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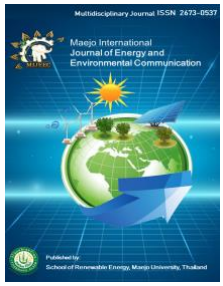

ARTICLE

Towards a circular economy for end-of-life solar panels: Governance frameworks and techno-economic pathways

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ABSTRACT

Rapid growth in the deployment of photovoltaic (PV) technologies is speeding up the development of end-of-life (EoL) waste streams, resulting in governance challenges if we consider emerging economies. This study gives a comparative techno-economic and institutional evaluation of PV circularity in Taiwan using an operational extended producer responsibility (EPR) regime in Taiwan, and a policy in Thailand that is still in development and not yet complete. The integrated system of Taiwan with prepaid recycling fees, a digital life-cycle registry (PVIS), and accredited treatment facilities has allowed enforcing take-back and high mass-recovery of glass and aluminum. However, flat capacity-based fees provide poor incentives for eco-design and a poor economic return of high-value materials such as silver and high-purity silicon during the recovery phase, due to the delamination energy and refining costs. In Thailand, although the expansion of renewables and PDP 2024 (51% renewables electricity share by 2037) is known, PV-specific EoL governance has yet to be matched. The absence of EPR legislation and treatment capability creates the risk of material leakage and fiscal liabilities. Analysis of a recovery pathway through the use of solvent delamination and hydrometallurgical refinement at an industrial scale. Thai EPR framework with eco-fees, registry system and informal actor integration is proposed by the study. In absence of producer responsibility, environmental and economic risks will arise through the next decade.

1. Introduction

The structure of the global energy system is in a deep, historically significant structural transformation, based on the accelerated deployment of renewable energy technologies in the electricity sector, heat sector, and transport sector (Balakrishnan et al., 2023; Mejica et al., 2023). Sustainable infrastructure development plays a crucial role in enhancing economic performance and long-term growth, particularly in ASEAN economies undergoing structural transformation (Chaiboonsri et al., 2024). Solar photovoltaics (PV), onshore and offshore wind, hydropower, bioenergy and biofuels, geothermal energy, and emerging marine technologies combine to form the basis of such a transition (Dussadee et al., 2022; Mejica et al., 2022; Nong et al., 2023). In the face of tightening climate change mitigation commitments, fossil fuel price volatility, geopolitical energy security concerns,

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and consistent technological innovation, renewable energy has emerged from its position as the supplementary alternative to become the fastest-growing and strategically prioritized segment of the global energy landscape (Onyemowo et al., 2024; Pandi et al., 2024; Ramaraj et al., 2025a). Hydropower for system stability, progressing wind power at a large scale, bioenergy and biofuels for dispatchable power, as well as transport decarbonization and geothermal for reliable baseload power generation in suitable areas. Of the lot, solar PV has become the leading source of new renewable capacity with the benefits of fast cost reduction, modularity, and scalability from utility-scale plants to distributed rooftop systems. As a result, renewables have become a peripheral part of energy systems, but foundational pillars of sustainable energy systems (Ramaraj et al., 2025b). However, this accelerating installation of renewable infrastructures also has new governance challenges, in particular, the challenge of managing the life cycle of the new energy technologies (Ramaraj & Dussadee, 2015; Sophanodorn et al., 2022; Vu et al., 2022).

Photovoltaics (PV) has become the main factor behind the global expansion of renewable energies, and it is fairly the cornerstone of decarbonization on the power sector. By the end of 2023, cumulative installed PV capacity stood at over 1.6 TW, and in 2024, solar additions alone reached over three-quarters of the global new renewable additions. Rapid cost decline, technology modularity, and scalability of utilities to rooftop-scale dispersed technologies have solidified PV's central role in the mid-century carbon emission mitigation strategies. However, in parallel to its unprecedented expansion, this presents a governance challenge of the emergence of large-scale photovoltaic end-of-life (EoL) waste streams over the coming decades. For example, PV modules usually have a virtually 25 - 30 years of operational lifespan. Installations that were deployed in the early 2010s will therefore start reaching retirement on a mass scale during the 2030s. As per the global projections, the cumulative waste of the PV module can reach the range of 60-78 million tonnes by 2050. While the content of glass in modules is the overwhelming mass content, economically significant fractions include aluminum frames, copper conductors and silver contacts. Accordingly, EoL PV management goes well beyond an environmental compliance question and represents an important strategic management of resources, with relevant aspects for secondary material markets, resilience of the supply chain, and economic circularity transitions.

Although technologies for recycling materials, such as mechanical dismantling and thermal delamination, and chemical or hybrid recovery routes, are still being further developed, they are highly dependent on the institutional frameworks. Effective PV circularity necessitates coming together of systems that address clear obligations on collection, cost-effective financing, digital traceability, and performance-based treatment standards. In jurisdictions where such frameworks do not exist, the risk of rapid deployment is creating patchy collection systems with informal leakage, as well as deferred fiscal liabilities. Thailand is the best example of the opportunity but also of the risk inherent in this global transition. The draft Power Development Plan 2024 (PDP 2024) has the objective of around 51% renewable electricity penetration by 2037 and terrestrial and floating solar are expected to have a major role in capacity addition. Installed PV capacity in Thailand reached more than 5 GW by 2023, and reforms to the country's regulations in recent years (not least is mandating removal of a factory license requirement for rooftop PV from 1 Jan 2022) are expected to rush distributed deployment and corporate power purchase agreements (PPAs). These generation-side reforms make the Thai market a rapidly growing solar market; however, they also mean that there will be a large future EoL waste stream starting in the 2030s.

In spite of this momentum, Thailand's waste governance architecture, which is specific to PV modules, is underdeveloped so far. Ongoing consultations concerning a Draft Waste Electrical and Electronic Equipment (WEEE) Act and a Draft Industrial Waste Management Act are signs of progress towards the adoption of the principles of extended producer responsibility (EPR). Nevertheless, the current absence of an operational EPR regime specific to PV, composed of collection and recovery targets, eco-modulated financing, accredited treatment capacity and unit-level traceability has not yet been enacted. Without such institutionalization, there is a risk of the country externalizing environmental costs and incentivizing handling them informally and postponing the necessary infrastructure investment. In contrast, Taiwan offers a principal example of the operationalization of EPR for PV modules. Based on Taiwan's existing implementation of a "4-in-1" Recycling Fund system, which already existed under Taiwan's Waste Disposal Act, Taiwan established a PV-specific recycling mechanism from 2019 to 2021. This framework includes compensation in the form of prepaid fees per amored various specified areas which are recycled, mandatory registration through a Photovoltaic Waste Information System (PVIS), and accreditation of treatment facilities. By combining a producer-financed responsibility for product "end of life" with conspicuous data flows and end-of-life tracking mechanisms, Taiwan has put in place an institutional architecture that can be enforced, and that can get on board both environmental protection and resource recovery.

While Taiwan and Thailand are different in institutional configuration, capacity for regulation and industrial structure, the policy instruments that are embedded in Taiwan's model - funded producer responsibility, digital lifecycle monitoring, and performance-based accreditation - is conceptually transferable. The most important question is not whether or not the two systems are identical, but whether or not the functional components of Taiwan's regime can be adapted to Thailand's fast-expanding solar context so that it can bring together the growth of renewables with the goals of circular economies. In order to examine these dynamics, this research uses qualitative comparative case analysis (QCA) methodology. The methodology uses three sources of evidence that work together to address a research question. First, a systematic review was made of international technical reports and policy guidance, including publications of the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), the International Renewable Energy Agency (IRENA), and national environmental authorities. Second, regulatory and legislative documents were reviewed, comparing Taiwan's Waste Disposal Act and new Resource Circulation Promotion Act and Thailand’s PDP 2024 and draft waste management legislation.

