Scale to examine the challenges of municipal solid waste management in Iran. Similarly, Kabirifar *et al.* (2021) applied a 5-point Likert Scale in a close-ended questionnaire to assess the effectiveness of construction and demolition waste management in Australia.

Data collection and analysis

The questionnaires were distributed to the selected 83 respondents via their official email addresses, of which 65 respondents successfully participated. Data collection spanned six months, from September 2022 to March 2023. The Statistical Package for Social Science (SPSS) software (Version 22.0) was then used for data processing, and the analysis employed descriptive statistics and correlation analysis as the primary statistical tools. Lastly, α was calculated for the EFs and CFs to assess the consistency level among these factors.

Table 1: Background characteristic summary of the respondents

Characteristic	Category	Frequency (*n*)	Percentage (%)
Gender	Male	59	90.8
	Female	06	09.2
Service level	Top-Level	08	12.3
	Senior-Level	17	26.2
	Mid-Level	31	47.7
	Junior-Level	09	13.8
Length of service (in years)	≤ 5	20	30.8
	5–10	21	32.3
	11–15	09	13.8
	16–20	08	12.3
	≥ 21	07	10.8
Level of education	Ph.D.	05	07.7
	Master	27	41.5
	Graduate	32	49.2
	Undergraduate	01	01.5
Organization's involvement in the solar energy sector (in years)	≥ 5	23	35.4
	6–10	28	43.1
	11–15	08	12.3
	16–20	04	06.2
	≥ 21	02	03.1

RESULTS AND DISCUSSION

The respondents' background profile

Table 1 tabulates the background characteristics of the respondents. Approximately 91% were male, with most (74%) occupying top and senior service-level positions. More than 23% of the respondents possessed job experience exceeding 16 years in the solar energy sector. Approximately 49% of respondents also held post-graduate degrees, including 8% with Ph.D. qualifications. This data highlighted the successful inclusion of a diverse group of participants in the survey, ranging from junior to top-level personnel, predominantly holding graduate degrees and possessing significant service experience in the solar PV sector.

The fact that only one-ninth of the female respondents exposed were females underscored women's significant underrepresentation in the solar energy sector. In contrast, the respondents possessed a substantial experience level in the solar PV sector and a high education level, indicating their capability to comprehend and discuss issues related to implementing the EPR policy tool in Bangladesh. In addition, nearly all the respondents' organizations had more than five years of involvement in the solar energy sector, with 22% having more than 10 years. This outcome suggested that the solar PV industry in this country had matured. Fig. 3 portrays a nearly equal representation of respondents in the survey from the government (29%) and the non-government (31%) sectors in the solar PV sector. Additionally, a commendable representation of other organizations related to the solar PV sector was visible.

Fig. 4 depicts that the 65 respondents' organizations encompass 14 distinct roles in the solar energy sector. Among these roles, solar energy project implementation ranked the highest (23%), and power distribution and waste management shared the second-highest position (11%). Following closely, the roles of the respondents' organizations as regulators and exporters/importers/suppliers of solar energy products also occupied the third-highest position (8% each). This result demonstrated that respondents from various solar PV industries actively participated in this study.

Enabling factors

EFs contribute positively to a system, policy, or tool, resulting in broader benefits for a larger population. Approximately seven EFs were included in the questionnaire to elicit the perspectives of solar energy industry stakeholders (see Materials and Methods). Table 2 lists the respondents' views, in which the mean values for all items and the individual mean for each item exceed 3.62. The respondents rated five items as 'highly important' and one as 'extremely

