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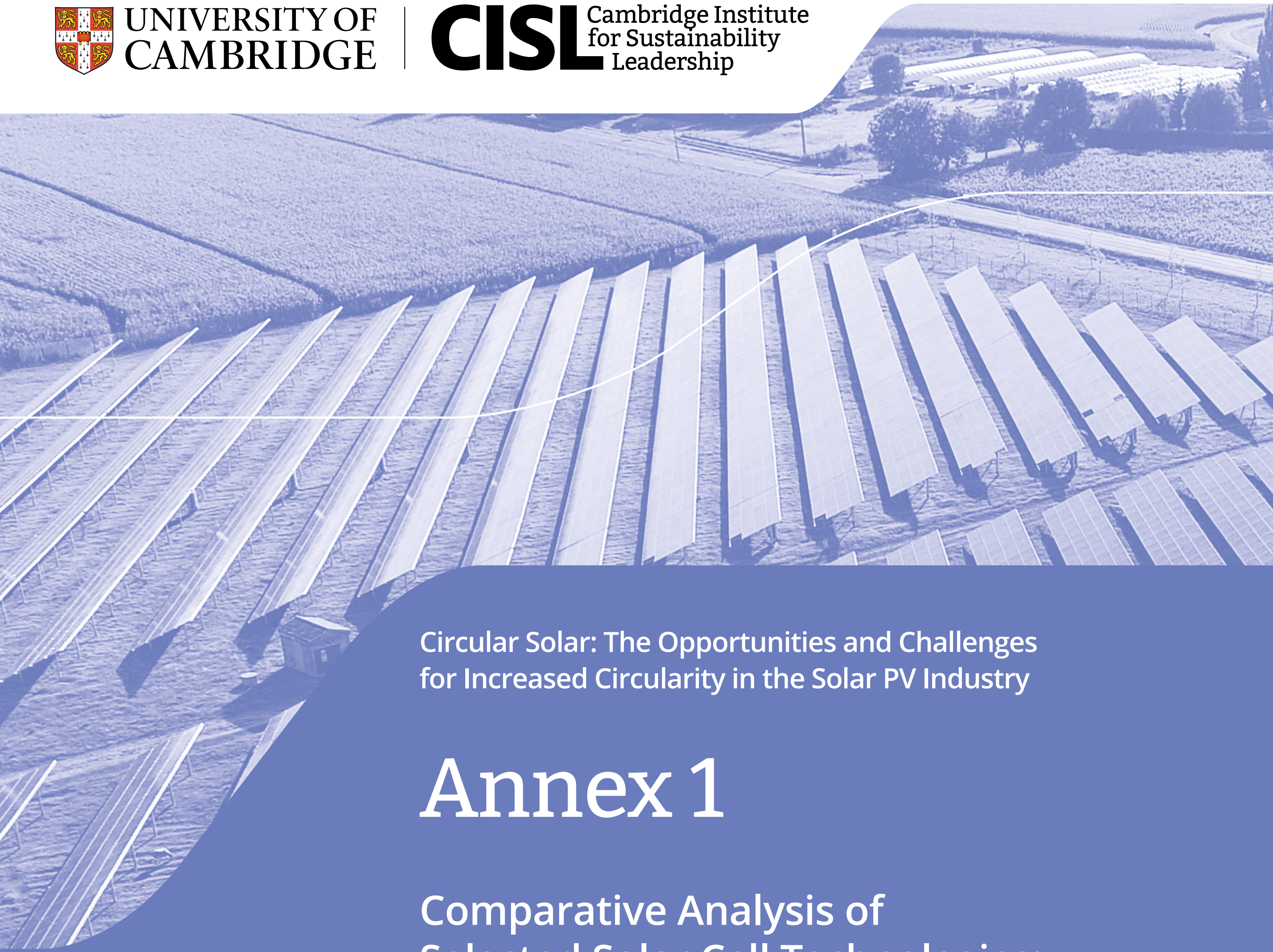

Circular Solar: The Opportunities and Challenges for Increased Circularity in the Solar PV Industry

Annex 1

Comparative Analysis of Selected Solar Cell Technologies: Implications Towards Circularity

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IfM Engage is a knowledge transfer company within the Institute for Manufacturing (IfM), which is part of the Department of Engineering at the University of Cambridge. By partnering with organisations across industry, government, and academia, IfM Engage supports and empowers them to address complex challenges, using innovative approaches and expertise developed at the IfM.