Third, a synthesis of academic literature, patents and techno-economic assessments for the maturity, cost factors, and recovery performance of alternative PV recycling technologies was performed. Through the process of methodological triangulation, the study provides more analytical robustness and ensures good structure for policy recommendations. By putting any developments on the end-of-life management of the PV in the wider context of the development of renewable energy and the circular economy, the research will feed into a burgeoning scholarship on life cycle energy governance. It argues that circularity in the PV sector is not an automatic discovery of technological deployment, but this can happen as a contingent result of representation as a policy, relying on institutional architecture, financing mechanism and technology coordination.

2. Taiwan’s Policy Architecture and Emerging Challenges

2.1 Institutional Architecture for PV End-of-Life (EoL) Governance

The end-of-life (EoL) management approach of the Taiwan government is derived from Taiwan's extended producer responsibility (EPR) regime, which is incorporated into its Waste Disposal Act and the Resource Recycling Act. Implementation is done in an operational sense via the well-established "4-in-1" Recycling Fund system by which fees are centrally collected, and funds are redistributed to support collection, treatment, and market development activities. This system for centuries has gotten strong collection rates across regulated waste streams, and it offers a stable financial backbone for producer-financing waste governance (Tsai, 2020; U.S. EPA, 2014).

In 2025, the Ministry of Environment (MOENV) announced quite a few amendments to update this regulatory framework as part of the 2025 Waste Prevention Act, with the Resource Recycling Act becoming the Resource Circulation Promotion Act, and the revamping of the circular economy instruments into the Waste Disposal Act (MOENV, 2025). These reforms are a strategic change from conventional waste management towards agencies of resource circulation.

Based on this institutional base, Taiwan has launched a PV-specific EPR mechanism since 2019. The Bureau of Energy - BOE - incorporated a one-off recycling fee - US$32.56 per kW - into the renewable electricity purchase schedule or FIT, which is payable at the time of installation and will contribute towards the Recycling Fund (MOENV, 2021). This upstream cost internalization can be used to ensure financial provisioning of EoL liabilities at the deployment stage.

Concurrently, MOENV also developed the Photovoltaic Waste Information System (PVIS), which is a digital life-cycle registry that requires developers to register installation data and, upon module retirement, contribute take-back applications, which link individual panels to approved treatment facilities (MOENV, 2020; PVIS, n.d.). This is a combination of mandatory registration, life span tracking, and financial punishment for enforcement. Each module is assigned a registration number, and if they are illegally dumped, the fines are up to US$97,675 (Taipei Times, 2020; EnergyTrend, 2020).

This combination of prepaid financing, digital traceability, and accreditation of treatment infrastructure is a vertically coordinated model of governance. Early pilot cases (for example, batches of module retirements in Penghu) proved that it works. Accredited domestic facilities may operate both routine EoL flows as well as surge volumes that come afterwards in the event of extreme weather events. Policy guidance stress on local treatment to the extent the environment and the economy should be preserved to maximize the recovery of glass, aluminum, and other valuable materials (MOENV, 2020; EnergyTrend, 2021). Collectively, Taiwan's PV-specific EPR framework provides a good example as to how financial responsibility, data transparency and institutional oversight can be integrated in an effort to operationalize the idea of circularity in an emerging renewable sector.

2.2 Organizational and Operational Challenges (2019-Present)

Despite the operational maturity of Taiwan's PV EPR system, it does have a number of structural issues, which tend to highlight areas of refinement.

Challenge 1: Fee Adequacy and Incentive to Design

The current recycling fee - US$32.56 per kW - is administratively easy but not differentiated by the complexity of the module design, the material composition, or the ease of recyclability. As module technologies change (e.g., adding different encapsulants, backsheets, or cell architecture) treatment costs may vary from the flat rate assumption. A uniform capacity-based fee may thus have a diminishing effect on incentives for design-for-recycling and provide long-term risks of fund-imbalance. There is now an increasing level of international guidance focused on eco-modulated fees for reward in this direction, for modularity, ease of disassembly and improved recovery yields (IEA PVPS Task 12, 2024). Without some recalibration on an ongoing basis, the system stands to become out of alignment, with upstream financial signals not being perfectly correlated with downstream treatment economics.

Challenge 2: Traceability of the Distributed Rooftop Systems

The presence of the rooftop dominating deployment pattern of Taiwan brings about the complexity of administration. Highly spread-out ownership and installer network, which means that the serialization, custody tracking and retirement notification compliance increase. Although PVIS requires per-panel registration and online filing, because of the number of installations (thousands of small installations) ensure that data are accurate is still resource-intensive. The no risk of leakage is retained without the capability of automatic tagging, effective auditing systems, and tenant installer integration (MOENV, 2020; Taipei Times, 2020). As the scale of deployment increases, it is going to become important to provide digital traceability to ensure system integrity.

Challenge 3: Maturation of the Treatment Capacity and Surge Management

Accredited recycling facilities are up and running, but market depth and maturity of technology, as well as the issue of high-value material recovery (such as silver and copper), are still being developed. Advanced processes of delamination and hydrometallurgical processes are sensitive to energy costs, chemical management, and throughput scale. Furthermore, extreme weather phenomena can also generate temporary surges in waste, which can provide an examination of the logistical resilience and processing capability. While authorities have suggested preparedness, to be resilient in long-term there is a need for contractual flexibility as well as buffer and continuity of technological updates (EnergyTrend, 2021; IEA PVPS Task 12, 2024). These challenges do not affect Taiwan's framework, but rather demonstrate its dynamic nature of circular governance in a fast-changing technology world.

2.3 Making New Responses Present and Policy Refining

Recognizing the above-mentioned limitations, several policy efforts are currently being implemented/recommended to enhance the robustness of the system.

(i) Change towards eco-modulated and Periodically Reviewed Fees

Institutionalization of biennial or scheduled reviews of fees under the Recycling Fund would provide for adjusting them based on observed treatment costs, material recovery money revenues and evolution of technology. Pilot eco-modulation for example, with lower fees for modules designed to have detachable frames or standardized backsheets or increased glass recovery rates, would bring financial incentives in line with circular design principles. This approach is consistent with the international best practice development (IEA PVPS Task 12, 2024).

(ii) Improving the Digital Traceability and Chain of Custody Process.

Improved tracking of the lifecycle would be achieved by improving PVIS by making it mandatory to label with QR or 2D codes that are associated with the serial numbers of the BOEs at the installation of the PV. Integrating at the installer level of licensing databases and electronic manifest (e-manifest) systems would give end-to-end visibility of the chain of custody. Risk-based audits of high-volume installers and/or areas with high rates of rooftop building may be particularly helpful to minimize the risk of leakage. These measures build on existing PVIS infrastructure as well as enforce regulatory oversight.

(iii) Instrumenting of Markets, Deepening and Treatment Accreditation

The energy policy levers can be used to reinforce the EPR compliance. For instance, the eligibility for FIT adders or renewable procurement programs could be made theologized on the demonstrable of paying the recycling fee and the keeping of the EoL obligations. Public procurement standards can also focus on modules that have disassembly documentation or better recyclability profiles, that is published. Maintenance of outcome-based technical standards amd. and not prescriptive technology mandates cognitive flexibility of innovation and sustainability to environment outcomes

(iv) Legal Path- Modernization and also Cross-Agency Integration

Advancing the 2025 amendments to establish the Resource Circulation Promotion Act is an opportunity for coding the principles of eco-design, data disclosure requirements and cross-agency information-sharing. Harmonisation of the environmental legislation and the sectoral energy laws would ensure less institutional fragmentation and improve coherence on the governance of energy.