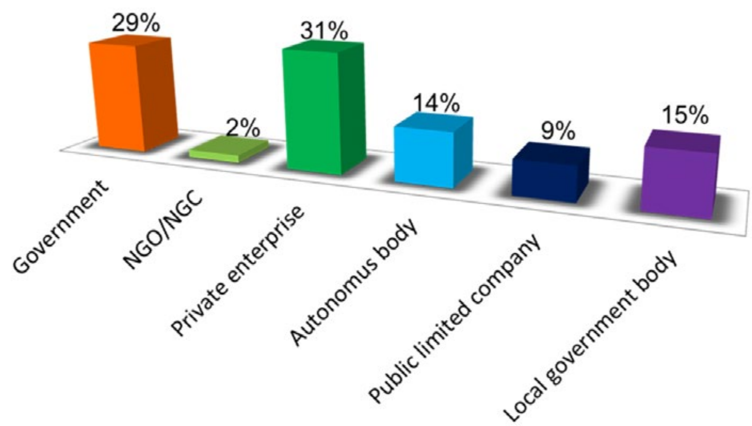

Fig. 3: The respondents' organization type

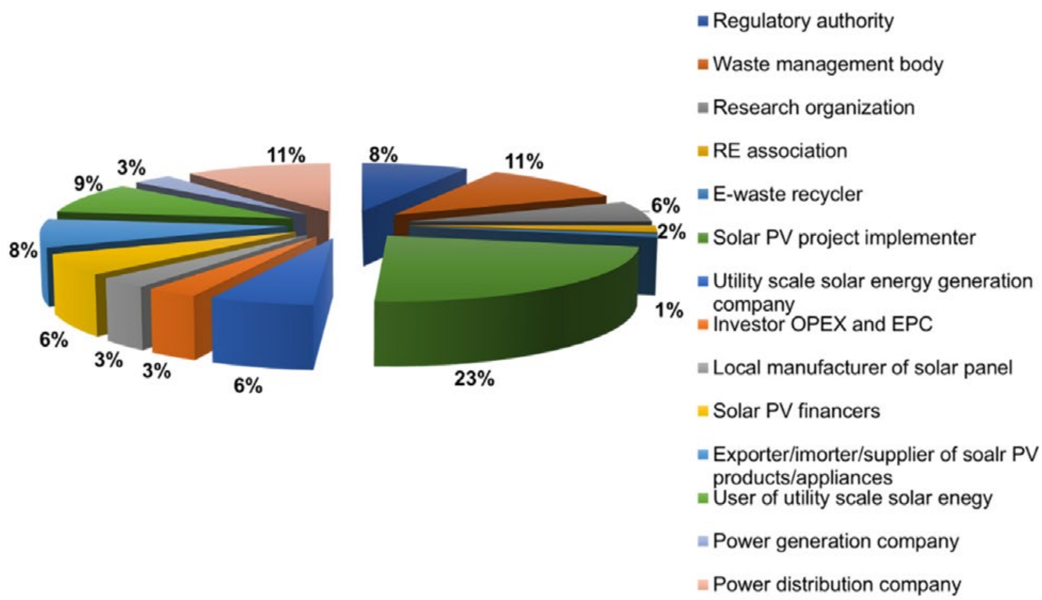

Fig. 4: The respondents' organization's role in the solar energy sector

important.' Meanwhile, the standard deviation (SD) of the item was approximately 1.0, indicating a response concentration around the mean. The α was also 0.885, suggesting a good internal consistency level among the items (0.8 ≤ α < 0.9 = good).

The implication was that the solar energy industry stakeholders placed significant importance on all the EFs of EPR. Among these factors, achieving higher collection and recycling rates was paramount. This emphasis on higher collection and recycling rates contributed to reducing environmental damage. For example, recycling EOL panels caused greenhouse gas emissions that were five times lower than landfilling (Lim *et al.*, 2022). The recycled aluminum also emitted only 4.16% of the emissions generated by extracting the same amount of aluminum from natural minerals (Xu *et al.,* 2018). In addition, recycling EOL panels prevented the depletion of scarce metals, such as silver. Silver is expected to encounter high demand by 2030, overtaking supply (Walzberg *et al.*, 2021). Globally, recovered materials can yield revenue of up to US$450 million by 2030 and US$15 billion by 2050

Table 2: Evaluation summary of the EFs for EPR application in EOL solar PV panel management (*N* = 65)

Factor	Aspect	Item	Mean	SD	Description
EFs	Achieving target (EF1)	Achieving a higher collection and recycling rate	3.68	1.047	Highly important
	Regulatory (EF2)	The practice of EPR in local e-waste management as an enabler	3.63	1.219	Highly important
	Financial (EF3)	Reduction of government expenses	3.97	0.935	Highly important
	Learning from developed economies (EF4)	The learning opportunity of EPR practice from developed economies	3.78	1.097	Highly important
	User's acceptance (EF5)	User's acceptance as they might feel relieved from the burden of EOL panels	3.89	1.062	Highly important
	Promoting eco-design (EF6)	Encouragement of eco-design in panel manufacturing	4.02	0.976	Extremely important
	Infrastructure and market (EF7)	Emergence of local recycling facility and secondary material market	3.89	0.831	Highly important
	Item mean = 3.84; α = 0.885				