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Citing this report

Khripko, D., Ilevbare, I., Abubakar, A., McKeon, T. A and Ong, P. (2025). *Annex 1: Comparative analysis of selected solar cell technologies: Implications towards circularity*. University of Cambridge Institute for Sustainability Leadership.

Acknowledgements

The authors would like to acknowledge the contributions of the following people to the preparation of this study: Cordula Wessendorf (ZSW) and Mukesh Kumar (IfM) as well as Prof Sam Stranks (University of Cambridge) and Prof Robert Hoye (University of Oxford).

While every effort has been made to faithfully reflect and build on the inputs provided, this paper does not necessarily reflect the views of these companies or the interviewees.

About this annex

This annex provides supplementary technical information relating to Chapter 3 of *Circular Solar: The Opportunities and Challenges for Increased Circularity in the Solar PV Industry*. The report is the final output of a collaborative, multi-disciplinary research project by the University of Cambridge Institute for Sustainability Leadership (CISL), IfM Engage at the University of Cambridge and E.ON Group Innovation GmbH. The year-long project, running throughout 2024, was funded by E.ON Group Innovation GmbH. It combined a background literature review with detailed technological analysis, insights from industry experts and policy analysis.

The material offers additional details and examples to support and expand on the topics discussed in Chapter 3 of the report. Readers are encouraged to consult this annex for a deeper understanding of the key issues and analyses presented in the main report.

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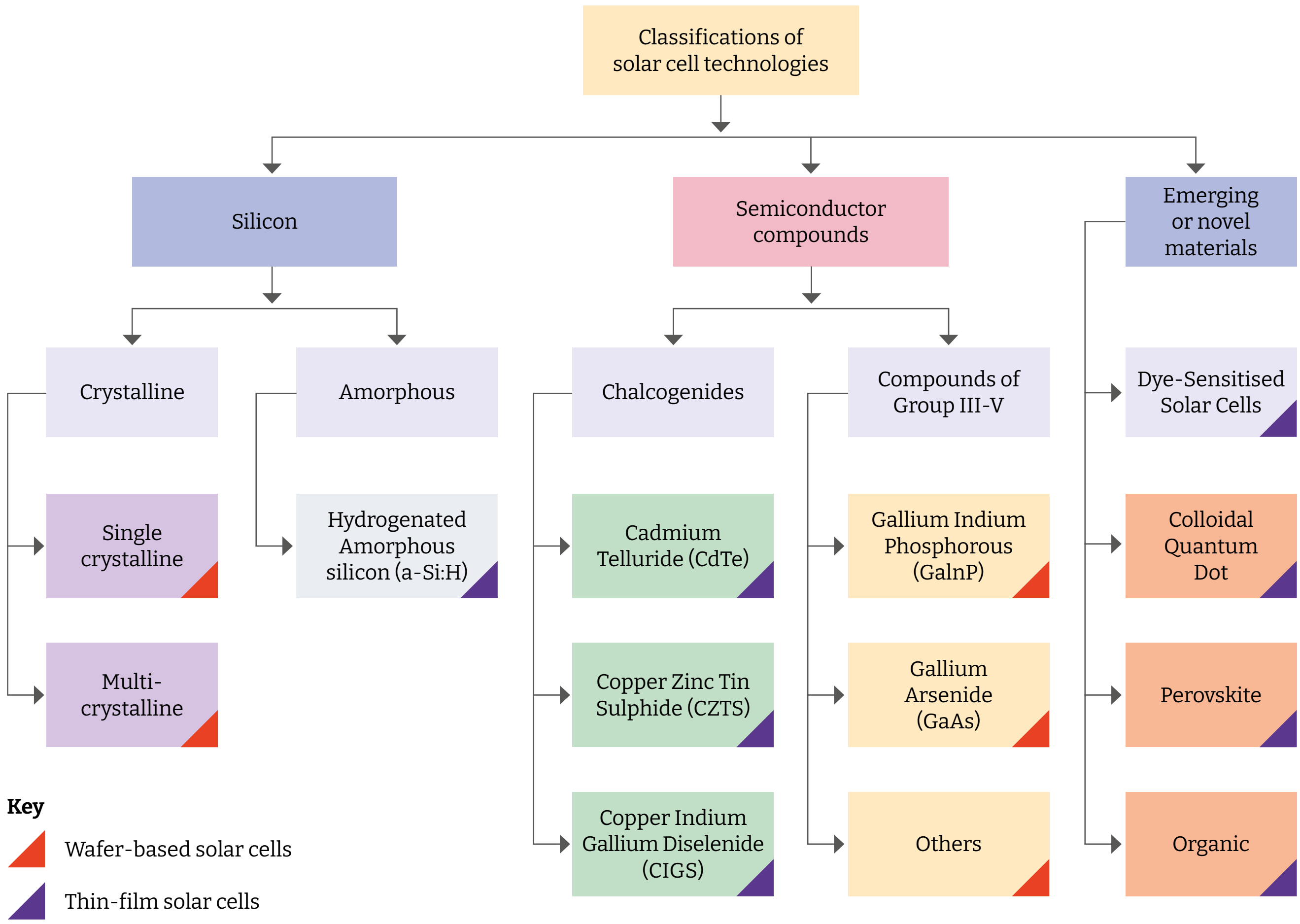
The types of materials used for solar cells differ in their properties, which enable the unique characteristics of the cells, such as flexibility, low weight and transparency. The material composition also has implications for circularity, which span across all life cycle stages of a panel, from the resource intensity of manufacturing to possible end-of-life strategies and ease of recycling.