Synthesis

Taiwan's PV-specific EPR regime proves that operation of circularity in the solar industry is institutionally feasible if upstream financing, digital traceability, and accredited treatment infrastructure are systematically inherently covered. However, changing technologies for modules, changing patterns of deployment, and more effective material recovery economics semantically mandated the need for adaptive (changing) governance. The case of Taiwan, therefore, offers something of a reference model. Its experience applies pressure to the point that circularity is not static but requires periodical recalibration of financial signals, an improvement of the digital infrastructure and the modernization of the law to keep up with the course of technological changes.

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3. Thailand’s Policy Landscape and Challenges

3.1 Policy Landscape: Rapid Solar Expansion Under the New Power Plan

Thailand is undergoing a clean energy transition that is much faster than the rest of the world. The planned increase of ambition from the draft Power Development Plan 2024 to 2037 (PDP 2024), developed as part of the National Energy Plan, is to have 51% of the electricity mix by 2037, coming from renewable sources, with the single largest planned source being terrestrial solar and supporting roles for floating PV, onshore wind and storage (Climate Policy Database, 2025; BloombergNEF, 2025).

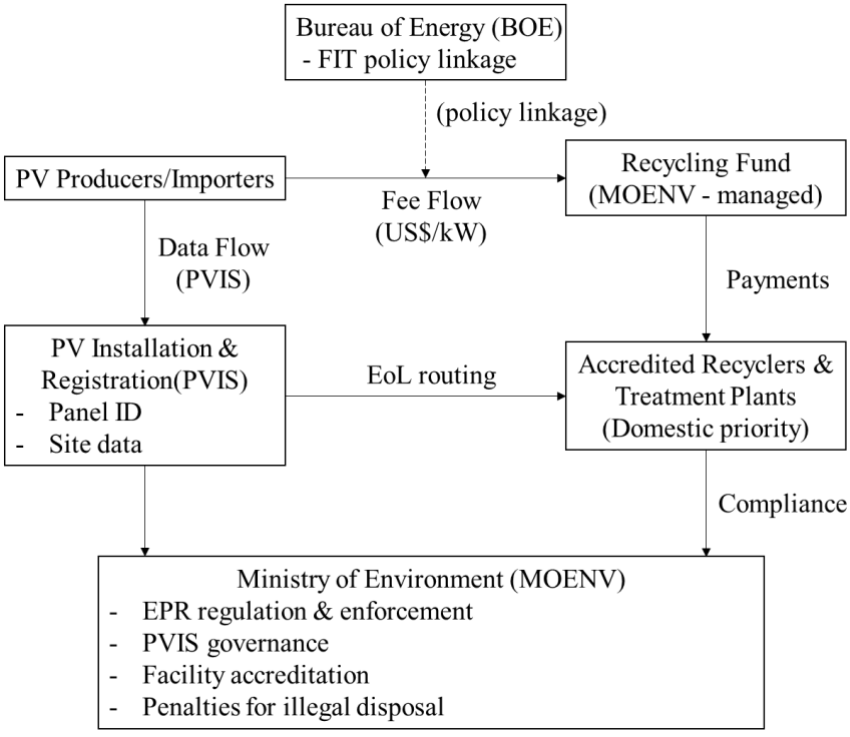

Figure 1. Governance architecture of Taiwan’s photovoltaic (PV) extended producer responsibility (EPR) system.

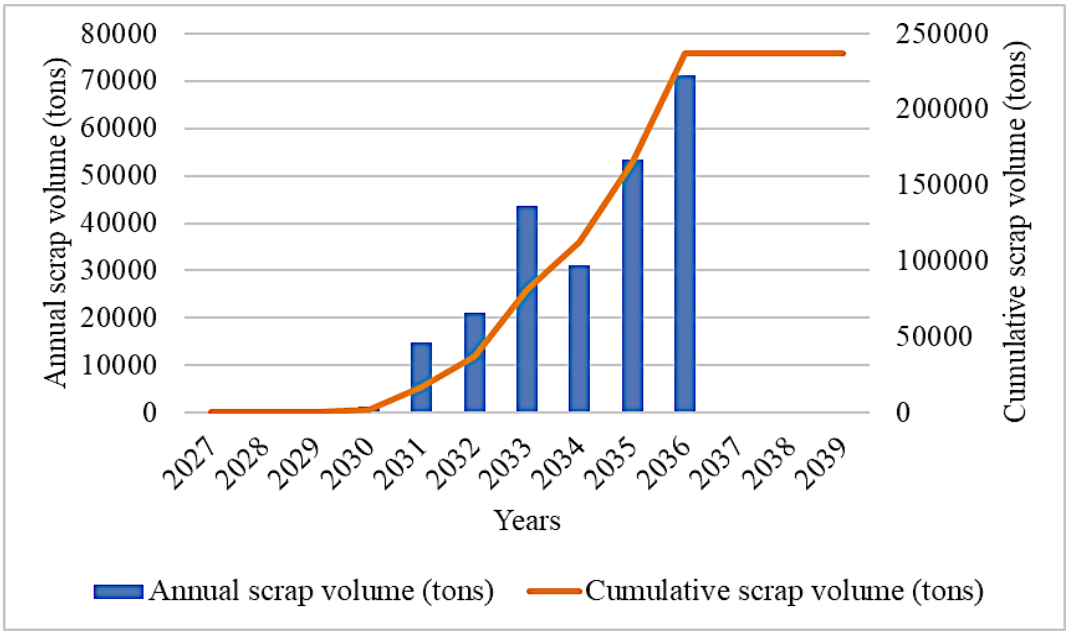

Figure 2. PV waste projection for Thailand (2027–2039). Source: Supapyam and Rachdawong (2024).

