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Repowering Without Removal: Field-Verified Multi-Year Outdoor Storage of Damaged Photovoltaic Modules on Agricultural Land in Czechia

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Abstract

Ground-mounted photovoltaic (PV) plants generate discrete end-of-life waste streams during repowering/revamping, yet damaged modules do not always leave the site. We document two field-verified case studies from Czechia, in which damaged PV modules remained stored outdoors on agricultural land after repowering/revamping. The two sites are treated as illustrative, field-verified cases rather than as a statistically representative sample of PV plants in Czechia or Europe. The sites were first identified during field visits in summer 2025, and a retrospective review of public CUZK orthophoto time series was then used to reconstruct when the stockpiles first became visible and whether they were still present in the latest available imagery. The stored module piles first became visible in 2022 and 2021 at the two sites, and were still present in summer 2025, corresponding to a minimum confirmed persistence of about 3 and 4 years, respectively. Orthophoto-based GIS supported by field photographs was used to quantify the land parcel area (19,560 and 22,100 m^2), PV plan-view area (4960 and 5080 m^2), storage footprint (109 and 100 m^2), approximate stored module count (~1800 and ~2000), and stored mass (39.6 and 36.0 t). Using site-specific module footprints and a representative 30-module stack, the local stack-based pressures were calculated to be 3.92 and 3.26 kPa, respectively. Soil chemistry, leachate, and groundwater were not measured; therefore, the environmental implications should be interpreted as precautionary risk and as a need for monitoring, not as measured contamination at the two sites. The study shows that repowering/revamping can create a multi-year gap between module replacement and actual site clearance, during which recycling and final disposal are effectively delayed.

Keywords: photovoltaic waste; repowering/revamping; delayed end-of-life management; agricultural land; outdoor storage; WEEE; circular economy; GIS; orthophoto time series; accountability

Academic Editor: Giulio Mario Cappelletti

Received: 13 April 2026
Revised: 18 May 2026
Accepted: 25 May 2026
Published: 2 June 2026

1. Introduction

Photovoltaic (PV) deployment has expanded rapidly worldwide, and the corresponding end-of-life (EoL) waste stream is expected to grow substantially over the coming decades [1–3]. Global projections indicate that PV waste will rise from today's relatively small quantities to millions of tonnes under future loss and lifetime scenarios [1]. EU-focused material-flow assessments provide an order-of-magnitude context: cumulative PV waste is projected to reach 6–13 million tonnes by 2040 and 21–35 million tonnes by 2050, with annual PV waste reaching approximately 0.9–1.5 Mt by 2040 and 2.1–2.5 Mt by 2050 [2]. More recent comparative work likewise projects very large PV waste volumes for the European Union and the United States and shows that the regulatory architecture strongly affects whether the material is recycled, stored, or lost from circular use [3].

In the European Union, photovoltaic panels fall under the Waste Electrical and Electronic Equipment (WEEE) framework, while broader waste concepts, such as waste, waste producer, waste holder, permitting, and record-keeping, are governed by the Waste Framework Directive [4,5]. Under Article 3 of Directive 2008/98/EC, a PV panel becomes waste when its holder discards it, intends to discard it, or is required to discard it [4]. Directive 2012/19/EU then requires separate collection and proper treatment of waste photovoltaic panels within the WEEE system [5]. Commission Implementing Regulation (EU) 2019/290 harmonizes the registration and reporting of producers of electrical and electronic equipment, while Commission Implementing Decision (EU) 2019/2193 lays down rules for WEEE data calculation and reporting, including separate reporting of photovoltaic panels within sub-category 4b [6,7]. EU law therefore structures producer registration and aggregated waste reporting, but it does not create a central EU register of individual photovoltaic plants as plant-level waste sources.

Practical EoL management remains constrained by logistics and economics, especially for dispersed waste streams, damaged laminates, and low-value fractions such as polymeric backsheets and encapsulants. Recycling reviews consistently note that recycling performance and economics are affected by laminated structures and heterogeneous designs across generations and that the separation of polymer layers remains challenging [8–14]. These constraints can make immediate removal unattractive or difficult in practice. Possible drivers of prolonged onsite storage include transport and collection costs; limited short-term economic value of damaged modules; delayed access to suitable recycling capacity; uncertainty over responsibility between plant operators, landowners, maintenance contractors, and producer-responsibility schemes; and the difficulty in handling cracked, mixed, or weathered modules. In the present study, these are treated as literature-informed explanatory categories rather than verified site-specific causes, because operator interviews and contractual records were not available.