(IRENA and IEA-PVPS, 2016). This yield also produces new job prospects, particularly in countries like the USA (Curtis *et al.*, 2021). Thus, the mandatory recycling promoted by EPR ensured material circularity and fostered sustainability within this sector, moving away from the linear model of material use. Adopting the EPR policy is expected to generate cost savings in managing EOL solar PV panels, as it places full life cycle responsibility on manufacturers. This adoption aligned with the findings of a study by Diggle and Walker (2020) on EPR implementation for single-use plastic packaging waste in Nova Scotia, Canada. The study estimated potential savings of C$14 to 17 million for municipalities implementing EPR. Nonetheless, in-depth investigations were required on the prospect of cost reduction in developing countries once EPR was adopted to manage EOL solar PV panels. The EPR policy adoption was likely to garner acceptance from users, as it relieved them of the burden of panel disposal after use. In addition, the EPR policy caused the creation of local recycling facilities, potentially creating a secondary material market with forward and backward linkages. This outcome was more likely because recovered aluminum and glass served as feedstocks for existing related industries in Bangladesh (Tasnia *et al.*, 2018). The respondents assigned substantial emphasis (mean = 4.02) on promoting eco-design in solar panel manufacturing (Item 6) as an outcome of EPR adoption, reinforcing expectations expressed in different studies. For example, a study in the USA context summarized that EPR inspired manufacturers to engage in eco-innovative product design, seeking a 'causal correlation' between EPR implementation and eco-innovation (Peng *et al.*, 2020). Another study in China revealed that EPR implementation led to a 35.51% increase in green innovation patents (Zhao *et al.*, 2021). Conversely, the stakeholders' expectation of eco-design panels necessitated more empirical investigation for solar panels. The significance of the results regarding EFs in this study was that the EPR initiation as a policy tool for managing EOL solar panels could produce similar positive outcomes in a developing country observed in developed regions.

Challenging factors

CFs are issues potentially hindering the implementation of a policy or system. Table 3 presents the individual means of the first four items (> 3 and < 4), while the individual means of the last two items are > 4 and < 5. The mean for all the items was 3.79 while α was 0.749, suggesting an acceptable internal consistency level among the items (0.8 > α ≥ 0.7 = acceptable).

The implications of these findings were extensive. Firstly, solar energy industry stakeholders were highly concerned regarding the collection targets for EOL solar PV panels, which were prioritized over recycling targets due to the mandatory EPR requirements. This preference for collection targets posed challenges

Table 3: Evaluation summary of the CFs for EPR application in EOL solar PV panel management

Factor	Aspect	Item	Mean	SD	Description
CFs	Achieving target (CF1)	Collection targets getting the upper hand over recycling	3.48	1.002	Highly important
	Financial (CF2)	Cost of compliance transferred onto users	3.68	0.986	Highly important
	Regulatory (CF3)	Solar PV-specific regulation might be required	3.72	1.083	Highly important
	Competition (CF4)	Informal sector of recycling as a competitor	3.63	1.069	Highly important
	Collection network (CF5)	Required the pre-existence of a collection network	4.20	1.003	Extremely important
	Institutional (CF6)	Weak institutional capacity	4.03	1.060	Extremely important
	Item mean = 3.79; α = 0.749				

to achieving a fully circular economy for waste PV panels in a developing country with limited waste management capacity. In this case, adjusted recycling targets that were not solely based on the weight of panels required establishment to encourage full recovery of materials from panels (El-Khawad *et al.*, 2022). Furthermore, the probability of transferring the compliance cost to users produced higher panel prices, which hindered the achievement of national RE targets. Therefore, the model application coordinating producers and third-party recyclers was a viable solution to mitigate producers' recycling costs (Wu *et al.,* 2019). The solar PV-specific regulation requirement suggested that separate regulation was more effective than including EPR in existing e-waste management rules (identified as a highly important CF in implementing EPR). In contrast, separate regulation involved independent management authorities, excess time, and higher costs. Policymakers should carefully consider this challenge regarding the capacity of the regulatory bodies, the size of the industry, and domestic economic realities. The informal sector also drew EOL panels due to its lower cost and ability to evade regulations, particularly in developing countries. The influence of the informal sector on regulations was disadvantageous (Gupt and Sahay, 2015), considering the complex social and environmental issues related to it (Herat and Agamuthu, 2012). A synergistic approach based on the formal and informal sector strengths could address this issue (Davis and Garb, 2015). This approach involved establishing competitive recycling plants and collection networks, raising user awareness, and enforcing environmental laws. The respondents' pre-existing collection network for implementing EPR (marked as 'extremely important') was highly significant as the weak or non-existent collection network was a reality in developing countries. In the case of EOL solar PVs, initiating voluntary product stewardship and awareness-building efforts was useful. Addressing the issue of weak institutional capacity within regulatory bodies was crucial (marked as 'extremely important' by respondents). Building up institutional capacity through training and resource allocation was necessary to overcome this challenge effectively. Thus, addressing these challenges could facilitate EPR initiation and implementation as a regulatory tool or managing EOL solar PV panels in a developing country.

