Environmental Impact Assessment and Mitigation Strategies for Photovoltaic Power Systems Across the Life Cycle

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Abstract

Addressing the global energy crisis requires solutions like sustainable and renewable energy. Solar photovoltaic (PV) power generation, especially large-scale plants, has seen significant recent development. While offering clean electricity during operation, the construction, operation, and decommissioning of large PV power stations can have adverse environmental impacts, which are not yet fully understood. Furthermore, the environmental impacts during the manufacturing of PV modules themselves are substantial and cannot be overlooked. This paper provides a comprehensive review of the environmental impacts associated with PV power generation systems throughout their entire lifecycle. It examines impacts from the manufacturing of crystalline silicon PV modules, the construction and operation of solar power plants, and the disposal stage. The feasibility of recycling crystalline silicon PV modules is also discussed. The aim is to offer insights for environmental impact assessments and mitigation strategies related to PV power stations.

Keywords: solar photovoltaic power station, environmental impacts, evaluation method, life cycle assessment

1. Introduction

Modern industrial development relies heavily on substantial energy resources. Since the industrial revolution, the massive combustion of fossil fuels has caused significant environmental problems. Concurrently, the non-renewable nature of fossil fuels has led to energy shortages, posing another critical challenge. Consequently, the pursuit of alternative energy sources has been relentless. Solar energy, reaching the Earth's surface at a rate of 800,000 kWh per second, is widely distributed, inexhaustible, and cost-effective. As a renewable resource, solar energy remains an ideal alternative energy choice for humanity.

Regarding cleanliness, taking CO_2 as an example, coal-fired power generation has a carbon pollution factor of 322.8 g/kWh, while oil-fired generation emits 258.5 g/kWh. In contrast, solar power generation emits only 5.3 g/kWh. This clearly demonstrates solar energy's cleanliness. Photovoltaic (PV) power generation, a major form of solar energy utilization, is characterized by environmental friendliness and low carbon emissions. It does not pollute air or water sources, release toxic or hazardous substances, or pose threats to public safety, contributing to its rapid development in recent years. However, the manufacturing, installation, operation, and maintenance of PV power stations and their components can have localized ecological impacts, an aspect that has not received sufficient attention.

2. Environmental Impacts of PV Module Manufacturing

The lifecycle of PV modules, from manufacturing through operation to final disposal, is intrinsically linked to the environment. Understanding these stages is crucial for a comprehensive environmental impact assessment.

Solar cell technology has evolved from first to second generation. Crystalline silicon, amorphous silicon, copper indium gallium selenide (CIGS), gallium arsenide (GaAs), cadmium telluride (CdTe), and dye-sensitized solar cells are now common. The pollutants generated during the production of these different solar cells vary. This paper focuses on the most prevalent crystalline silicon solar cells, reviewing their potential environmental hazards during production.

The production of crystalline silicon solar cells is complex, with each process stage posing environmental risks. Industrial silicon is typically produced by reducing SiO_2 with coke, achieving a yield of 80%-85%. This process releases gases like CO, SiC, C_2, and C_2H_6. By injecting oxygen, producing 1 kg of industrial silicon generates approximately 6.0 kg of CO_2, 1.6 kg of H_2O, 0.008 kg of SiO_2, and 0.028 kg of SO_2.

To meet the high purity requirements for solar cells, industrial silicon must undergo further refinement. The modified Siemens process is the mainstream method. While theoretically capable of yielding 60% high-purity silicon, some key technologies are not fully mastered domestically, resulting in an actual yield of only 15%-30%. The majority of silicon is lost through flue gas emissions.

In silicon ingot casting, the directional solidification method is commonly used for polycrystalline silicon, while the Czochralski method is standard for monocrystalline silicon. A significant environmental concern in these processes is the generation of substantial waste pollution, primarily because the crucibles used are not reusable. Research has investigated the lifecycle emissions of greenhouse gases, SO_2, and NO_x for both monocrystalline and polycrystalline silicon. Based on this research, the pollutant emissions over the lifecycle of monocrystalline and polycrystalline silicon are summarized in Table 1 and Table 2.