Repowering/revamping in this study refers to the partial or full replacement of aging PV plant components, most commonly PV modules and often inverters, at an existing site while the site and grid connection are retained in order to restore or improve plant performance. The term is central here because repowering/revamping creates a discrete waste-generating event at an operating PV site and explains why batches of damaged modules can remain at the same agricultural location after module replacement. Failure-mode syntheses and field observations demonstrate that some module populations can experience substantial failures earlier than the commonly cited 25-year lifetime, with practical consequences for maintenance, replacement, and repowering/revamping decisions [15–18].

Ground-mounted PV systems on agricultural land include both purpose-built agrivoltaic systems and more conventional solar farms on agricultural parcels managed as grasslands. Agrivoltaics is promoted as a sustainability concept enabling dual land use for energy and agricultural production [19,20]. However, across both agrivoltaic and solar-farm settings, PV structures can reshape the microclimate and redistribute rainfall, while stormwater management has become an important environmental topic for solar farms [21–23]. Within this land-use context, soil protection and vegetation management are key dimensions of sustainability.

https://doi.org/10.3390/su18115632

Agricultural land is also methodologically important. Open-air stockpiles can be independently reconstructed from public orthophoto time series, whereas storage inside warehouses or halls is far less transparent to external observers [24]. In Czechia, this observability is supported by the public CUZK orthophoto dataset, which is updated in a two-year cycle, with half of the national territory refreshed each year [24]. Agricultural land is therefore treated here as the observable fraction of a broader current storage problem. The general applicability of the present cases therefore lies less in statistical representativeness and more in the transferable observability of the phenomenon. Similar stockpiles on agricultural or other open land can be detected, dated, and quantified using the same minimum indicators: storage footprint, module count, stored mass, storage duration, storage interface, condition class, removal status, and responsible entity.

Delay is not environmentally neutral. Recent IEA PVPS work reports that long-term outdoor storage of first-life PV modules has, in some cases, led to additional degradation, including water infiltration, connector corrosion, and frame damage [25]. Official statistics likewise describe only waste that has already entered formal collection pathways; in Europe, 48,395 tonnes of PV module waste was collected from 18 countries in 2022 [26]. Collected waste and unresolved onsite stocks are therefore not the same thing. From a resource-recovery perspective, prolonged exposure may also reduce later reuse potential and increase the cost or difficulty of recycling, because water ingress, encapsulant ageing, corrosion, glass breakage, and soil contamination can complicate sorting, handling, and material separation.

The legal handling of such material also depends on classification. Under EU waste law, hazardous waste is waste that displays one or more hazardous properties; a waste PV panel is therefore not automatically hazardous solely because it is a PV panel [4]. Whether a particular waste panel is classified as hazardous depends on its composition and applicable waste-classification rules. In the present study, we did not assign a hazardous-waste code to the stored panels. However, because the modules were visibly damaged and remained outdoors directly on agricultural soil, precautionary handling within formal WEEE pathways is clearly justified.

In the peer-reviewed and institutional sources reviewed here, we found extensive work on PV waste volumes, WEEE regulation, recycling technologies, second-life degradation, toxicity assessment, and agrivoltaic land-use interactions [1–26]. By contrast, we did not identify a peer-reviewed study specifically focused on multi-year outdoor storage of damaged or used PV modules on agricultural land after repowering/revamping: this is the central novelty of the present work. The article therefore addresses a visible pre-collection gap between module replacement and actual site clearance, while also responding to recent calls for more traceable end-of-life systems for photovoltaic waste [27].

Therefore, the objectives of this article are to: (i) quantify the land parcel area, PV plan-view area, storage footprint, stored module counts, and stored mass using orthophoto-based GIS supported by field photographs; (ii) reconstruct the minimum confirmed persistence of onsite storage from orthophoto time series; (iii) interpret such storage as a visible pre-collection gap in PV end-of-life management after repowering/revamping; (iv) quantify both parcel-scale and local stack-based loading on soil using the actual module footprints; and (v) propose a minimal reporting and accountability framework that makes this practice visible for monitoring, management, and circular-economy planning. A further objective is to clearly separate measured indicators from precautionary environmental interpretation because this study did not include soil, leachate, or groundwater chemistry.

2. Materials and Methods

2.1. Case Study Sites and Anonymization

Two ground-mounted PV power plants in Czechia were selected on the basis of repeated observations of onsite storage of damaged PV modules on agricultural land within PV parcels. Because the authors do not have explicit permission from the plant operators and landowners to disclose the precise locations, both sites are anonymized and presented as Locality 1 (L1) and Locality 2 (L2). The studied installations are conventional ground-mounted solar farms located on parcels managed as grasslands rather than purpose-built elevated agrivoltaic crop-production systems. The practice is nevertheless relevant to both solar-farm and agrivoltaic contexts because it temporarily excludes agricultural land uses and shifts part of the EoL burden onto soil and vegetation management.

Because the sites were identified opportunistically and only two cases were analysed, this article does not estimate how common onsite storage is across PV plants. We therefore treat the two case studies as illustrative rather than representative. The purpose of the case selection was to document and quantify a field-verified phenomenon and to develop transferable indicators, not to infer national prevalence.