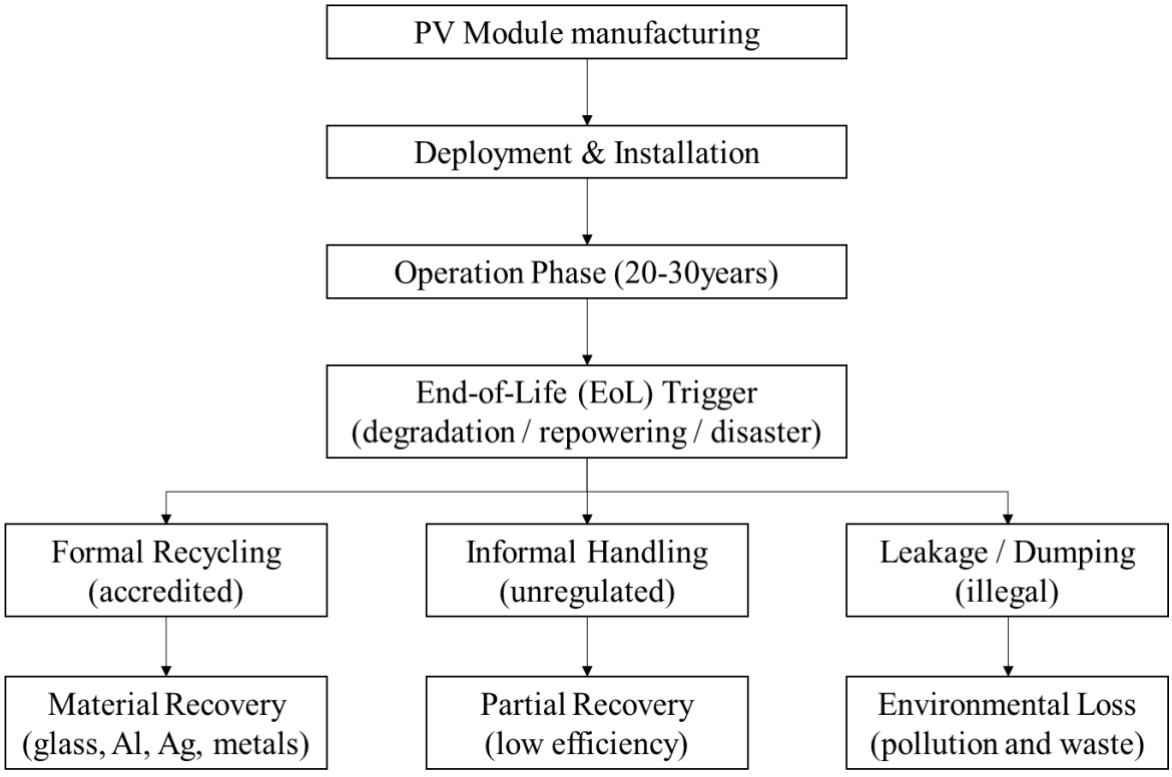

Figure 3. PV life-cycle and EoL material flows

In parallel, regulatory streamlining has reduced obstacles to distributed PV. A ministerial regulation that takes effect on December 28, 2024, eliminated the existing factory-license requirement to install rooftop PV, to speed up the installation process and make it easier for corporations to offer PPAs (Nishimura & Asahi, 2025; Tilleke & Gibbins, 2025). Utility-scale innovation is evident in another area as well - hybrid floating PV-hydroponic. The Sirindhorn project (45 MW), which has been operational since late 2021, is a good example of how PV can be used with existing hydropower projects to enhance flexibility and minimise evaporation losses (EGAT, 2021, 2021b). Against this backdrop, the cumulative installed PV capacity of Thailand is now over 5 GWp (in 2023), with rooftops being pinpointed as the mode of take-off (Agora Energiewende, 2024).

3.2 The end-of-life (EoL) Policy Gap for PV

Despite a gathering of players on the generation side, no PV-specific extended producer responsibility (EPR) statute is in place. Thailand has made a few steps forward on several cross-cutting waste bills, which incorporate EPR principles, such as a Draft Waste Electrical and Electronic Equipment (WEEE) Act as well as a Draft Industrial Waste Management Act (DIWMA), but these are at the draft or consultation stages (Enviliance, 2024; Baker McKenzie, 2025; ERP Global, 2025). To put these global projections in the national context, the projected photovoltaic (PV) waste generation trajectories of Thailand during 2027-2039 is presented in Figure 2. The figure shows the likely concentration of end-of-life flows over time under alternative assumptions on deployment and the lifetime of PV modules, highlighting the timeliness of checking and developing PV-specific Collection, finance and treatment systems.

In the absence of a specific PV-based end-of-life management framework, end-of-life management outcomes are determined largely by the general waste regulations and not by PV-specific obligations. To provide some context to such issues, Figure 3 presents a summary of the different life-cycle stages of PV modules, and the key material flow paths seen at the end of life for them in current policy circumstances.

More broadly, the government also stepped up control over e-waste imports in 2025, beefing up a list of banned items-literal of a bigger strategy to in effect, continue to curb illicit flows, but a horizontal such liquidity control does not quite create PV modules take-back, traceability, and eco-modulated financing domestically (The Nation, 2025; PRD Thailand, 2025).

The whole picture is consistent with the international assessments: outside the EU and a few jurisdictions with PV-specific rules, most countries still handle PV EoL under their general waste laws - Thailand included (IEA PVPS Task 12, 2022). To combine and solidify the information of Thailand's specific context as mentioned in the above section, Table 1 summarizes salient indicators relating to photovoltaic deployment, end-of-life waste generation, and system characteristics. The table gives a structured overview of scale and timing, the makeup being of materials, and conditions of governance, which can be used as an analytical point of reference for the following section on identifying gaps in policy and institutional design considerations.

Table 1. Overview of photovoltaic deployment, end-of-life waste projections, and system characteristics in Thailand

Dimension	Key indicators	Evidence / notes
PV deployment	Installed capacity (~5 GW by 2023); rapid expansion under PDP 2024	Utility-scale, floating, and rooftop PV prioritized
Policy drivers	PDP 2024 targets ~51% renewable share by 2037; rooftop PV deregulation (Dec 2024)	Corporate PPAs and cost declines accelerate uptake
Module lifetime	Typical service life 25–30 years	Early replacement possible due to repowering or extreme weather
Waste projections	EoL PV waste expected to increase sharply after 2030; peak flows in late 2030s	Scenario-based projections shown in Figure 1
Material composition	Dominated by glass; economically relevant fractions of Al, Cu, Ag	High-volume/low-value vs low-volume/high-value materials
Current governance	No PV-specific EPR; reliance on general waste regulations	Draft WEEE Act and DIWMA under consultation
System challenges	Fragmented collection, informal handling, limited traceability	Horizontal measures insufficient for PV-specific EoL

3.3 Present Challenges in PV Waste Management

First, the lack of an EPR and eco-modulated fees specific to PV results in low incentives for design-for-recycling, producer take-back, and standardized dismantling/logistics. Legislation that draws attention to the direction is a signal, but the details of implementation (scope, design of fees, data systems, and producer responsibility organizations' roles, etc.) are still on the table (Enviliance, 2024; Baker McKenzie, 2025).

Second, there is still difficulty in traceability and compliance of small systems in a dominant rooftop market. Panel-by-panel serialisation, combined with integrated e-manifesting. If you want to know more details: shortage to informal channels, premature dumping and so on For (download). No documentation provided to these units, the leakage to informal channels etc can happen - Inense Safety (ja) Rating. Nothing and is connected to the E-waste Initiative (EEI) of IEA PVPS. Which approach is taken by > Product life cycle approach: keep in mind, this ae the only way to prevent PV panels from ending up in the most dangerous end-of-life, appearing as garbage dumping, as garbage incineration Discard PV. Third, the ability to treat and the technology readiness are immature. Official and industry sources comment on the lack of dedicated PV waste lines; academic and policy reviews emphasise the fact that high-value recovery and laminated glass delamination at scale is still a maturing process, often uneconomic without policy support. Fourth, with decreasing stringent enforcement of the e-waste movement, an increased cross-border option of interim processing strategies may become scarce: an element to highlight the need to develop domestic, compliant routes for PV EoL (AP News, 2025; ChemLinked, 2025).

3.4 Opportunity space under Thailand's green-energy push

Thailand is also adding more solar power with large-scale solar power projects, floating solar panels, and corporate sourcing. This is an opportunity to make solar energy more sustainable in the first

place. Important actions include: Making laws for solar panel recycling, with fees corresponding to the cost of recycling, according to global advice. Use of digital codes on panels to track them and link them to a national system for end-of-life management. Setting standards for recycling facilities and using energy policy to encourage proper recycling. Choosing solar panels that are easy to dismantle and contain fewer harmful materials. Using floating solar panels with hydroelectric power to better manage the replacement and minimization of the damage from weather. Overall, Thailand plans to contribute to the enhancement of its solar energy system by making recycling an integral component. In Thailand, by having clear rules, better tracking, and matching incentives to the outcome of recycling, it will be possible to develop a reliable system, not only for the environment, but also for the economy.

4. Recycling Technologies

4.1 Global Overview

Current end-of-life (EoL) processing of crystalline-silicon photovoltaic (PV) modules typically consists of three successive steps - (i) pre-processing, in which frames, junction boxes, and other ancillary components are removed; (ii) delamination, by which the encapsulant and cell layers are separated from one another using various mechanical, thermal or chemical methods; and (iii) material recovery. With glass and aluminum making up a lion's share of the bill of materials, mass-based recovery rates of over 90% are put forth within the industry, while high-value streams (e.g. Ag, high purity Si) have been noted to still be sensitive to each of the delamination energy, reagent footprint, and the down-stream refining costs (IEA PVPS Task 12, 2024; American Clean Power Association [ACP], 2024; NREL, 2025). The schematic (Figure 4) compares mechanical, solvent-assisted, and hydrometallurgical approaches with respect to the major steps in the process and the recovery process outcomes and illustrates the technological diversity that is the backbone of policy considerations in setting performance-based standards for recycling.

