



Sustainable Management of Solar Panels within the Framework of a Circular Economy

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ABSTRACT

The rapid expansion of solar energy systems has played a significant role in reducing greenhouse gas emissions and accelerating the global transition toward renewable energy. However, the increasing deployment of photovoltaic (PV) technologies has also led to growing concerns regarding the management of end-of-life (EoL) photovoltaic modules, which are emerging as a major environmental, economic, and managerial challenge. As the installed capacity of PV systems continues to increase worldwide, a substantial volume of PV waste is expected to be generated in the coming decades. Consequently, developing effective strategies for the collection, recycling, and recovery of valuable materials has become an essential prerequisite for achieving a circular economy in the renewable energy sector. This study aims to comprehensively examine the challenges associated with end-of-life photovoltaic panel management and to identify sustainable recycling strategies through a descriptive-analytical review of recent scientific literature, international reports, and global best practices. The study investigates the technical, economic, environmental, institutional, and social dimensions of PV waste management while evaluating current mechanical, thermal, and chemical recycling technologies, Extended Producer Responsibility (EPR) policies, Design for Recycling (DfR) principles, regulatory frameworks, stakeholder engagement, and circular economy approaches. The findings indicate that insufficient recycling infrastructure, high processing costs, technological limitations, weak regulatory enforcement, inadequate investment, and the absence of integrated waste management systems remain the primary barriers to sustainable photovoltaic recycling, particularly in developing countries. Conversely, strengthening domestic recycling technologies, implementing Extended Producer Responsibility schemes, promoting recyclable product design, expanding secondary materials markets, enhancing collaboration among governments, industry, and research institutions, and increasing public awareness can significantly improve material recovery rates, reduce environmental impacts, and enhance resource efficiency throughout the photovoltaic value chain. The main contribution of this study is the development of an integrated and locally adaptable framework for sustainable end-of-life photovoltaic panel management in Iran. By combining technical, economic, institutional, and policy perspectives, the proposed framework provides practical guidance for supporting the transition toward a circular economy and improving resource sustainability within the renewable energy sector.

Introduction

The rapid growth of renewable energy technologies, especially photovoltaic systems, has played a pivotal role in the global transition to sustainable development and reduced dependence on fossil fuels. However, the accumulation of end-of-life solar modules has become one of the world's emerging environmental and management challenges. Estimates indicate that by the middle of this century, more than 78 million tons of photovoltaic panels will be discarded worldwide; a figure that, in the absence of recycling infrastructure, could pose a serious threat to soil, water, and human health. Solar panels are composed of materials such as glass (more than 70% by weight), aluminum, silicon, and silver, which have high economic value, but at the same time contain compounds such as lead and cadmium, which, if improperly disposed of, cause serious environmental pollution. The multilayer structure and thermal bonding of the panel components make separation and recycling difficult and costly. In Iran, with the growth of small-scale and home solar power plants (more than 500 MW of installed capacity by the end of 1402), the issue of end-of-life management of this equipment is becoming a national concern, but it still lacks binding laws, technological infrastructure, and effective regulatory mechanisms. The theoretical framework of this research is based on the principles of circular economy, which aims to preserve the value of materials in the production cycle and reduce resource waste. In this regard, two key concepts, including Extended Producer Responsibility (EPR) and Design for Recyclability (DfR), play a central role. The main objective of this research is to analyze the challenges and opportunities of photovoltaic panel waste management and to provide an integrated and indigenous framework for Iran that is based on Extended Producer Responsibility, product design with recyclability, development of mechanical, thermal, and chemical technologies appropriate to domestic capacity, and tracking and stakeholder participation mechanisms. The importance of the research is that by combining EPR policy, recyclable design, localized technologies, and stakeholder participation, it provides an operational model for sustainable management of solar waste in Iran that can be used as a model for other developing countries with similar conditions.