- Locality 1 (L1): Commissioned in 2010; nominal installed capacity of 0.861 MWp; repowered in 2022; land parcel area, A_{land} = 19,560 m^2.
- Locality 2 (L2): Commissioned in 2009; nominal installed capacity of 1.109 MWp; repowered in 2021; land parcel area, A_{land} = 22,100 m^2.

2.2. Field Observations and Photographic Documentation

Both sites were visited and photographed after repowering/revamping. The two sites were therefore not identified from desk analysis alone. They were first identified during field visits in summer 2025, when the authors directly observed damaged PV modules stored outdoors within fenced PV parcels. Field photographs were used to verify visible module damage, stack arrangement, storage interface, and the fact that storage occurred directly on grass/soil. The stored modules were visibly damaged, including cracked backsheets and/or broken front glass. Representative field photographs of the stored damaged modules are shown in Figure 1.

Figure 1. Anonymized field photographs showing damaged PV modules stored directly on grass/soil within fenced PV parcels.

2.3. Orthophoto-Based GIS Mapping of Plan-View Footprints and Storage Persistence

Orthophoto imagery from the Czech Office for Surveying, Mapping and Cadastre (CUZK) was used as the basis for GIS delineation [24]. For each site, we delineated three plan-view areas:

- A_{land} (m^2): total land parcel area of the PV plant parcel;
- A_{PV} (m^2): projected area occupied by PV panel rows/tables visible in the orthophoto;
- A_{store} (m^2): projected footprint occupied by stored PV modules placed on grass/soil.

These are 2D projected footprints and do not capture 3D stacking height, but they do represent the soil surface area that is directly covered and effectively unavailable for vegetation management.

A retrospective review of the public CUZK orthophoto series was used to determine when the stockpiles first became visible and whether they remained present in the latest available imagery [24]. Storage duration is therefore reported as a minimum confirmed persistence derived from dated evidence rather than as an exact storage start date. An anonymized schematic of the delineated PV plan-view area and stored-module footprint is shown in Figure 2.

Figure 2. Schematic delineation of PV plan-view area (A_{PV}) and stored-module footprint (A_{store}) at the two anonymized localities.

2.4. Estimation of Stored Module Counts and Stored Mass

Module counts were estimated from orthophoto interpretation cross-checked by field photographs. Because the modules were stored in visible piles with discernible stack arrangements, counts were estimated by: (i) counting the piles and their approximate base dimensions, (ii) estimating the number of modules per pile from the visible edges and stack height, and (iii) cross-checking the totals against the observed storage footprint. The counts should therefore be interpreted as approximate values.

The total stored mass was calculated as

$$M_{store}(t) = \frac{N_{store} \times m_{module}}{1000} \quad (1)$$

where N_{store} is the estimated number of stored modules and m_{module} is the documented module mass.

The installed module types were as follows:

- **L1 module type:** Solarfun SF220-30 series (e.g., SF220-30-1P220/SF220-30-P240). Nameplate mass: **22 kg/module**. The observed nameplate lists dimensions of **1652 × 1000 × 50 mm**.
- **L2 module type:** SunLink PV SL220-20P220. Nameplate mass: **18 kg/module**. The exact dimensions were not legible on the photographed label; for calculation purposes, the authors used the archived technical specification retained in the working calculation file: **1640 × 992 × 35 mm**. This technical sheet is not listed as a formal bibliographic reference.

All module masses used in the calculations are reported in kg/module, and all total stored masses are reported in tonnes.

2.5. Parcel-Scale Footprint-Averaged Loading

To indicate the order of magnitude of the mechanical burden associated with on-soil storage at the parcel scale, we calculated the footprint-averaged surface loading over the mapped storage footprint A_{store},

$$L_{Astore}(kg\,m^{-2}) = \frac{N_{store} \times m_{module}}{A_{store}} \tag{2}$$

and the corresponding footprint-averaged pressure:

$$q_{Astore}(kPa) = L_{Astore} \times \frac{g}{1000} \tag{3}$$

where $g = 9.81\,m\,s^{-2}$.

This metric is a parcel-scale average across the mapped occupied storage area. It does not represent the local pressure beneath a single stack resting on soil.

2.6. Stack-Based Local Loading Using the Real Footprints of the Installed Modules

All arbitrary representative square footprints were removed from the loading analysis. To represent the direct burden on soil more realistically, we calculated a **stack-based local loading metric** using the **actual plan-view footprint of one module** and a representative stack of **30 modules** placed flat one above another on grass/soil.