4.2 Taiwan: Technologies at a Glance

Under the framework of a PV-specific extended producer responsibility (EPR) scheme and Photovoltaic Waste Information System (PVIS), Taiwan focuses on emphasis on local treatment enhanced by life cycle registration. Commercial processes combine mechanical dismantling (frame, box and glass removal) and thermal delamination for cell stack release, metals sorting and single or multiple wet chemistry (Ag/Cu) in cases where it wereeconomically feasible (MOENV-PVIS, 2025; MOENV, 2020). Research and pilot projects focus on module designs that are very easily dismantled and innovations in encapsulants to reduce thermal and chemical loads at the end of life (EoL). An ITRI-URE demonstrator also regards high recoverability rates of cells and glass, and demonstrates a way towards automation with higher throughput (PV Magazine 2022). Overall, the approach to Taiwan is in line with the latest Task-12 approach that makes use of digital traceability (PVIS) to coordinate take-back logistics and routing to accredited handlers (MOENV-PVIS, 2025; MOENV, 2020; IEA PVPS Task 12, 2024; pv magazine, 2022).

4.3 Thailand Technologies and Capacity to Date

Thailand's rapid solar growth has not yet been reflected in PV-specific EoL processing capacity. Government-led forums acknowledge this gap and promote domestic solutions, and in the last feasibility studies, the potential plants of mechanical recycling are modeled that have the delamination and separation steps, but confirm that dedicated commercial lines are in the infancy of their existence (PMUC/MHESI, 2024, 2025; Sukaviriya, 2025). Stricter controls in e-waste imports add more cross-border constraints to act on localizing the extent of accredited goods after exploring the enhanced producer-funded take-back once PV-specific EPR changes are implemented (Sukaviriya, 2025).In terms of mass, it is mainly glass, aluminum and precious metals like silver and copper recovered through specific hydrometallurgical processes where economic conditions permit it (IEA PVPS Task12, 2024; U.S.DOE SETO, 2022). Amid these constraints in terms of capacities and the development of the regulatory environment, Table 2 provides a comparative summary of the key photovoltaic module recycling pathways discussed in the present section. By underscoring their respective process characteristics, benefits, and constraints, the table helps to understand why no one path of technology can be considered optimal if considered in isolation, and why policy approaches have tended to focus more on performance-based standards than technology-prescriptive approaches. While Table 2 describes the main benefits and limitations of the alternative photovoltaic module recycling pathways from a policy and implementation perspective, techno-economic characteristics further differentiate the appropriateness of the recycling pathways under different policy and market conditions. To complement this qualitative comparison, Table 3 presents an indicative overview of the techno-economic prospects of some of the major recycling pathways as an indication of differences in energy demand, key cost drivers, and possible material recovery rates.

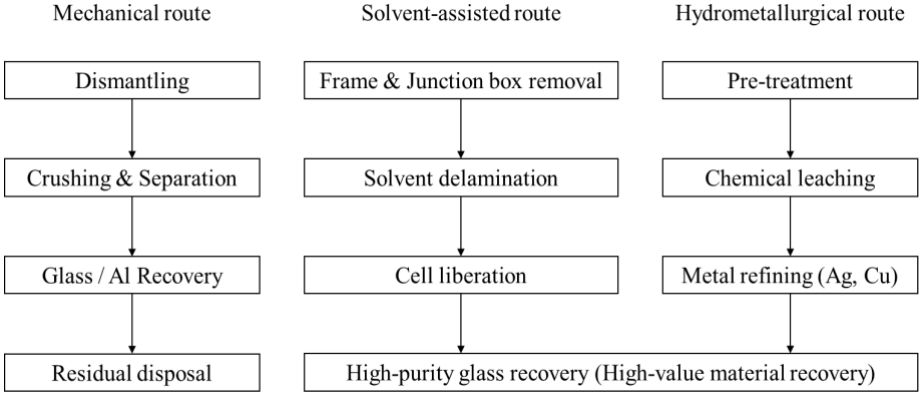

Figure 4. Comparative photovoltaic module recycling process routes and material recovery pathways.

Table 2. Benefits and limitations of major photovoltaic module recycling pathways

Recycling pathway	Key processes	Benefits	Limitations	Policy implications
Mechanical	Dismantling, crushing, physical separation	Low chemical input; scalable; lower cost	Limited recovery of Ag and Cu; lower material purity	Suitable for baseline recovery; requires downstream controls
Solvent-assisted	Delamination using organic solvents; cell liberation	Higher glass purity; improved cell recovery	Solvent management required; higher energy use	Appropriate where environmental safeguards exist
Hydrometallurgical	Chemical leaching and metal refining	High recovery rates for Ag, Cu; high value capture	Capital- and chemical-intensive; requires skilled operation	Best governed through performance-based accreditation

Table 3. Indicative techno-economic characteristics of major photovoltaic module recycling pathways

Recycling pathway	Key process features	Indicative energy demand	Major cost drivers	Achievable material recovery
Mechanical dismantling	Physical separation, crushing, screening	Low to moderate	Labor, logistics, mechanical equipment	High glass and aluminum recovery; limited precious metal recovery
Thermal delamination	High-temperature treatment to remove encapsulants	High	Energy input, emission control systems	Improved cell liberation; moderate metal recovery
Solvent-assisted delamination	Organic solvent-based encapsulant removal	Moderate	Solvent management, energy, safety controls	High-purity glass and cell recovery
Hydrometallurgical processing	Chemical leaching and metal refining	Moderate to high	Chemicals, effluent treatment, skilled operation	High recovery rates for silver, copper, and other metals

5. Comparative Analysis: Taiwan Vs. Thailand

5.1 Governance Architecture and Policy Intent

About Reflective practice 5 5.3 Practice hopefully helps 12 5 4 Practice is key 12 6 Indicators of practice and reflection 12 6.1 Reflective practice on all levels-Environmental, Curriculum, Personal, Institutional, Organisational and systems 15 6 2 Indicators at the classroom level 20 6 3 Indicators at the class level 23 6 4 Indicators at the school level 24 6 5 Indicators at the school level Taiwan has established an EPR system that is relevant for PV based on the Waste Disposal Act and implemented through a special Recycling Fund and the Photovoltaic Waste Information System (PVIS). This system integrates a fee collection mechanism, mandatory life cycle registration and approved handlers, and allows the regulators to continue to oversee the system from installation to end-of-life (MOENV, 2020, 2021). In contrast to this, the development of its power sector policy is very rapid in Thailand, particularly the draft Power Development Plan 2024 (PDP 2024) which aims at around 51% renewable electricity by the year 2037, and the planned removal of the factory-license requirement for rooftop PV in late 2024. However, an EPR law that is specific to PV has yet to be implemented (Climate Policy Database, 2025; Nishimura & Asahi, 2025; Tilleke & Gibbins, 2025). As a result, Taiwan is "already operational" while Thailand is "policy-enabling on the generation side but nascent on EoL" (MOENV, 2020, 2021; Climate Policy Database, 2025; Nishimura and Asahi, 2025; Tilleke and Gibbins, 2025).