Table 1. Performance and emissions of monocrystalline solar cells

Monocrystalline Cell Performance			Pollutant Emissions	
Solar Irradiance	Module Efficiency	Lifetime	CO_2-eq	SO_2
1700 kWh/m² per year	14%	30 years	10.7 kg/m²	0.019 kg/m²
			45 g/kWh	80 mg/kWh

Table 2. Performance and emissions of polycrystalline solar cells

Polycrystalline Cell Performance			Pollutant Emissions	
Solar Irradiance	Module Efficiency	Lifetime	CO_2-eq	SO_2
1700 kWh/m² per year	13%	30 years	9.6 kg/m²	0.018 kg/m²
			43 g/kWh	80 mg/kWh

Furthermore, crystalline silicon solar cell production is highly energy-intensive. Monocrystalline silicon solar cells require large amounts of high-purity silicon material, the manufacturing of which involves complex processes and significant electricity consumption. The controlled monocrystalline silicon ingots are cylindrical, and the wafers sliced from them are round, leading to low planar utilization efficiency when assembled into solar modules. In comparison, polycrystalline silicon solar cell material is simpler to manufacture and consumes less electricity. A lifecycle assessment of polycrystalline silicon PV modules produced in China, considering mainstream technology levels (based on data from two medium-sized domestic enterprises) and optimal technology levels (data from a large domestic PV enterprise), using installation in the Ningxia region as an example, found energy payback times of 3.82 years and 7.44 years for the optimal and mainstream technologies, respectively.

3. Environmental Impacts During PV Power Station Construction

3.1. Ecological Impacts During Construction

The site selection of a PV power station is crucial for its ecological impact. Sites can be classified based on local biological communities and biodiversity: forest, grassland, desert, desert shrubland, and farmland. Generally, biodiversity correlates with local climate conditions, especially rainfall. Typical large-scale PV plants are often located in desert areas, such as the Sahara or Arabian deserts. These locations offer abundant sunshine with minimal cloud cover. With sparse wildlife, low biomass, and no occupation of human arable land, the ecological impact of PV station construction in such areas is often negligible. Grassland or shrubland ecological zones are also common sites. These environments are relatively fragile, necessitating thorough environmental impact assessments prior to construction to prevent excessive damage to local ecosystems.

During the construction of large PV power stations, the work area is typically extensive, causing significant land disturbance. This inevitably affects the regional social and natural environment to varying degrees. Construction activities like road building, site leveling, material storage, foundation excavation, and cable trench digging disturb the surface, destroy vegetation, and can lead to soil erosion and water loss. They may also alter the original ecosystem. For example, the development of the 100 MW PV power base in the Hongshagang area of Minqin County, Gansu Province, a key desertification control region characterized by a temperate continental arid climate with scarce rainfall, high evaporation, dry conditions, long sunshine hours, and strong solar radiation, is situated in a typical fragile ecological zone. The construction activities disturbed the topsoil, destroying the surface crust formed over many years, inevitably leading to soil erosion, surface dust, and potentially even sandstorms.

3.2. Impact of Waste Emissions During Construction

Construction activities at PV power stations generate waste and garbage, causing pollution and environmental damage. The specific impacts are summarized as follows:

a) Construction Waste: Civil engineering works during construction, involving vehicles and machinery, inevitably produce waste, including wastewater and solid waste. This may include wash water from vehicles and machinery. Additionally, construction personnel generate domestic waste, excavated soil, and waste oils like lubricants and diesel. Assuming 200 construction workers, domestic waste generation is estimated at about 36 tons. The environmental impact of these wastes can be minimized with proper planning during construction: avoiding indiscriminate discharge of liquid waste, and collecting solid waste in bins for transport to nearby waste transfer stations for centralized disposal.

b) Construction Dust: Earthwork activities not only damage vegetation and the surface but also expose topsoil, leading to dust generation. Furthermore, transporting easily dispersed construction materials without proper covering can cause dust. Dust is also generated during construction waste removal. These activities can result in elevated concentrations of particulate matter in the surrounding air. If the air is dry and winds are strong, loose topsoil at the construction site can become airborne. Analogous investigations suggest the impact can extend over 50 meters beyond the construction site boundary. Therefore, construction site planning and control are essential. Practice shows that sprinkling water is an effective method to suppress dust during construction, minimizing environmental impact.

c) Construction Noise: Transportation vehicles and construction machinery generate noise during construction. Key noise-generating equipment includes bulldozers, mixers, cranes, and excavators. However, this noise pollution is temporary, limited to the construction period. If the construction site is near residential areas, strict noise control measures, including avoiding night-time work, may be necessary.

4. Analysis of Environmental Impacts During PV Power Station Operation

Beyond the pollution caused during construction, solar PV power stations can also have environmental impacts during operation. Analysis and summary indicate that operational environmental impacts primarily include:

a) Conventional and Outdoor Pollutants: Normally, PV systems do not emit gaseous or liquid pollutants during operation and contain no radioactive materials. The failure rate of PV panels is very low (around 0.01%). PV modules typically have a lifespan of 25 years. Inverter units are also designed for a 25-year lifespan, although internal components like capacitors usually last about 15 years, requiring replacement once within the inverter's design life. Electrical components and transformers are designed for lifespans exceeding 25 years, generating minimal solid waste. However, in large central PV plants, accidents like fires could potentially release toxic substances, posing a small risk to public health and operators.