For the two installed module types,

$$A_{panel,L1} = 1.652 \times 1.000 = 1.652\,m^2 \tag{4}$$

$$A_{panel,L2} = 1.640 \times 0.992 = 1.62688\,m^2 \tag{5}$$

For a representative stack of $n_{stack} = 30$ modules,

$$M_{stack} = n_{stack} \times m_{module} \tag{6}$$

$$L_{stack}(kg\,m^{-2}) = \frac{M_{stack}}{A_{panel}} \tag{7}$$

$$q_{stack}(kPa) = L_{stack} \times \frac{g}{1000} \tag{8}$$

For **L1**, this gives the following:

- $M_{stack} = 30 \times 22 = 660\,kg$;
- $L_{stack} = 660/1.652 = 399.5\,kg\,m^{-2}$;
- $q_{stack} = 3.92\,kPa$.

For **L2**, this gives the following:

- $M_{stack} = 30 \times 18 = 540\,kg$;
- $L_{stack} = 540/1.62688 = 331.9\,kg\,m^{-2}$;
- $q_{stack} = 3.26\,kPa$.

The plausibility of the 30-module stack assumption was checked against mapped A_{store} and N_{store}. The implied mean stack size if all modules were distributed uniformly over A_{store} is

$$n_{implied} = \frac{N_{store} \times A_{panel}}{A_{store}} \tag{9}$$

yielding approximately **27.3 modules per stack** at L1 and **32.5 modules per stack** at L2. A 30-module stack therefore represents a realistic mid-case for both localities.

2.7. First-Order Stress Screening with Depth

To avoid an oversimplified interpretation based only on surface-loading metrics, a light mechanical screening of the vertical stress increment within the soil profile beneath the centre of the loaded footprint was added. The stress increment beneath the centre of a uniformly loaded rectangle was calculated by numerical integration of the Boussinesq point-load solution over the **actual module footprint** of each locality. Classical influence-chart formulations for rectangular loads are given by Fadum and Newmark [28,29].

The resulting vertical stress increment can be written as

$$\Delta\sigma_z(z) = q_{stack} \cdot I(B, L, z) \tag{10}$$

where $I(B, L, z)$ is the depth-dependent influence factor for a uniformly loaded rectangle of width B, length L, and depth z beneath the centre.

This screening is not a substitute for site-specific geotechnical assessment, because actual soil response depends on soil type, soil moisture, load duration, and any associated trafficking [30,31]. It is included only to provide a first-order profile of how the local stack load attenuates with depth when the **real module footprints** are used.

2.8. Literature-Informed Interpretation of Prolonged Onsite Storage

Potential reasons for prolonged onsite storage are interpreted via a literature-informed framework rather than site-specific contractual data. Prior work on PV end-of-life management supports recurring categories of constraints that can delay off-site treatment:

(i) Technical constraints of PV module recycling [8–14];

(ii) Technoeconomic and logistical constraints, where collection, transport, and processing costs can dominate [9–11];

(iii) System-level needs for stronger traceability and accountability in EoL governance [26,27].

In addition, damaged modules stored after repowering/revamping may have lower reuse potential and more uncertain material value than intact modules removed under controlled conditions. Outdoor exposure can accelerate water ingress, corrosion of connectors and frames, degradation of encapsulants and backsheets, and glass breakage. These factors do not necessarily prevent recycling, but they can increase handling, sorting, and pretreatment requirements, and may reduce the economic attractiveness of later resource recovery.

2.9. Environmental Measurements and Technology-Scope Statement

No soil chemistry, leachate, or groundwater measurements were conducted at L1 or L2. The present study therefore does not provide site-specific analytical evidence of contamination, nor does it quantify the concentration of metals, metalloids, or other substances in the soil or water. Therefore, environmental interpretation is limited to documented exposure conditions—damaged modules stored outdoors directly on grass/soil for several years—and to risks discussed in the literature.

The observed modules were crystalline-silicon PV modules. The footprint, mass, and persistence indicators proposed here can be applied to other PV technologies, but the toxicity and recycling interpretation must be technology-specific. In particular, CdTe and perovskite modules may involve different hazardous constituents, degradation pathways, recycling routes, and monitoring priorities compared to crystalline-silicon modules. For this reason, future applications of the framework should record module technology or material class as a mandatory indicator.

3. Results

3.1. Plan-View Footprints, Persistence, and Stored Module Counts

Stored module piles were first visible in the **2022 orthophoto at L1** and in the **2021 orthophoto at L2**, and remained present in **summer 2025**, corresponding to a minimum confirmed persistence of approximately **3 years** and **4 years**, respectively. The key empirical result is therefore not only that outdoor storage occurred, but that it **persisted for years after repowering/revamping**. Table 1 summarizes the site characteristics, plan-view occupation metrics, mass estimates, and both parcel-scale and stack-based loading indicators.

Table 1. Site characteristics, storage indicators, and loading metrics for onsite stored PV modules after repowering/revamping.