5.2 Financing Model Economic Signals

Taiwan's design of the fee (BTW, a one-off NT$1,000 each/kW at sale/installation), internalizes EoL costs up-front and capitalizes the Recycling Fund, the contract for take-back and domestic treatment (MOENV, 2021). Task-12 technical syntheses the importance of occasionally renormed fees and by transitioning into eco-modulation to remunerate designs that cleanse the value specifications for lower delamination energy and higher high worthful recoveries (IEA PVPS Task 12, 2024). Thailand has yet to define PV-module obligations or a mechanism for financing. EPR-related bills (WEEE and the Draft Industrial Waste Management Act) are still on the draft/consultation stage and will dictate whether Thailand implements capacity-based fees, eco-modulated levies, or producer responsibility organization (PRO) models (Enviliance, 2024; Baker McKenzie, 2025). (MOENV, 2021; IEA PVPS Task 12, 2024; Enviliance, 2024; Baker McKenzie, 2025).

5.3 Traceability and Data Systems

Systems of traceability and data PVIS provides Taiwan traceability at a unit level: developers are required to register

installations, stick stickers and submit applications for retirement that connect certain modules with accredited handlers. This helps in making it more enforceable and to plan (MOENV, 2020; PVIS, 2025.). IEA PVPS guidance identifies digital tagging, e-manifesting and panel-level serialization as best practice across rooftop-dominant markets (IEA PVPS Task 12, 2024). Thailand currently does not have any PV specific registry or e-manifest stack for PV waste transfers, and so designing one in conjunction with any EPR law would be a key to preventing leakage to informal channels. (MOENV, 2020; PVIS,2025.; IEA PVPS Task 12, 2024).

5.4 Treatment Capacity and Technology Readiness

Taiwan has accredited domestic lines that are a combination of mechanical dismantling and thermal delamination; the public briefing has shown the system's ability to handle routine volumes and short-term spike deal loads after extreme weather conditions, and pilot research has been focused on designs that are easy to disassemble and encapsulant removal systems that are lower impact (EnergyTrend, 2021; pv magazine, 2022). Thailand's dedicated PV EoL capacity is minimal suffice policy fora and feasibility studies which indicate modeled mechanical recycling lines, but limited commercial plants, thus need standards, accreditation and investment PMUC/MHESI (2024, and 2025); Sukaviriya (2025) (EnergyTrend, 2021; pv magazine, 2022; PMUC/MHESI, 2024, 2025; Sukaviriya, 2025).

5.5 Enforcement Context and Cross-Border Constraints

Thailand has tightened the controls on the import of E-Waste, which creates a larger list of forbidden items in 2025 & it is implementing stricter controls enforcing the law, narrowing the on cross-border option for disposal of E-Waste and leading to a premium on the way for E-Waste disposal in Thailand (compliant routes) (The Nation Thailand, 2025; AP News, 2025). Taiwan's, in contrast, already channels flows to accredited domestic flows through the Recycling Fund. For Thailand, a process of matching import controls to domestic treatment expansion and EPR implementation will be required so as not to unintentionally stockpile or leak. (The Nation Thailand, 2025; AP News, 2025).

5.6 At-a-glance synthesis (policy technology alignment) Policy Framework

Currently in Taiwan, the Extended Producer Responsibility (EPR) and Photovoltaic Information System (PVIS) are in operation. On the other hand, in Thailand, reforms on the generation side are moving ahead with the Power Development Plan (PDP) 2024 and removal of rooftop licensing, although the End-of-Life (EoL) legislation is still pending (MOENV, 2020, 2021; Climate Policy Database, 2025; Tilleke & Gibbins, 2025). Financing Mechanisms: Taiwan has established a capacity-based fee of US$32.56/kW, which goes to a Recycling Fund. In contrast, Thailand is yet to set up a photovoltaic-specific fee, and EPR drafts continue to be deliberated (MOENV, 2021; Enviliance, 2024; Baker McKenzie, 2025). Traceability Measures: Taiwan requires registration of panels and filing of retirement documents with the PVIS, while Thailand does not have a national photovoltaic registry and electronic manifest system (PVIS, n.d.; IEA PVPS Task 12, 2024). Treatment Preparedness: Taiwan has accredited facilities and pilot projects that emphasized on enabling easy dismantling, of which Thailand is in the preliminary stages, conducting feasibility studies and promoting the establishment of domestic plants (EnergyTrend, 2021; pv magazine, 2022; PMUC/MHESI, 2024, 2025; Sukaviriya, 2025). External Constraints: In Thailand, import bans and increased enforcement measures heighten the need for the development of domestic capacity; in Taiwan, the material flows are strategically steered in the direction of domestic development (The Nation Thailand, 2025; AP News, 2025; MOENV, 2020).

5.7 Impacting on policy designs

The evidence of the comparative approach indicates a phased process of change for Thailand, another Sarawa of Taiwan's regime, reinning it's localized to Thai energy market actualities. Near-term priorities include: (i) legislation of PV-specific EPR, with a transparent, reviewable, fee schedule and defined scope/roles; (ii) ensuring of a national PV registry and witness e-manifest solution linked to installer licence and audit; and (iii) publishing of outcome-based treatment standards and capacity accreditation, utilizing FIT/auction eligibility/adders to remunerate fee-payment and documented EoL performance (IEA PVPS Task 12, 2024; Climate Policy Database, 2025; Tilleke & Gibbons, 2025). For Taiwan, the adoption of incremental improvements come adoption of eco-modulated fees, further disclosure of EoL flow data through PVIS, and further support of a higher-value Ag/Si recovery where the techno-economic is still marginal (IEA PVPS Task 12, 2024; MOENV, 2021).

6. Discussion: Opportunities and Challenges of Policy Transfer

The Taiwanese extended producer responsibility (EPR) model for photovoltaic (PV) modules is a potential good reference for Thailand, but policy transfer is not a mechanical exercise. Outcomes are dependent on the fit to the institutional setting, the market structure and socio-technical conditions of the recipient country (Majewski et al., 2021; World Bank, 2018). Effective transfer is, therefore, context sensitive. EPR requirements in Taiwan combine fee collection, life-cycle registration, and routing to accredited handlers within a single environmental authority that can oversee everything, from end-to-end, and offer enforceable take-back. Thailand's energy transition and waste governance are spread across a number of ministries. For an EPR law to work, a formal coordination arrangement - linking energy, natural resources, and environment, and industry portfolios - will be a necessary precondition to align flows of fees, data systems and compliance functions (Majewski et al., 2021; World Bank, 2018).

Designing technology pathways and standards. The current processing method of Taiwan focuses on mechanical dismantling combined with thermal delamination, which is in line with the existing treatment capacity and research direction in the country. As one of the late movers, Thailand can appraise emerging chemical routes (e.g. solvent-based delamination and selective leaching) that are still at the laboratory-to-pilot scale but show the potential to reduce energy inputs and increase the yield of high-value materials such as silver and silicon (Weckend et al., 2023). This calls for performance-based, instead of prescriptive, standards that determine recovery and quality of product (e.g., cullet quality, aluminum purity, Ag/Si yields) and are technology-neutral so as to allow for innovation (Majewski et al., 2021; Weckend et al., 2023).

Only one practical consideration, and that is just 'transition considerations'. A lack of appropriate management of PV waste, which potentially externalises risks for the low-income communities and labourers of informal recycling networks. International assessments emphasize the need for green transition strategies to incorporate both merely skills development and pathways of formalization to reduce the health risks and further boost sector productivity (International Labour Organization [ILO], 2019). Thailand's EPR design can include transitional measures (i.e. registrations and training for informal collectors as certified collection points or processing workers) that reduce the leakage and more equitably distribute the gains of the energy transition (ILO, 2019; World Bank, 2018). In sum, the experience of Taiwan shows the viability of linking fees, life cycle data, and accredited treatment in an EPR structure. For Thailand, to develop

PV end-of-life (EoL) governance in step with rapid generation side expansion, a context-specific transfer (i.e., inter-ministerial coordination, performance-based technical standards and inclusive integration of the informal sector) would be more likely to increase the chances for PV end-of-life (EoL) governance to mature (Majewski et al., 2021; Weckend et al., 2023; World Bank, 2018; ILO, 2019).