The effects of the solar cell materials on the circularity of solar modules were analysed using the example of six technologies. Drawing from desk research and consultation with experts, these include the commercially mature and the most advanced emerging technologies:

1. Crystalline silicon-based PV
2. Cadmium telluride (CdTe)
3. Copper indium gallium (di-)selenide (CIGS)
4. Organic PV (OPV)
5. Dye-sensitised solar cells (DSSC)
6. Perovskites and perovskite-inspired[1] solar cells (in the following as 'perovskites')

Figure 1: Categories of solar cell technologies[2]



For the analysis, a set of six factors was developed using the Cambridge Innovation Velocity Tool.[3] The characteristics of the conventional crystalline silicon-based PV were considered the current industrial standard, and the potential strengths and limitations of the new technologies were compared to the conventional technology. The assessment was conducted following a two-stage process: first, a comprehensive review of current scientific publications and grey literature, such as industrial reports; second, the findings were validated through individual surveys of selected solar cell material experts. The results of this analysis are presented in Figure 2.

Conversion efficiency: The analysis on conversion efficiency includes both conversion efficiency in the laboratory and conversion efficiency in a real field operation. Higher efficiency solar cells generate more electricity per unit area, which means that fewer panels are needed to achieve the same energy yield, which has a positive impact on the environmental footprint in two ways. A higher efficiency means that the modules generate more electricity over their lifetime, and less land is needed to generate the same amount of electricity. The in-field efficiency of monocrystalline silicon solar cells reaches 20–25 per cent and 15–20 per cent for polycrystalline cells.[4]

With the exception of perovskite solar cells, which have a conversion efficiency (in laboratory) of up to 35 per cent in tandem configurations with silicon,[5] the efficiency of the other materials is currently comparable or lower than the conventional cells.

Durability and lifespan of solar cell materials: Durability is the ability of solar cell materials to withstand physical, chemical and environmental degradation over time. This includes factors such as humidity, temperature fluctuations, ultraviolet radiation, mechanical stress and corrosion. These factors influence how long the cell can efficiently generate electricity without a significant drop in performance. Reduced durability leads to earlier cell failure, a shorter lifespan and consequently more waste from a circular economy perspective.