Metric	Locality 1 (L1)	Locality 2 (L2)
Commissioned/repowered	2010/2022	2009/2021
Nominal capacity (MWp)	0.861	1.109
Land area A_{land} (m^2)	19,560	22,100
PV plan-view area A_{PV} (m^2)	4960	5080
Storage footprint A_{store} (m^2)	109	100
A_{store}/A_{land} (%)	0.56	0.45
Approximate number of stored modules N_{store} (pcs)	~1800	~2000
Module model	Solarfun SF220-30 series	SunLink PV SL220-20P220
Nameplate mass m_{module} (kg/module)	22	18
Real panel footprint A_{panel} (m^2)	1.652	1.6269
Stored mass M_{store} (t)	39.6	36.0
Stored mass per MWp (t/MWp)	46.0	32.5
Mean parcel-scale loading over A_{store} (kg/m^2)	363	360
Mean parcel-scale pressure q_{Astore} (kPa)	3.56	3.53
Implied mean stack size from A_{store} and N_{store} (modules/stack)	27.3	32.5
Representative stack size used for local loading (modules)	30	30
Stack-based local loading L_{stack} (kg/m^2)	399.5	331.9
Stack-based local pressure q_{stack} (kPa)	3.92	3.26
First orthophoto showing stored module piles	2022	2021
Latest confirmation of onsite presence	Summer 2025	Summer 2025
Minimum confirmed storage persistence	~3 years	~4 years
Storage interface	Directly on grass/soil	Directly on grass/soil
Observed condition class	Visibly damaged	Visibly damaged
Removal status as of summer 2025	Still present	Still present

Note: Module counts are approximate; module mass is reported in kg/module, total stored mass in tonnes, and pressure in kPa.

3.2. Stored Mass and Loading Metrics

Using the documented module masses, the stored mass was estimated as **39.6 t** at L1 (≈1800 modules) and **36.0 t** at L2 (≈2000 modules) (Table 1). Normalized by nominal installed capacity, this corresponds to **46.0 t/MWp** at L1 and **32.5 t/MWp** at L2.

At the parcel scale, the mapped Astore values yielded footprint-averaged surface loadings of **363 kg/m^2** (L1) and **360 kg/m^2** (L2), corresponding to mean parcel-scale pressures of **3.56 kPa** and **3.53 kPa**, respectively.

At the local stack scale, the real-footprint method gave **399.5 kg/m^2** and **3.92 kPa** at L1, and **331.9 kg/m^2** and **3.26 kPa** at L2. These stack-based values describe the direct burden beneath the stack footprint itself rather than the broader burden distributed over the mapped occupied area A_{store}.

The difference between the parcel-scale and stack-scale metrics is informative. Parcel-scale loading is controlled by the mapped occupied area A_{store}, whereas stack-based local loading is controlled by the actual footprint of one module and the chosen stack size. Because the implied mean stack size from A_{store} and *Nstore* is 27.3 at L1 and 32.5 at L2, the fixed 30-module stack aligns closely with the mapped geometry at both sites.

3.3. First-Order Stress Profile with Depth

Selected depth values for the vertical stress increment beneath the centre of the actual stack footprint are given in Table 2, and the continuous depth profiles are shown in Figure 3.

Table 2. Vertical stress increment beneath the centre of the actual stack footprint at selected depths.

Depth z (m)	L1 Influence Factor I	L1 $\Delta\sigma_z$ (kPa)	L2 Influence Factor I	L2 $\Delta\sigma_z$ (kPa)
0.3	0.927	3.63	0.926	3.01
1.0	0.448	1.75	0.444	1.44
2.0	0.165	0.65	0.163	0.53