7. Future Pathways

7.1 Lessons from the Taiwan Experience

An example of how an end-of-life (EoL) regime for PV modules in Taiwan shows how an extended producer responsibility (EPR) statute, dedicated recycling fund, and a life cycle registry can be used in conjunction to achieve enforceable take-back. Key elements are: (i) upstream, capacity based fee to buoy a fund for collection and treatment, (ii) panel level registration and retirement filings which will be facilitated through a national platform (PVIS) that connects the units with accredited handlers and (iii) protocols for operation, which put the domestic treatment at the forefront where environmentally and economically a justifiable. Public documentation reveals the mechanism was launched in 2019-2021 with well-defined roles for energy and environment agencies, which is currently used to coordinate the logistics and compliance (MOENV, 2020, 2021). International technical work (IEA PVPS Task 12) facilitates such an architecture and recommends calibration of fees over time and so-called eco-modulation, allowing to match incentives with recyclability and high-value recovery (IEA PVPS Task 12, 2024).

To explain the difference between this reference model and the present Thai situation, Table 4 is a table structure to compare the governance of photovoltaic waste in Taiwan and Thailand from key institutional points. By comparing legal systems, funding systems, tracking systems, and treatment capacity, the table shines a light on the particular components operational and enforceable in Taiwan and fragmented or emergent in Thailand. This comparison is meant to define the policy gap that we deal with in the next section and to indicate which aspects of Taiwan's experience may be potentially transferable after adaptation to the institutional and market conditions of Thailand.

Table 4. Comparative overview of photovoltaic waste governance frameworks in Taiwan and Thailand

Dimension	Taiwan	Thailand
Legal framework	PV-specific EPR under Waste Disposal Act; mandatory compliance	No PV-specific EPR; reliance on general waste laws; draft WEEE Act and DIWMA
Financing mechanism	Prepaid recycling fee (per kW) paid at installation; centralized Recycling Fund	No dedicated PV recycling fee; financing mechanisms under consultation
Responsible authorities	Ministry of Environment (MOENV) with coordination from energy authorities	Multiple agencies (energy, environment, industrial works, local governments)
Traceability system	Mandatory registration via Photovoltaic Waste Information System (PVIS); unit-level tracking	No national PV registry; limited traceability across lifecycle
Treatment standards	Accredited recycling facilities with defined performance requirements	General industrial waste standards; no PV-specific accreditation
Domestic treatment capacity	Established and accredited facilities; pilot-scale operations demonstrated	Limited and emerging; feasibility studies ongoing
Informal sector role	Largely excluded from PV waste handling	Active in collection and pre-sorting, largely unregulated
Governance maturity	Operational and enforceable	Fragmented and transitional

7.2 Future Pathways for Thailand

Thailand is quickly progressing with its energy programs, with a goal of having about 51% of its energy from renewable sources by 2037. To help with this, the country has made the installation of solar panels on top of buildings more cost-effective by doing away with the need for a factory license. The next step is to put in place regulations for handling solar panel waste, perhaps as part of new waste management legislation. These laws will outline responsibilities for repairs, recycling, and other related tasks. Drafts are already under discussion and their enacting will improve the waste management. A fee should be levied when solar panels are installed to pay for the cost of managing the waste in the future and with periodic reviews like every two years to ensure that it is adequate. In Taiwan, a similar approach is used. A national registry for solar panels should be created, which tracks solar panels by codes associated with installer licenses and audits, like the system in Taiwan, and consistent with international recommendations.

Standards should be established for the recovery of materials from old panels to ensure the quality of materials recovered. A list of approved facilities should be compiled, and only these facilities should be allowed to handle waste. Reports show that there is an improvement in the method of recycling, and thus there is a need to update standards with new data. Companies should show they are meeting the regulations for their fees and waste management to become eligible for certain benefits, linking quick solar panel installation with responsible waste management. Public procurement should favour solar panels that are easy to dismantle and have fewer harmful materials. Companies should also annually disclose their waste management practices, which could help with market oversight and entry.

Thailand has added to the bans on the importation of e-waste in Thailand, and the enforcement in 2025 reduces the interim cross-border processing options, making it much more necessary to find compliant domestic routes and contracts. "EPR implementation should be sequenced with capacity accreditation and logistics planning to avoid stockpiling or leakages." The Nation Thailand, 2025; AP News, 2025. Competitive grants and cost-share pilots should be offered to help lower delamination energy, better EVA/POE removal, and put a larger yield on Ag/Si recovery, and data sharing would be part of the standards review cycle. Support needs to be coupled with deployment through eligibility into public procurement and utility programs. It is reiterated in the international literature that high-value recovery economics are marginal without such policy signals, despite areas in which mass-based recovery (glass/Al) is already well above 90%.

7.3 A Proposed EPR Governance Model for PV End-Of-Life Management in Thailand

Drawing on comparative analysis of the operational experience from Taiwan (Section 7.1) and the policy instruments examined for Thailand (Section 7.2), in this study, a conceptual governance model for a photovoltaic (PV)-specific extended producer responsibility (EPR) system for Thailand's institutional and market context is to be synthesized. Rather than adding further policy elements, the model builds on the previously identified legal, financial, digital and social components in a coherent system architecture, which is intended to support enforceable take-back, traceability, and environment-friendly end-of-life (EoL) management. At the heart of the proposed model is an eco-modulated financing mechanism, where contributors, producers and importers send recycling fees, which are determined based on various features of module design, ease of recyclability, and expected treatment costs. Such modulation is based on international EPR practice and helps overcome the flaws of flat, capacity-based fees, by finding the right fit between economic signals and design-for-recycling objectives. Fee revenues are collected in a special national recycling fund that provides a source of financing for the certified collection, treatment, and compliance monitoring functions under the oversight of the public.

A second building block of the governance model is the creation of a national PV registry that is linked to an electronic manifest (e-manifest) system. Mandatory registration at the installation stage ensures that unique identifiers to PV modules are assigned, while e-manifest reporting monitors the movement of PV modules at the end of life. This digital infrastructure delivers unit-level traceability, allows enforcement, and enables regulators to monitor materials flows, treatment results, and compliance despite the predominantly rooftop-based market. In the proposed architecture, the registry becomes the major backbone of data for connections between the producers who are obligated to report and the accredited recyclers and regulatory authorities. Treatment and recovery operations are regulated by performance-based accreditation of recycling facilities. Rather than dictate particular types of technologies, the criteria for accreditation is outcome-oriented with standards for minimum rates of recovery, minimum quality of material, and environmental safeguards. This way, technological flexibility can be achieved while ensuring that public funds and flows financed through the EPR are directed only towards facilities that are able to meet set environmental and resource efficiency benchmarks.

Important to model the integrated pathways of waste collection by informal collectors and small-scale handlers, who are important to informal solid waste collection. Under the proposed framework, informal actors will be allowed to be involved as registered collection points or pre-sorting points, according to basic training, reporting obligations, and inter-linkage to accredited downstream facilities. This conditional integration is to limit discharge to uncontrolled channels, enhance data coverage, and support a just transition in the waste management industry. The overall institutional configuration of the proposed Thai PV EPR system - including connections between eco-modulated flows of fees, digital traceability, standards for performance-based recycling, and formalized roles for informal actors - is summarized in Figure 5. By bringing these elements together into one multi-level governance architecture, the model takes the set of policy pathways as outlined in Section 7.2 and converts this into an operational blueprint that can be implemented step-by-step in tandem with Thailand's further expansion of solar generation capacity.