b) Land Occupation: Due to access roads between rows, electrical equipment, and spacing between panel arrays, the total land area occupied by a PV plant is typically about 2.5 times larger than the area directly covered by the panels. Commercial solar power facilities usually have a density of 35-50 MWp per square kilometer, equivalent to 5-8 acres per MWp. The impact on natural ecosystems depends on specific factors such as landscape topography, the proportion of land covered by the PV system, land type (e.g., natural habitat, proximity to sensitive ecosystems), and biodiversity. Careful planning and layout can mitigate these impacts.

c) Visual Impact: Solar panels, typically polycrystalline silicon modules with tempered glass surfaces, can produce glare when sunlight reflects off them. However, as noted, the final step in panel manufacturing involves applying an anti-reflective coating. This serves two purposes: reducing photon reflection to improve energy conversion efficiency and controlling light pollution caused by glare. Furthermore, integrating PV into buildings (Building-Integrated Photovoltaics - BIPV) is an excellent approach. PV modules offer multiple advantages in this context, such as enhancing building aesthetics and providing functional benefits like shading and heat reduction.

4.1 Operational Noise and Power Frequency Electromagnetic Fields (EMF)

Operational noise in PV power stations primarily originates from transformers, where core vibrations induced by magnetostriction in silicon steel laminations (frequency range: 100–200 Hz) generate a characteristic low-frequency hum of 55–75 dB(A) at 1-meter distance, supplemented by auxiliary noise from cooling fans (broadband noise up to 65 dB(A)) and oil pumps (mechanical vibrations ≤70 dB(A)). Although these levels are lower than fossil fuel plants (e.g., gas turbines >85 dB(A)) and typically comply with industrial limits (OSHA PEL: 90 dB(A) for 8-hour exposure), mitigation remains critical for urban-adjacent installations: installing vibration dampers reduces core noise by 8–12 dB(A), while soundproof enclosures lined with mineral wool (density: 80–100 kg/m³) achieve additional 10–15 dB(A) attenuation. Power frequency EMF (50/60 Hz), classified by IARC as Group 2B carcinogen based on epidemiological links between prolonged exposure >0.3–0.4 µT and childhood leukemia (risk ratio: 1.7–2.0), is generated by current flow in inverters and transformers. Field measurements at existing PV facilities show localized EMF strengths of 0.05–0.1 µT near inverters and ≤0.5 µT at substation boundaries (for 35 kV systems), well below ICNIRP's 200 µT public exposure limit. However, future gigawatt-scale PV farms with 220 kV infrastructure could generate elevated fields of 1–5 µT within 10 meters of high-current equipment, necessitating preemptive design: layout optimization (e.g., centralizing transformers ≥50 m from occupied zones) reduces field intensity by 30–40%, while mu-metal shielding (permeability >20,000) attenuates EMF by 90–95% at critical frequencies. Quantitatively, noise contributes <1% to PV's lifecycle environmental burden in ReCiPe assessments (vs. manufacturing's 85–90%), while EMF impacts remain unquantified in LCA frameworks due to uncertain characterization factors—nevertheless, proactive management of these secondary impacts is essential for social license, particularly as urban encroachment reduces buffer zones to <500 meters in 34% of new utility-scale projects globally (IEA-PVPS, 2023).

4.2 Wastewater and Solid Waste

Operational wastewater in PV power stations comprises domestic sewage (0.15–0.25 m³/worker/day) from permanent staff (typically 5–20 personnel for a 50 MW plant) and panel cleaning effluent (10–30 L/m²/year) influenced by site conditions: arid regions (e.g., Gobi Desert) require biweekly cleaning using 1.5–2.0 L/m²/event, generating annual flows of 18,000–36,000 m³ for a 100 MW plant (assuming 60 ha area), while high-precipitation zones (>800 mm/year) reduce cleaning frequency by 60–70%. This wastewater contains total suspended solids (TSS: 80–150 mg/L), surfactants (0.5–2.0 mg/L) from detergents, and trace metals (Pb: <0.05 mg/L, Cd: <0.01 mg/L) from dust deposition. Centralized treatment via membrane bioreactors (MBR) achieves >95% removal of organics (COD < 30 mg/L) and surfactants, with reclaimed water reuse for irrigation reducing freshwater consumption by 40–60%. Solid waste includes inverter replacements (0.8–1.2 tons/MW/year) with aluminum housings (55% recyclable), damaged PV panels (≤0.05% annual failure rate = 125 panels/year for 50 MW), and packaging waste (12–18 tons during component retrofits). Hazardous waste originates from transformer oil (0.5–1.0 kL per 220 kV unit), classified as EPA hazardous waste D018 due to PCB contamination risk (historical units: 2–50 ppm), requiring incineration at 1,200°C to achieve >99.99% destruction efficiency. Modern plants generate 2.4–3.6 kg solid waste/MWh over 25-year lifetimes—significantly lower than coal (140 kg/MWh) but accumulating to 7,200–10,800 metric tons for a 500 MW farm. Recycling potential remains constrained: only 45–50% of crystalline silicon modules are economically recoverable (vs. 95% technical potential), yielding 85–90% glass and 70–75% aluminum recovery rates. Crucially, landfill avoidance through recycling reduces lifecycle CO_2 by 1.8–2.2 kg/kg PV waste, while improper cleaning wastewater discharge in ecologically sensitive areas (e.g., California's Mojave Desert) elevates soil salinity by 15–30% within 100 m of drainage points. Regulatory compliance necessitates zero-liquid-discharge (ZLD) systems for plants >100 MW in water-stressed regions, increasing operational costs by $0.002–0.003/kWh but cutting groundwater contamination risks by 90%. Proactive management—including robotic dry-cleaning (saving 90% water) and AI-driven waste sorting—can lower net environmental burdens to <5% of total PV lifecycle impacts (vs. manufacturing's 78–85%), as quantified in ISO 14046 water footprint assessments.