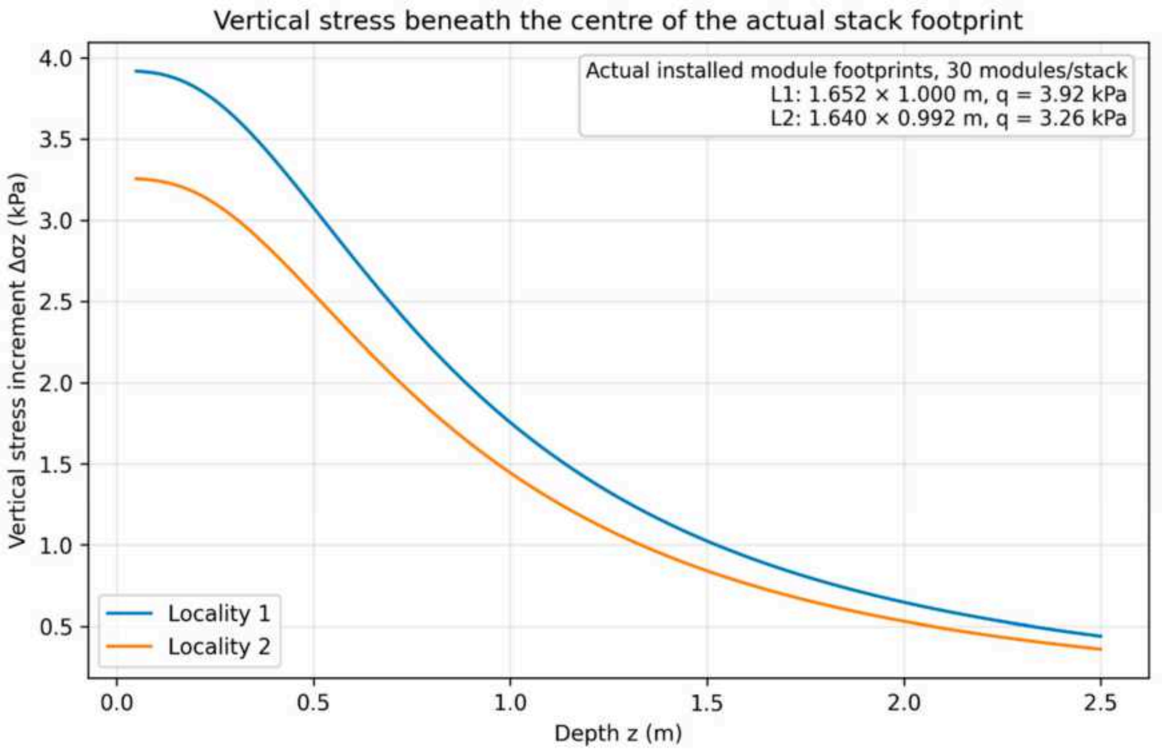

Figure 3. Vertical stress increment beneath the centre of the actual stack footprint, calculated for the real module footprints at Localities 1 and 2 using a representative 30-module stack.

At z **= 0.3 m**, the calculated stress increments were **3.63 kPa** at L1 and **3.01 kPa** at L2.

At z **= 1.0 m**, they decreased to **1.75 kPa** and **1.44 kPa**, respectively.

At z **= 2.0 m**, they were **0.65 kPa** and **0.53 kPa**, respectively.

These values remain in the kPa range and demonstrate gradual attenuation with depth beneath the centre of the real stack footprint.

4. Discussion

4.1. Repowering/Revamping Without Removal: A Visible Pre-Collection Gap

The main finding of the present study is not primarily a soil-mechanics result but one related to **repowering/revamping without removal**. The damaged PV modules had left service, yet they had not left the generating site. This makes the observed stockpiles a **current waste management issue** rather than merely a future recycling issue. The two cases therefore document a visible **pre-collection gap** in PV end-of-life management.

In the present cases, recycling or final disposal was not actually taking place during the storage period. The modules remained physically stored outdoors on the original agricultural parcels for a minimum of approximately 3–4 years, which means that they had not yet entered formal collection and treatment pathways as of summer 2025. In this sense, repowering/revamping solved an immediate operational problem at the PV plant, but it did not resolve the end-of-life handling of the replaced modules.

The two cases should not be interpreted as evidence that such storage is widespread at all PV plants. They do, however, show that the practice is technically possible, externally observable, and quantifiable. This distinction is important: the article provides evidence of occurrence and a measurement framework, not a prevalence estimate.

4.2. Why 3–4 Years Matter: Timing Compression of the Waste Problem

The documented 3–4-year persistence is not just an administrative delay. It also reveals a temporal mismatch between the **nominal service-life narrative** of PV modules and the **actual timing of waste appearance** in the field. While module lifetimes are often framed around approximately 25 years, the two present localities were repowered after only about 12 and 13 years of operation. Earlier-than-expected repowering/revamping therefore brings the waste stream forward in time [15–18].

This timing compression matters because collection planning, take-back arrangements, decommissioning budgeting, and practical responsibility chains are often implicitly framed around much longer service lives. The present study did not examine site-specific financing contracts or compliance-scheme records. However, it does show a general management risk: if module replacement occurs much earlier than originally expected, the waste stream can appear sooner than the practical removal and treatment arrangements are fully activated.

This may explain why long-term stockpiling can occur even in a regulated waste environment. Repowering creates an immediate physical surplus of modules, whereas transport, ownership clarification, collection scheduling, and recycling contracts may operate on a slower timeline.

4.3. Long-Term Storage on Agricultural Land as a Land and Soil Burden

The burden documented here is twofold. First, the stacks directly occupy agricultural land, suppress vegetation beneath them, and exclude the affected footprint from routine mowing and other management. Second, the modules impose a **persistent localized static load** on the same grass/soil footprint for approximately 3–4 years. This is not a neutral interim condition.

We did not directly measure bulk density, penetration resistance, infiltration, or soil chemistry, and therefore do not claim to have measured soil compaction or contamination.