Enabling factors and respondents' service level, organization type, and years of involvement in the solar PV sector

Fig. 5 reveals that solar energy industry stakeholders occupying top positions in their organizations generally give high importance to all the EFs except for EF2 (EPR practice in e-waste management as an enabler). This group prioritized a wide range of factors related to EPR adoption. Senior-level respondents placed the highest importance on EF3 (reduction of government expenses) and EF7 (emergence of local recycling facilities and secondary material markets) while still recognizing the importance of various EFs. Mid-level respondents focused the most on EF6 (encouragement of eco-design in panel manufacturing). Meanwhile, junior-level respondents placed the highest priority on all EFs except for EF1 and EF4. Most top, senior, and junior-level respondents identified the highest priority on the lower government expenses and the emergence

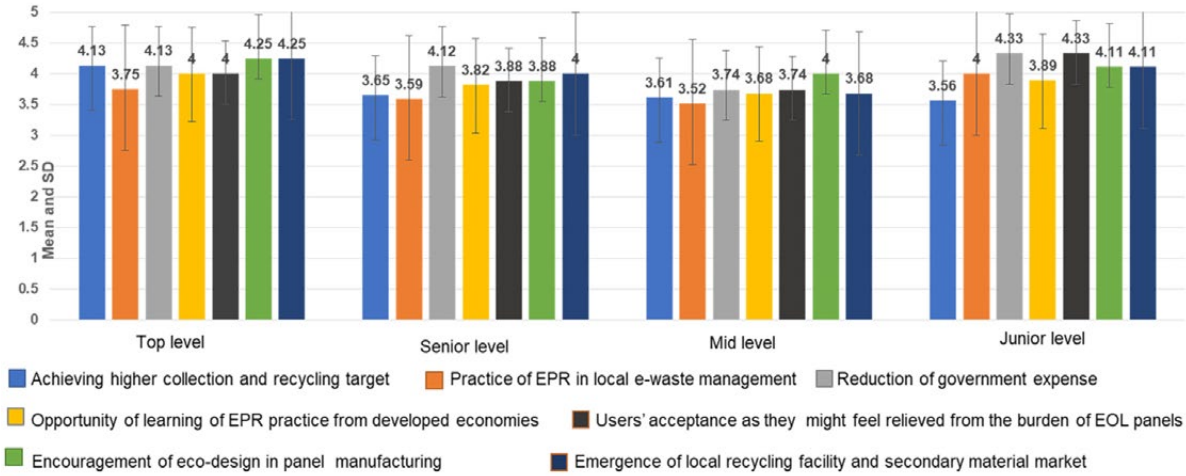

Fig. 5: The respondents' service levels and perspectives on EPR-based EFs

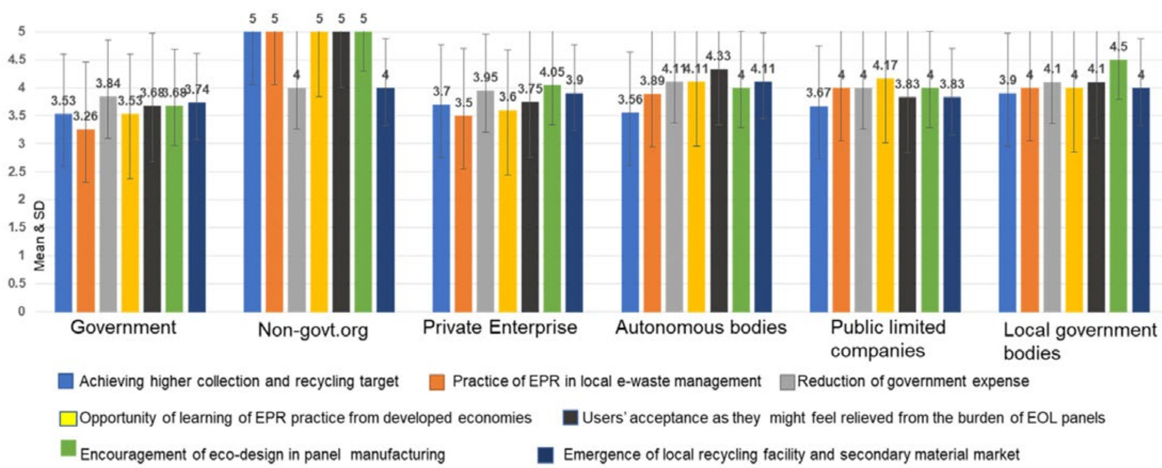

Fig. 6: The respondents' perspectives on EFs of their organization types

of local recycling facilities and secondary material markets. Therefore, initiating EPR for managing EOL solar PV in Bangladesh could guarantee these benefits at least.