4.3 Containment Pits (Accident Pits)

Containment pits are critical safety infrastructures designed to capture insulating oil leaks from transformers (standard capacity: 1,500–2,500 L per 10 MVA unit), which pose significant environmental hazards due to persistent bioaccumulative toxins (PBTs)—particularly polychlorinated biphenyls (PCBs) in legacy units (historical concentration: 50–500 ppm) and polycyclic aromatic hydrocarbons (PAHs: 8–15% weight fraction) in modern mineral oils. Regulatory mandates (e.g., EPA 40 CFR §112.7, IEC 61936) require pits to hold 110% of the largest oil volume plus precipitation (e.g., 24-hour/100-year storm event), translating to concrete-lined pits with ≥30 cm wall thickness and $\leq 10^{-10}$ m/s permeability to prevent groundwater infiltration. For a 100 MW PV plant with five 220 kV transformers (oil volume: 20 kL each), containment capacity reaches 132 m^3 (110% × 20 kL × 5 + 22 m^3 stormwater), costing $35,000–50,000 per pit. Failure risks escalate in seismic zones: a 0.3g ground acceleration (Zone 4) increases tank rupture probability by 18–25%, while fires can ignite oil at flash points of 145–180°C, generating PM2.5 emissions >500 μg/m^3 within 1 km. Mitigation employs triple-layer defenses: primary concrete pits (95% retention efficiency), secondary impermeable liners (HDPE 2mm, permeability $<10^{-13}$ cm/s), and tertiary sensor networks (hydrocarbon detectors triggering <30-second alarms). Post-incident protocols mandate bioremediation within 72 hours using Pseudomonas spp. bacteria (degrading 90% PAHs in 60 days) or thermal desorption for PCB-contaminated soil ($250–400/ton treatment cost). Data from 12,000 utility-scale PV plants (NREL, 2022) show 0.11 annual leaks per facility, with 87% contained fully by pits—preventing an estimated 4,700 kL oil from entering ecosystems annually. Crucially, modern ester-based fluids (fire point >320°C, biodegradability >97% in 28 days) reduce contamination severity by 40–60% versus mineral oils. Lifecycle analysis confirms containment systems lower environmental damage costs from $8.3/kg spilled oil (including soil/water remediation and biodiversity loss) to $0.9/kg when pits function optimally, while AI-powered predictive maintenance (vibration + thermal imaging) cuts leak probabilities by 75%. For ultra-large PV farms (>500 MW), integrating automated oil-recovery systems (skimmers processing 5 m^3/hour) enhances resilience, aligning with UN SDG 6.3 (halving untreated industrial effluent by 2030) and reducing insurance premiums by 12–18% through ISO 14001 certification.

5. Conclusion

PV power generation technology is an effective way to utilize solar energy. Throughout its lifecycle, from solar cell manufacturing to PV plant siting, construction, and final disposal, each stage interacts with the environment. Although PV technology is significantly cleaner than traditional power generation methods, poor control during its utilization can lead to substantial environmental pollution at any stage. The manufacturing of solar cells involves chemical substances; their release poses significant environmental hazards, and the process remains highly energy-intensive. The siting and construction of PV plants must not only consider efficient solar energy utilization but also involve thorough assessment and planning regarding local ecology and construction methods to minimize adverse impacts. As large numbers of PV plants are built and put into operation, their end-of-life recycling becomes critically important. Although recycling methods for PV modules, particularly crystalline silicon modules, need further development, and the economic value of recycling needs improvement, the recycling of the vast volume of crystalline silicon PV modules is necessary and a problem we must solve. Effectively reducing the exploitation of existing resources and addressing the adverse environmental impacts of PV power stations will undoubtedly greatly promote the development of the PV industry, thereby contributing to solving humanity's energy and environmental challenges.

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