While the typical lifespan of a silicon solar panel is around 25 years,[6] technological advances have extended module performance to 30–35 years.[7] CdTe and CIGS cells have achieved a similar performance.[8] For other materials, this is an area where further research and development is needed, for example in terms of material improvements and innovative design approaches.[9]

Availability and affordability of raw materials: The economic viability and circularity potential of solar cells are significantly influenced by the availability, geographic distribution and accessibility of the materials required for both the cells themselves and their manufacturing processes. Limited material availability tends to raise manufacturing costs and could hinder large-scale deployment of the technology, thereby affecting its economic feasibility. Consequently, sustainable manufacturing practices prioritise the use of abundant and easily accessible materials.

Figure 2: Comparative analysis of solar cell technologies

Aspects impacting circularity and environmental footprint	(crystalline) Silicon	CdTe	CIGS	OPV	DSSC	Perovskites
Conversion efficiency						
Durability and lifespan						
Availability and affordability of raw materials						
Toxicity of raw materials and materials for manufacturing						
Resource intensity and ease of manufacturing						
Economic and environmental aspects of recyclability						

Note on colour coding: grey indicates performance of the baseline technology (silicon PV) or similar to it; orange indicates performance lower than the baseline technology; green indicates performance better than the baseline technology.

From a circular economy standpoint, the scarcity of certain materials, particularly high-value ones like silver, gold, aluminium, copper and nickel, increases the incentive for their recovery and reuse, making it profitable. The mining of rare and scarce materials is often associated with serious environmental problems and pollution, especially in the Global South.[10] Thus, circular approaches are important strategies in addressing these issues. If the materials are widely available, there is less commercial incentive in recycling leading to greater waste streams as shown in the example of silicon, which is the world's second most abundant resource.[11] Most conventional solar panels end currently as landfill.[12]

OPV is typically made of non-toxic carbon-based polymers and does not encompass any high-value materials.[13] Compared to silicon-based cells and OPV, other technologies use rare materials and metals, eg tellurium in CdTe,[14] rare metals for dye molecules and platinum for counter electrodes in DSSC.[15] Perovskites require a variety of minerals and materials, and while rare earth metals are under investigation for doping in some cell designs, they are not necessarily required.[16]

The other components of all types of solar modules also contain high-quality materials and critical metals such as aluminium, which is required for the frames and backsheets and is classified as a critical raw material (EU law on critical raw materials (CRM)[17]). The increasing demand for aluminium for the green energy transition could more than double the demand for aluminium by 2050.[18]

Toxicity of raw materials and materials needed for manufacturing: Potential environmental and health hazards can be posed by using certain hazardous substances in the cells themselves as well as in the manufacturing, deployment and disposal stages of solar cell technologies. Key among these substances are heavy metals known for their toxic effects on human and environmental health when released.

Lead is used in silicon and perovskite solar cells and is a commonly recognised issue driving research and development of lead-free cells.[19] CdTe cells contain highly toxic cadmium and tellurium.[20] In CIGS, the compounds of indium and gallium have a higher toxicity than these metals in their pure form,[21] and selenium has toxic effects on aquatic ecosystems and humans when present in large concentrations.[22] Organic polymers and molecules required in OPV are generally considered less toxic than inorganic materials.[23] Nanoparticles are used in DSSC and can pose some specific health and environmental problems.[24] However, when used, solar cells must be designed for longevity. Disintegration and resulting leakage of toxic materials into the environment is not considered a major problem. The toxic substances present in solar cells can pose a significant environmental risk if they are not properly managed during disposal, reuse or recycling and are released into the environment.[25]

Understanding the need for potentially hazardous substances in the manufacturing processes generally depends on how mature the technology itself is and whether it has reached volume production. For all solar technologies, the solvents used in manufacturing processes and at the end of the life cycle to separate and recover materials are often problematic chemicals, including some that may be volatile organic compounds (VOCs).[26] If released into the environment, these substances can have direct toxic effects on humans, animals and plants. They therefore require strict handling and disposal methods to avoid contamination and damage. Research is being conducted into alternative organic (green) solvents.[27]