Fig. 6 provides that regardless of the organization types of the respondents, high importance is attributed to all the EFs of EPR implementation in Bangladesh. Like public limited companies and autonomous bodies, local government bodies (n = 10) responsible for waste management at the provincial and municipal levels placed extreme importance on all these EFs. Conversely, private enterprises (n = 20) mostly emphasized the eco-design of solar PV panels.

Fig. 7 presents that organizations whose involvement in the solar energy sector spans over five years or more assign the highest importance to certain EFs for EPR implementation. These factors included lower public expenses in managing EOL solar PV panels, user acceptance, promoting eco-design for solar panels, and developing secondary material markets and recycling facilities. One noteworthy exception was that organizations with 16 to 20 years (n = 4) of RE sector experience expressed disagreement (mean = 2.50) with EF2. This finding underscored the necessity for a dedicated regulatory framework focused on EOL solar PV management.

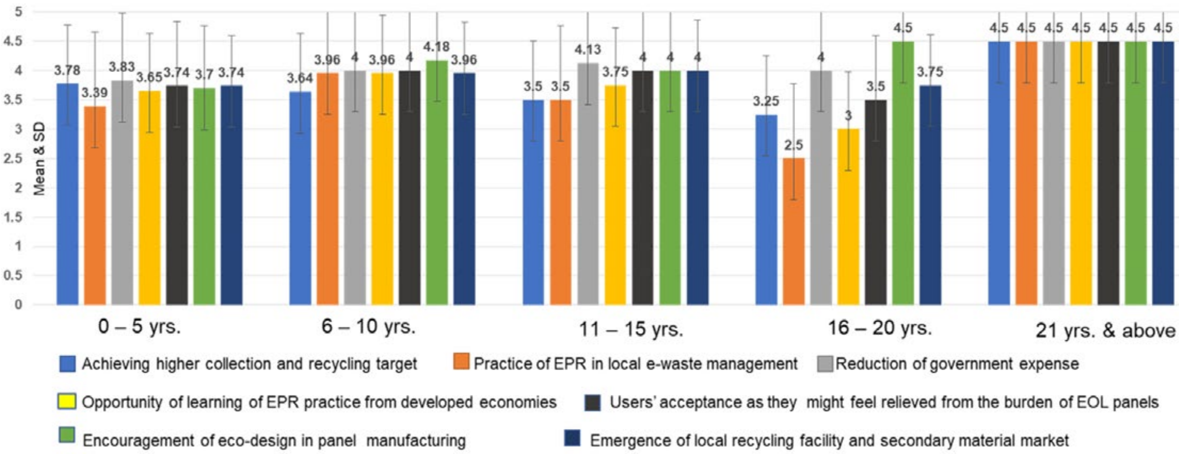

Fig. 7: The respondents' perspectives on EFs of their organizations' years of involvement in the solar energy sector