Method

This research is an analytical review study with a qualitative approach and is based on library and document studies. A systematic search was conducted in reputable international databases including ScienceDirect, Scopus, SpringerLink, and Google Scholar, as well as Persian databases including SID, Magiran, and Civilica with the combined keywords "solar panel recycling", "photovoltaic waste management", "circular economy", "extended producer responsibility", and their Persian equivalents including "solar panel recycling", "photovoltaic waste", "circular economy", and "producer responsibility". The search period was from 2010 to 2025 to cover the latest research, global policies, and technological developments in the field of solar panel recycling. Inclusion criteria included (1) direct relevance to the topic of photovoltaic panel waste management or recycling, (2) provision of quantitative or qualitative data on recycling technologies, EPR policies, or environmental-economic analysis, and (3) publication in reputable scientific journals or official reports of international organizations (such as IRENA, IEA, and EPA). From 112 primary sources, 40 articles and reports that were most relevant to the topic were selected and analyzed. The data extraction process was carried out qualitatively using the oriented content analysis method, and the information was categorized into four main axes: (1) technical challenges, (2) economic challenges, (3) institutional and legal challenges, and (4) cultural challenges and public awareness. Also, successful global models in the field of PV waste management (such as the European Union's experience in implementing the WEEE Directive, the EPR model in Germany and France, and the PV CYCLE project) were analyzed for localization in Iran. To analyze the current

situation in Iran, reports from Tavanir Company, the Renewable Energy Organization (SATBA), and related domestic research were used. The data were examined using comparative and content analysis methods, and based on that, a proposed integrated framework for sustainable management of solar panel waste and transition to a circular economy in Iran was designed.

Results

A systematic review of the literature and qualitative data analysis revealed that sustainable solar panel waste management faces significant challenges across technical, economic, institutional, and social dimensions. From a technical perspective, the complex multilayer structure of photovoltaic (PV) panels and the strong bonding of their components make recycling difficult and expensive. Recovering valuable materials such as silver and silicon requires advanced thermal and chemical technologies that are not yet widely commercialized. In addition, the lack of international standards for design for recyclability has limited the development of more recyclable PV modules.

Economically, the high cost of recycling, combined with the relatively low market value of some recovered materials, reduces the profitability of recycling activities. Limited government subsidies, insufficient financial incentives, and the absence of well-developed secondary markets further discourage private investment in recycling infrastructure. Institutionally, many countries, including Iran, still lack comprehensive regulations, monitoring systems, and unified technical standards for end-of-life PV management. The absence of Extended Producer Responsibility (EPR) mechanisms also weakens the collection and recycling of discarded panels. From a social perspective, limited public awareness regarding proper disposal and recycling, together with the rapid evolution of PV technologies and the increasing diversity of panel designs, creates additional challenges for establishing efficient recycling systems.

To address these challenges, several opportunities and policy measures were identified. These include promoting a circular economy through design for recycling, component reuse, and material recovery; implementing Extended Producer Responsibility (EPR) policies based on successful international experiences; developing indigenous recycling technologies using mechanical, thermal, and chemical processes, supported by emerging technologies such as artificial intelligence and nanotechnology; creating economic incentives through subsidies, tax exemptions, and take-back programs; improving panel design to facilitate recycling; establishing national monitoring and traceability systems using digital databases and QR codes; strengthening international cooperation and technology transfer; and enhancing public awareness through education and outreach programs. Together, these strategies can improve resource recovery, reduce environmental impacts, and support the long-term sustainability of the photovoltaic industry.

Conclusions

A systematic review of the literature and analysis of the challenges and opportunities of photovoltaic panel waste management showed that this issue is not just an environmental challenge, but a strategic issue for sustainable development in which smart policy-making, technological innovation, interagency cooperation, public participation, and culture-building play a central role. The challenges can be summarized in five categories: technical, economic, institutional, cultural, and emerging technologies, and opportunities such as the development of green recycling technologies, redesigning panels based on recyclability, strengthening the EPR system, establishing a national database, and active participation of the private sector pave the way for the transition to a circular economy. The proposed framework for Iran is based on three main axes: (1) an institutional and policy framework including the establishment of a national recycling institution, the adoption of an EPR law, and a digital

tracking system; (2) the technical and economic model including the combination of mechanical, thermal, and chemical technologies, regional centers with the PPP model, and the support system and economic incentives; and (3) the role of stakeholders and public participation including the government, municipalities, the private sector, the media, and citizens. If countries like Iran can respond to this issue in a timely manner and properly localize global models, they will not only prevent future environmental threats, but also provide them with new opportunities in the field of green economy, employment, and resource efficiency. It is suggested that future research should focus on quantitative assessment of waste generation, techno-economic feasibility of regional recycling centers, and comparative study of EPR policies in different countries. The establishment of the proposed integrated framework can increase the recovery of valuable materials, reduce environmental risks, and facilitate the transition to a circular economy in the renewable energy sector.

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