However, long-term direct-on-soil storage clearly combines persistent surface coverage, vegetation suppression, localized static loading, and loss of routine management access. It should therefore be treated as both a **waste management problem** and a **land/soil burden**, especially under wet conditions or when combined with handling traffic [30,31].

The observed storage configuration is also noteworthy because the WEEE framework refers, for storage prior to treatment, to impermeable surfaces and weatherproof covering for appropriate areas [5]. The present study does not claim a site-specific legal finding, but directly-on-grass/soil outdoor storage is clearly the kind of visible configuration that deserves regulatory and managerial attention.

The mechanical results also make practical sense. Parcel-scale footprint-averaged pressures were only about 3.5 kPa, but this does not mean that the soil was unaffected. The relevant issue is **duration plus localization**: the load remained concentrated on the same small footprint for multiple years, while the same footprint was simultaneously covered, vegetation was suppressed, and routine management was excluded. The stack-based loading metrics and the depth profile therefore serve as transparent indicators of a persistent localized burden, not as proof of measured compaction.

4.4. Toxicity and Leaching: Risk, Not Measured Outcome

The environmental concern is therefore not only land occupation and vegetation suppression but also the fact that the damaged modules remained outdoors in direct contact with grass/soil for years. Reviews of solar PV module toxicity assessment show that PV modules can contain potentially hazardous constituents and emphasize the importance of appropriate testing and handling of module waste [32]. A European Commission study prepared for the WEEE recast also discussed leaching considerations for photovoltaic panels [33]. Independent work has examined the potential for leaching of heavy metals and metalloids from crystalline-silicon PV systems [34], and experimental work under worst-case natural scenarios has demonstrated leaching potential from real silicon solar cells as well [35].

The present study did not measure soil chemistry, leachate, or contaminant migration at either locality; therefore, toxicity is discussed here as a **precautionary risk** rather than as an observed site outcome. Nevertheless, prolonged outdoor storage of damaged modules directly on agricultural soil should be regarded as environmentally undesirable, especially when formal recycling or treatment has not yet begun.

Whether leaching has occurred at the two investigated localities cannot be concluded from the present data. Confirming actual site contamination would require targeted soil, leachate and/or groundwater sampling, preferably including background/control samples.

4.5. Module Technology Matters: Crystalline-Silicon, CdTe, and Perovskite Modules

The observed modules in this study were crystalline-silicon modules. This distinction matters because environmental risk and recycling challenges are not identical across PV technologies. Crystalline-silicon modules are commonly associated with glass, aluminium frames, silicon cells, metallization, encapsulants, and polymer backsheets. CdTe modules raise different material-specific questions because cadmium and tellurium are central constituents, and they may require technology-specific collection and recycling routes. Perovskite modules, especially lead-containing variants, raise different stability, leaching, and encapsulation questions. Therefore, the mass, footprint, and persistence indicators proposed here are broadly transferable, but toxicity and recycling interpretation must be technology-specific.

For this reason, future reporting of onsite PV module storage should record the module technology class at minimum: crystalline-silicon, CdTe, CIGS, perovskite, tandem, or unknown. Where possible, the bill of materials, nameplate information, and manufacturer-specific take-back route should also be recorded.

4.6. Delay Is Not Environmentally Neutral, and Accountability Matters

The 3–4-year persistence documented here is not just a waiting period. Recent IEA PVPS work reports that long-term outdoor storage of first-life PV modules can lead to additional degradation, including water infiltration, connector corrosion, and frame damage [25]. In other words, unresolved outdoor storage can further degrade already damaged modules. That matters for circularity, because delay can reduce reuse potential, worsen handling conditions, and degrade the quality of later treatment options.

Resource recovery is especially sensitive to module condition. Broken glass can increase handling hazards and contamination of material fractions. Water ingress and corrosion can affect contacts, frames, and junction components. Ageing of EVA and backsheets can make delamination or separation more difficult. Soil and biological contamination can increase cleaning, sorting, and pretreatment needs. These processes do not mean that recycling becomes impossible, but they can reduce the practical and economic value of recovery compared with timely collection and controlled storage.

A practical response is to standardize a minimal reporting and accountability set for repowering/revamping projects. The purpose of this would be not only to document how many modules are stored, but also to make responsibility, storage persistence, and removal progress visible. This is consistent with broader calls for traceable end-of-life systems for photovoltaic waste [27].

EU law already structures producer and waste reporting, but not as a plant-level EU register of individual PV power plants as waste sources [4–7]. That is one more reason why field-verifiable indicators are useful at project level. Orthophoto-based mapping and routine inspections can support scalable reporting and time-bounded storage rules, while remote sensing can strengthen broader environmental monitoring approaches [36]. Cleaner recycling routes and disassemblable module concepts may reduce some of these pressures in the longer term [37]. A proposed minimal reporting and accountability framework is summarized in Table 3.