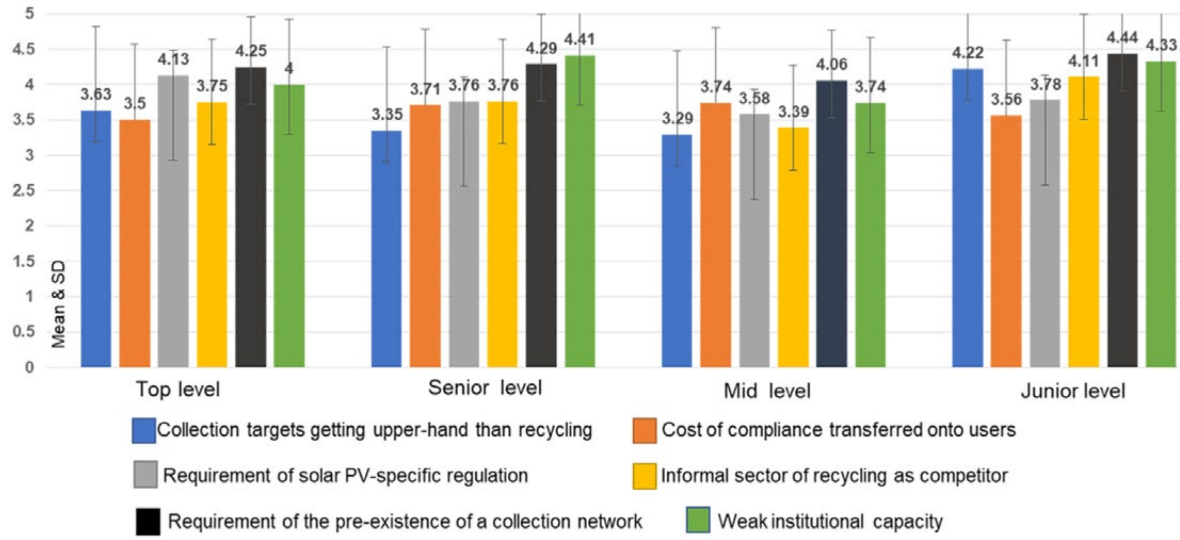

Fig. 8: The respondents' perspectives on CFs of their service levels

Challenging factors with the respondents' service level, organization type, and years of involvement in the solar PV sector

This study aimed to understand whether the service level of the respondents influenced their perceptions of the CFs associated with EPR. Fig. 8 exhibits that respondents from all service levels assign high importance to all challenging EPR factors in managing EOL solar PV panels in Bangladesh. Nevertheless, the highest degree of importance (regardless of service levels) was given to the necessity of a pre-existing collection network and weak institutional capacity as key challenges in the EPR implementation. Moreover, respondents at the highest service level (*n* = 8) emphasized that the need for specific solar PV-related regulations posed the most critical challenge in the successful implementation of EPR.

The respondents from all six organization types assigned the highest importance to weak institutional capacity and the requirement for a pre-existing collection network due to the EPR implementation challenges in Bangladesh (see Fig. 9). Additionally,