While Figure 5 summarizes the institutional and governance architecture required to operationalize a PV-specific EPR framework in Thailand, the implications of such a framework for material flows and circular-economy outcomes warrant separate consideration. From a resource perspective, the effectiveness of EPR is ultimately reflected not only in regulatory compliance but also in whether end-of-life photovoltaic modules are redirected from dissipative disposal pathways toward closed-loop or high-value recovery routes.

Figure 6, therefore, conceptualizes a circular economy scenario for photovoltaic modules in Thailand under an EPR regime. Under this scenario, eco-modulated fees, mandatory registration, and e-manifest tracking function jointly to channel end-of-life modules into accredited collection, sorting, and recycling systems, including structured participation by registered informal collectors at the pre-treatment stage. Recovered secondary materials such as glass, aluminum, and metals are subsequently reintroduced into domestic or regional value chains, thereby reducing reliance on primary resources and mitigating environmental leakage. The figure emphasizes that circularity is not an automatic outcome of solar deployment, but rather a policy-contingent result that depends on the alignment of financial incentives, traceability infrastructure, and performance-based treatment standards. To further clarify the allocation of institutional responsibilities under the proposed PV-specific EPR framework for Thailand, Table 5 summarizes the respective roles of energy, environmental, industrial, and local authorities across key regulatory functions.

8. Conclusion

Drawing on the comparative analysis of the operational experience from Taiwan and the policy instruments studied for the case of Thailand, in this study, a conceptual governance model for photovoltaic (PV)-specific extended producer responsibility (EPR) system for the institutional and market context of Thailand is to be synthesized. Rather than incorporating additional policy elements, the model builds on the already identified legal, financial, digital, and social components in a coherent system architecture, which is supposed to support enforceable take-back, traceability, and environment-friendly end-of-life (EoL) management. At the heart of the proposed model is an eco-modulated financing mechanism, where contributors, producers, and importers send recycling fees,

which are determined based on various features of module design, ease of recyclability and expected treatment costs. Such modulation is based on international EPR practice and helps overcome the flaws of flat, capacity-based fees by finding the right fit between economic signals and design-for-recycling objectives. Fee revenues collected in a national recycling fund to finance approved collection and treatment in public oversight and certified compliance monitoring. A major part of this is the national PV registry linked to an electronic manifest system. Mandatory registration at the installation stage and e-manifest reporting give PV modules a unique identifier, which allows their traceability at the unit level and facilitates monitoring of the exact materials flow by the regulators, despite the rooftop-based market.

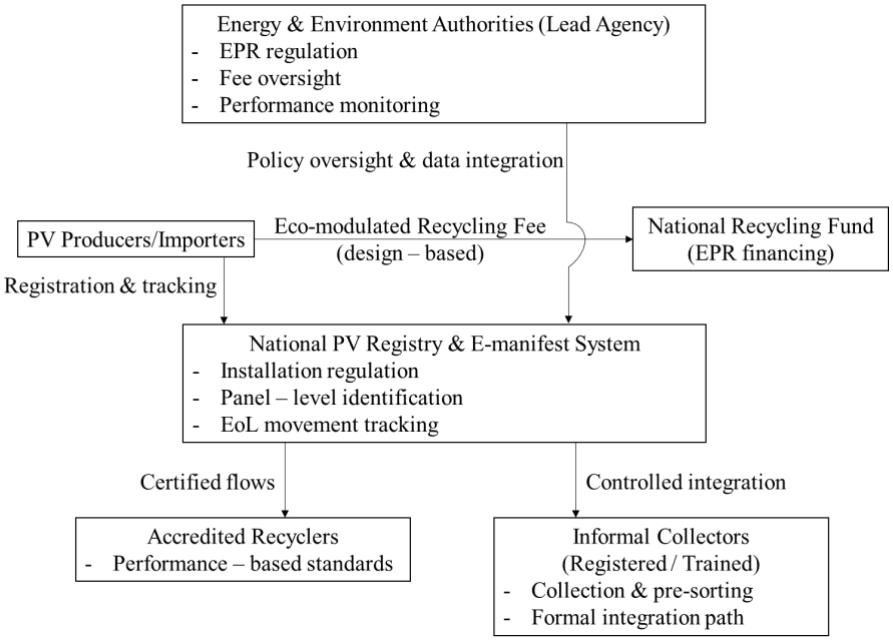

Figure 5. Conceptual governance model of a proposed PV-specific EPR system for Thailand

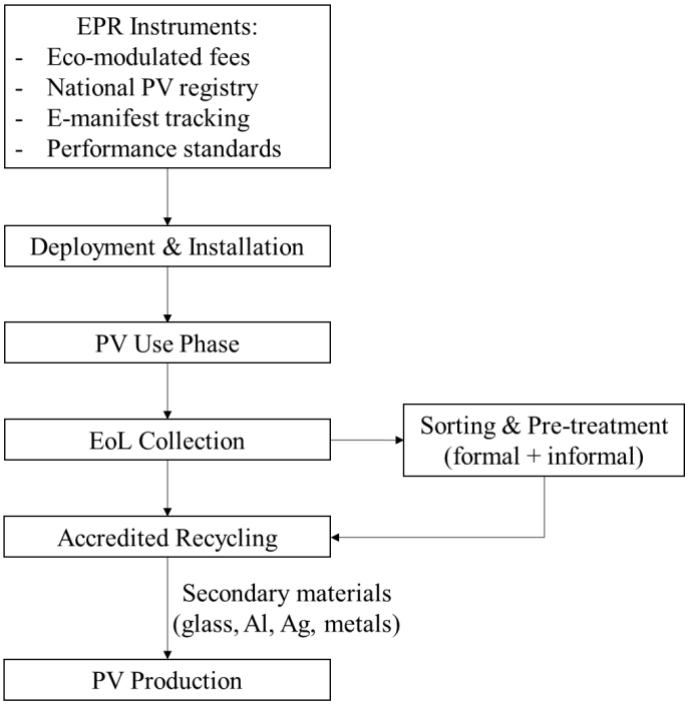

Figure 6. Circular economy scenario for photovoltaic modules in Thailand under an EPR regime

Table 5. Allocation of regulatory responsibilities for PV end-of-life governance under the proposed EPR framework in Thailand

Regulatory function	Energy authorities	Environmental authorities	Industrial works authorities	Local governments
PV deployment & market incentives	FIT, PDP, rooftop policy	-	-	-
EPR legislation & fee setting	-	EPR law, fee modulation	-	-
Recycling fund management	-	Fund administration	-	-
National PV registry & e-manifest	-	Data governance	-	-
Recycler accreditation & standards	-	Environmental criteria	Facility licensing	-
Monitoring & compliance	-	Audits & reporting	Plant inspections	Local enforcement
Informal sector integration	-	Registration & safeguards	-	Community-level coordination
Illegal dumping & enforcement	-	Penalties	-	On-site enforcement

The registry forms the data backbone for the producers, accredited recyclers, and authorities. Treatment operations are regulated by performance-based accreditation of recycling facilities, having outcome-oriented criteria for recovery rates, quality of material, and environmental protection. This ensures the technological flexibility, and it channels EPR-financed flows to facilities with minimum efficiency levels. The framework provides opportunities for informal collectors and handlers to become part of the registration to act as collection / pre-sorting points with training and reporting requirements. This integration helps limit uncontrolled discharge, improve data coverage, and support the transition of this industry. The Thai PV EPR system confines laws that coordinate eco-modulated fees, digital traceability, performance-based recycling standards, with formalizing roles for informal actors into a multi-level governance architecture that provides an operational blueprint for its implementation alongside the expansion of solar capacity in Thailand.

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