Resource intensity and ease of manufacturing: The amount of energy and other resources (including raw materials and water) required to manufacture a unit of production determines the environmental footprint of the solar cells themselves. The energy required to purify silicon to obtain solar grade (SG) silicon is extremely high, between 50 and 75 kWh per kg.[28] This is significantly higher than that of all other PV technologies[29] affecting the energy payback time of silicon-based modules. Although the in-field energy payback time for the other technologies[30] is currently longer due to their lower efficiencies,[31] this may change over time as 'new generation' technologies mature. For example, with economies of scale, thin-film PV technologies could have the advantage of potential low-cost and low-material production, which would improve their energy payback period.[32]

As the decarbonisation of electricity in the public grid advances, the environmental impact of silicon solar cell production will improve. But it is also important to note that silicon (and large market shares of CIGS) cells are currently mainly produced in China,[33] a country still heavily dependent on fossil fuels.[34] And even despite energy transition efforts, the high energy intensity of silicon cell manufacturing requires energy efficiency measures and can also be seen as a driving factor for repair and refurbishment of the solar panels.

In respect of ease of manufacturing, the production of silicon PV panels includes complex processes such as silicon purification, crystal growth, wafer slicing and cell fabrication, but it has become more standardised and well established. CdTe scaled production has been successfully demonstrated and commercially deployed by First Solar, as well as some other companies in the US, EU and China.[35] CIGS are produced through advanced methods like sequential processes (eg AVANCIS),[36] demanding a high degree of precision and sensitive process conditions, increasing complexity of manufacturing. Nonetheless, the first commercial manufacturing sites such as Japan's Solar Frontier[37] demonstrate the competitiveness of large-scale CIGS product. OPVs can be manufactured using roll-to-roll printing processes.[38] This method allows for rapid and large-scale production, significantly reducing costs and making the technology more accessible.[39] Fabrication of DSSC is done at lower temperatures compared to silicon and using relatively simple techniques, such as screen printing or doctor blading, contributing to simplicity of production, scalability and the potential for lower production costs.[40] Various scalable techniques have been explored for perovskites, including slot-die coating, spray coating and co-evaporation or hybrid processes,[41] with roll-to-roll (R2R) and sheet-to-sheet (S2S) processes being promising for large-scale production.[42] Perovskite cells also have a greater tolerance to defects in the structure than silicon, contributing to ease of manufacturing.[43] Currently, key challenges include achieving uniform quality of films over large areas and controlling crystallisation,[44] while the first companies are establishing in the market.[45]

In summary, the manufacturing costs of silicon solar panels are significantly driven by its energy intensity; and, therefore, all thin-film technologies share the advantage of the potential for low-cost and low-material production, and fast energy paybacks, provided economies of scale are achieved.[46]

Economic and environmental perspectives of recyclability: Four aspects related to recycling and recovery of the materials used in solar cells are evaluated here:

1. Technology readiness level (TRL) of the equipment required and ease of recycling and recovery processes
2. Energy- and resource-intensity of recycling and recovery processes
3. Achievable quality of the recovered materials
4. Market demand for the recovered materials

The global market demand for materials recovered from silicon-based PV is on the rise, driven by the solar industry's growth, sustainability efforts and the need for raw materials. Key recovered materials include high-purity silicon, valuable metals like silver, aluminium and copper, as well as glass. These materials are highly sought after in various industries, including electronics, automotive and renewable energy, due to their critical role in product manufacturing. The demand is estimated to grow substantially over the next decade, with market estimates for a Compound Annual Growth Rate (CAGR) of 19.3 per cent between 2024 and 2029.[47] Silicon-based PV recycling is complex, while the mechanical processes have commercialised in Europe and other approaches are relatively mature. Although technological advancements are still needed, existing processes face challenges related to costs.[48] The economic viability of recycling of silicon solar panels often hinges on the recovery rates of the valuable materials and their market prices.