Table 3. Proposed minimal reporting and accountability framework for PV modules stored onsite on agricultural land.

Indicator	What Should Be Recorded	Why It Matters
A_{store}	Plan-view footprint occupied by stored modules on soil/grass (m^2)	Shows direct land occupation and localized exclusion from management
N_{store}	Number of stored modules and counting method	Makes the waste stock visible and comparable
M_{store}	Stored mass (best estimate or range, with assumptions)	Supports logistics, treatment planning, and material-stock accounting
t_{store}	Minimum confirmed storage duration (months/years)	Distinguishes short interim handling from prolonged unresolved storage
Condition class	Intact/cracked backsheet/broken glass/delaminated/unknown	Indicates handling, safety, and treatment implications
Storage interface	On soil/on pallets/on impermeable pad/under cover	Shows degree of direct land contact
Land-use context	Grassland/arable land/agrivoltaic system/other	Links storage to actual agricultural function
Removal status	Awaiting collection/contracted/removed/treated	Improves traceability and accountability
Responsible entity	Operator/landowner/other identified party	Clarifies accountability

Table 3. *Cont.*

Indicator	What Should Be Recorded	Why It Matters
Evidence of contracted take-back	Yes/no/unknown	Indicates whether removal is actually progressing
Module technology/ material class	Crystalline-Si/CdTe/CIGS/perovskite/tandem/unknown; nameplate or bill-of-material evidence where available	Allows toxicity, leaching, and recycling challenges to be interpreted by module type
Environmental screening status	Whether soil, leachate, and/or groundwater sampling was conducted; sampling date; analytical method; analytes; background/control samples; result summary	Separates measured contamination from precautionary risk and supports future monitoring
Storage protection condition	Open-air/covered/weatherproof covering/impermeable surface/pallets/mixed condition	Shows whether storage reduces or increases weathering, leaching, and resource-recovery risks

4.7. Future Large-Scale Surveys and Sampling Needs

The next research step should be a larger-scale survey rather than another isolated case description. A practical workflow would include: (i) national or regional screening of orthophoto time series to identify visible PV-module stockpiles; (ii) field verification of selected sites, including module technology, condition class, storage interface, and removal status; and (iii) targeted environmental sampling at a smaller number of representative sites, including soil, leachate, and/or groundwater where appropriate. Such a design would allow future work to estimate prevalence, identify risk factors, and distinguish visible storage from measured environmental impact.

Large-scale surveys should also attempt to connect field-visible stockpiles with WEEE collection or take-back records where legally and practically possible. This would help determine whether long-term onsite storage reflects temporary logistics, unclear responsibility, limited treatment capacity, economic barriers, or other governance gaps.

5. Conclusions

The main conclusions are as follows:

1. **Repowering/revamping created a waste stream, but there was not immediate site clearance.** Damaged PV modules left service without leaving the generating site and remained stored outdoors on agricultural land for approximately 3–4 years.
2. **The methodological contribution lies in combining direct field visits, field photographs, retrospective orthophoto time-series reconstruction, parcel-scale GIS quantification, and local loading estimates based on the actual footprints of the installed panel types.**
3. **The practice documented here is both a waste management problem and a land/soil burden.** It delays transfer into formal WEEE pathways while simultaneously imposing persistent direct-on-soil occupation, vegetation suppression, and localized static loading.
4. **Long-term outdoor storage is not environmentally neutral.** It can further degrade already damaged modules and is associated with a precautionary risk of toxic substance release; although no soil chemistry, leachate, or groundwater measurements were performed in the present study.
5. **A practical response is minimal reporting and accountability.** Repowering/revamping projects should document at least the storage footprint, module count, stored mass, minimum confirmed storage duration, storage interface, condition class, removal status, and responsible entity.

6. The two sites should be interpreted as illustrative field-verified cases, not as a representative estimate of how common this practice is. The proposed indicators are intended for broader screening and monitoring.
7. Future work should add technology-specific reporting, especially for crystalline-silicon, CdTe, and perovskite modules, and should include soil, leachate, and/or groundwater screening where environmental impact needs to be substantiated analytically.

Author Contributions: Conceptualization: M.K. and V.P. Methodology: M.K. and V.P. GIS analysis: M.K. Investigation and field documentation: M.K. and V.B. Data curation: M.K. Formal analysis: M.K. and V.P. Economic/agronomic context: V.B. and T.F. Writing—original draft: M.K. and V.P. Writing—review and editing: all authors. Supervision: V.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Derived GIS area measurements and calculation sheets can be made available by the corresponding author upon reasonable request, subject to site anonymization constraints. No soil chemistry, leachate or groundwater dataset is available because such measurements were not conducted in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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