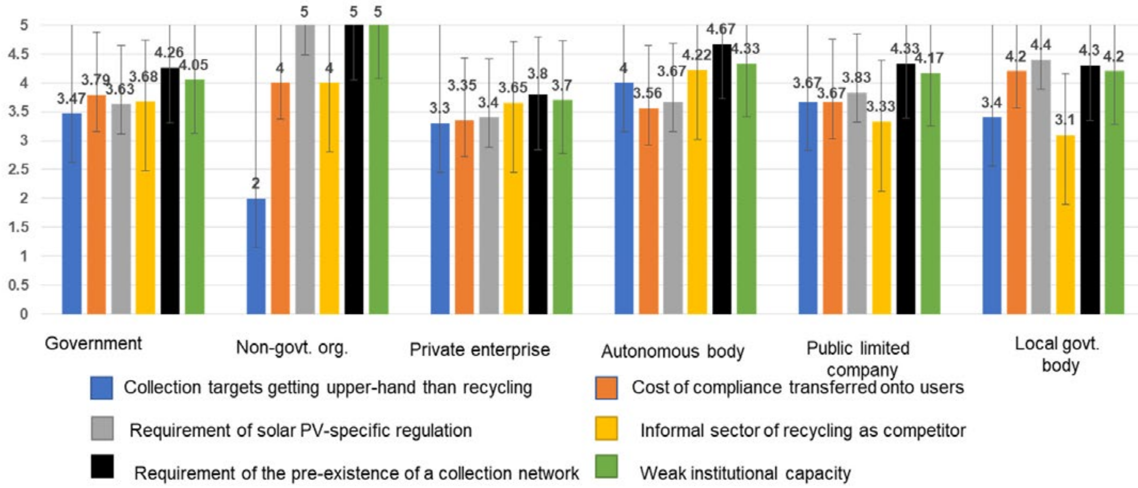

Fig. 9: The respondents' perspectives on CFs of their organization types

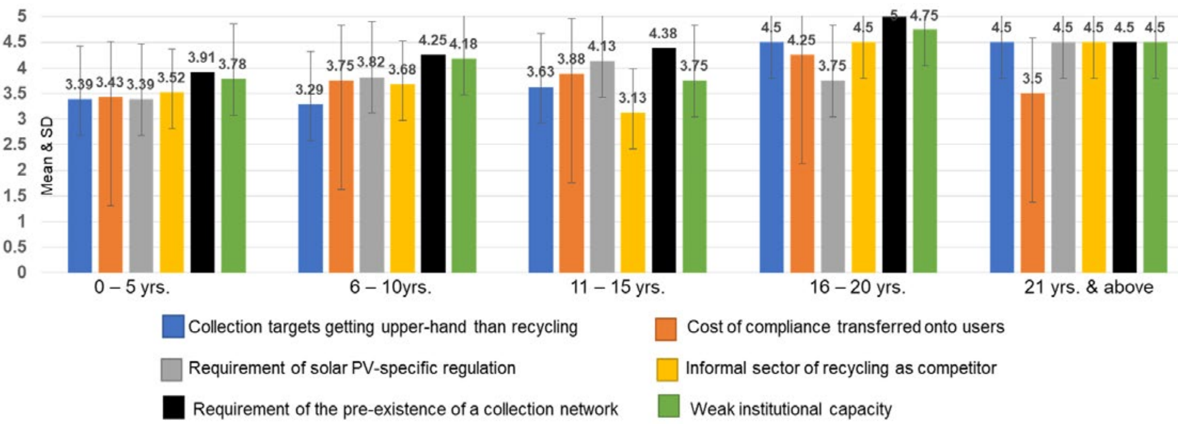

Fig. 10: The respondents' perspectives on CFs of their organizations' involvement in the solar PV sector

respondents from autonomous bodies (n = 9) highlighted the informal sector as a competitor to formal recycling of EOL solar PV with the highest importance. An established collection network was a prerequisite for successful EPR implementation, particularly in rural areas of Bangladesh. These findings aligned with a study by Steenmans and Malcolm (2023), which identified the absence of waste collection services in rural areas as a significant challenge in the EPR implementation for managing plastics.

Fig. 10 displays that regardless of the number of years besides involvement in the solar PV industry, the respondents generally assign importance to all the CFs associated with the EPR implementation. Nonetheless, greater emphasis was placed on the necessity of a pre-existing collection network and weak institutional capacity as CFs. The organizations with over 16 years of experience (n = 6) also emphasized collection targets, getting preference over recycling targets and the informal sector as a competitor. The findings on the whole reaffirmed the views expressed by stakeholders.

Inter-item correlation matrix of the factors

The inter-item correlation matrix of the EFs and CFs identified in this study. Table 4 showcases the correlation coefficients (r) between X_{11} with X_{12}

Table 4: Summary of the inter-items correlation (EFs)

Items	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}
x_{11}	1.000						
x_{12}	.396**	1.000					
x_{13}	.210	.134	1.000				
x_{14}	.328**	.078	.221	1.000			
x_{15}	.355**	.398**	.268*	.522**	1.000		
x_{16}	.398**	.353**	.266*	.465**	.626**	1.000	
x_{17}	1.000	.396**	.210	.328**	.355**	.398**	1.000

Note: x_{11} = Achieving higher collection and recycling rate; x_{12} = Practice of EPR in e-waste management as an enabler; x_{13} = Reduction of government expenses; x_{14} = Opportunity to learn EPR practice from developed economies; x_{15} = Users' acceptance of EPR as it relieves them from the burden of EOL panels; x_{16} = Eco-design in panel manufacturing; x_{17} = Emergence of local recycling facilities and secondary material markets; *$p < 0.05$; **$p < 0.00$.

Table 5: Summary of the inter-items correlation (CFs)

Items	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	x_{26}
x_{21}	1.000					
x_{22}	.396**	1.000				
x_{23}	.210	.134	1.000			
x_{24}	.328**	.078	.221	1.000		
x_{25}	.355**	.398**	.268*	.522**	1.000	
x_{26}	.398**	.353**	.266*	.465**	.626**	1.000

Note: X_{21} = Collection targets get the upper hand over recycling; x_{22} = Cost of compliance transferred to users; x_{23} = Solar PV-specific regulation might be required; x_{24} = Informal sector of recycling as a competitor; x_{25} = Required the pre-existence of a collection network; x_{26} = Weak institutional capacity; *$p < 0.05$'; **$p < 0.00$.

, x_{14}, x_{15}, and x_{16}; x_{12} with x_{14}, x_{15}, and x_{16}; x_{13} with x_{15} and x_{16}; x_{14} with x_{15}, x_{16}, and x_{17}; x_{15} and x_{16}; x_{16} and x_{17}. Notably, the highest correlation coefficients were between x_{14} (opportunity to learn EPR practice from developed economies) and x_{15} (users' acceptance of EPR as it relieves them from the burden of EOL panels), x_{14} and x_{16} (promotion of eco-design in panel manufacturing), and x_{15} with x_{17} (emergence of local recycling facilities and secondary material markets). Therefore, the interpretations and inferential analysis of the EFs of EPR presented in this study were considered dependable.