In CdTe PV technology, cadmium and tellurium are two valuable materials that drive the need for recycling, reuse and reprocessing of solar cells, especially as their market share is expected to grow in the future. The metals are typically recovered with the chemical leaching process.[49] First Solar has developed and tested commercial recycling models for CdTe panels, capable of recovering up to 90 per cent of the tellurium and other materials for reuse.[50]

CIGS, DSSC and perovskites contain a wide range of partially toxic materials but also rare and critical materials, which increases the need and complexity of requirements on recovery and recycling. Given that these technologies are in earlier maturity stages, material recovery has been demonstrated in lab conditions, but different technological challenges exist and therefore, the recycling processes require further development. For example, in the case of perovskite solar cells, the literature suggests recovering and reusing the most valuable components, such as glass/transparent conducting oxide (TCO) substrates, while the remaining parts of the cell are recycled using layer-by-layer or one-step methods that have been tested under laboratory conditions.[51] Similarly, for organic photovoltaics (OPV), it is recommended to recover valuable materials like silver electrodes and indium tin oxide (ITO) substrates through chemical and physical processes, highlighting the economic advantages of recycling in reducing overall cell costs.[52] However, recycling processes for emerging technologies are less developed, putting them at a disadvantage compared to silicon-based cells. The advancement of recycling methods for these newer technologies will also depend on future market adoption, the availability of panels ready for recycling, and the demand for specific materials. Ecodesign of solar cells is also an emerging area of research.[53]

Finally, despite the differences between various types of solar cells, the panels share common structural components, such as glass, frames, connectors and wires. These components can be reused, recovered, or recycled on a commercial scale, while others such as encapsulant and backsheet materials require further development of recycling processes.[54]

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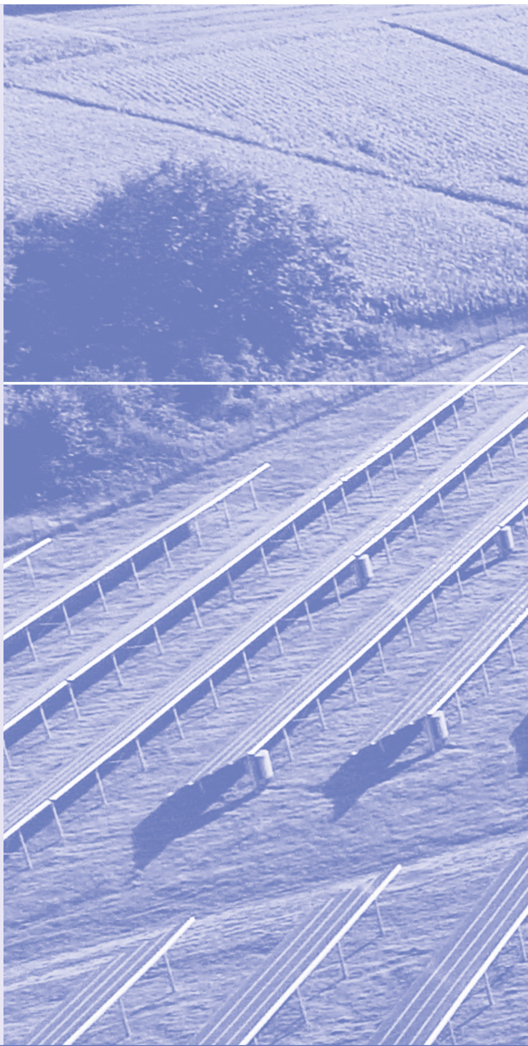

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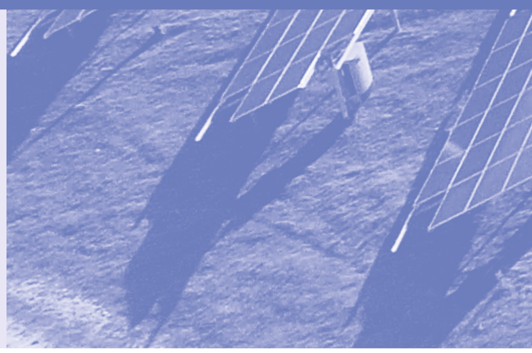

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