Table 5 denotes the *r* between x_{21} with x_{22}, x_{24}, x_{25}, and x_{26}; x_{22} with x_{24}, x_{25}, and x_{26}; x_{23} with x_{25} and x_{26}; x_{24} with x_{25} and x_{26}; x_{25} and x_{26}. Particularly, the highest significant correlations were between x_{24} (informal sector of recycling as a competitor) and x_{25} (required the pre-existence of a collection network), x_{24} and x_{26} (weak institutional capacity), and x_{25} and x_{26}. These correlation coefficients solidified the inferences and analyses of the CFs hindering the EPR adoption and implementation in managing EOL solar panels in a developing country context.

CONCLUSION

This study revealed that adopting EPR as a policy tool for managing EOL solar PV panels benefited developing countries. When implementing EPR, consideration was required for all the EFs and CFs identified in this study. Nevertheless, three EFs were more significant. These factors were accelerated users' acceptance (mean = 3.89) due to the shifting of disposal burden to manufacturers or wholesalers, a higher probability of lower government expenses (mean = 3.79) if EPR was adopted, and the potential emergence of a domestic secondary material market and recycling facility under EPR (contingent upon the existence of an industry ready to use recovered materials as feedstock). Like EFs, three challenging aspects were more crucial. Developing countries with weak institutional capacity and no existing collection network encountered challenges in fully adopting EPR. Thus, enhancing institutional capacity through awareness campaigns and motivation initiatives addressed this concern. Furthermore, implementing a solar PV-specific regulation rather than incorporating solar PV waste management into existing e-waste regulations was more effective. Conversely, regulators should consider several factors when establishing a separate law for managing EOL solar PV panels, such as capacity, resources, industry size, and implementation costs. Transferring EPR compliance costs to consumers also hindered solar PV expansion. Therefore, measures such as involving third-party recyclers, fostering coordination between third parties and producers, offering government subsidies, and providing tax exemptions were beneficial. Gaining views directly from stakeholders actively involved in the solar PV industry of Bangladesh provides valuable insights, preventing the replication of policies from developed nations and considering local realities. The findings of this study can aid policymakers in Bangladesh and countries encountering a similar challenge in managing end-of-life solar PV panels, a significant form of e-waste. Future studies should explore the issue of adopting mandatory or voluntary EPR, cost-benefit comparisons between the inclusion of solar PV waste in existing e-waste management rules, and the implementation of a separate solar PV waste-specific regulation. Consequently, examining how manufacturers reconcile compliance costs with their economic interests in a developing country context is another promising study area.

AUTHOR CONTRIBUTIONS

S.E. Kabir performed the study design, literature review, data collection, compilation, analysis, and interpretation of data along with the manuscript text preparation and edition. M.N.I. Mondal performed data validation, analysis, manuscript preparation, and edition. M.K. Islam helped prepare the manuscript and edit it. I.A. Alnaser helped prepare and edit the manuscript. M.R. Karim helped prepare and edit the manuscript. M.A. Ibrahim helped prepare and edit the manuscript. K. Sopian helped prepare and edit the manuscript. Md. Akhtaruzzaman supervised the whole work and helped prepare and edit the manuscript. All authors evaluated the results and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS

α	Cronbach's alpha
>	Greater than

≥	Greater than or equal to
<	Less than
≤	Less than or equal to
%	Percent
C$	Canadian dollar
n	Number
p	probability
r	Correlation coefficient
yrs.	Years
CF	Challenging factor
e-waste	Electronic waste
EPC	Engineering, procurement, and construction
EF	Enabling factor
EOL	End-of-life
EPR	Extended producer responsibility
EU	European Union
Fig.	Figure
GO	Government organization
GW	Gigawatt
MW	Megawatt
NGC	Non-government company
NGO	Non-government organization
OECD	Organization for Economic Co-operation and Development
OPEX	Operational expenditure
Ph.D.	Doctor of Philosophy
PRO	Producer responsibility organization
PV	Photovoltaic
RE	Renewable energy
SD	Standard deviation
SHS	Solar Home System
SPSS	Statistical package of social science
SREDA	Sustainable and Renewable Energy Development Authority
USA	United States of America
WEEE	Waste Electrical and Electronic Equipment

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