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Analysis of solar photovoltaic module parks in Ukraine: forecasting their further operation and end-of-life management

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Abstract. This article examines solar energy's rapid growth and evolving role in Ukraine, focusing on the challenges and opportunities presented by the end-of-life management of photovoltaic (PV) modules. Despite only actively developing over the past decade, solar energy accounts for over 5% of Ukraine's total electricity generation, ranking it 8th in Europe for installed PV capacity. The war in Ukraine has further underscored the importance of solar energy for the country's energy security and resilience. However, with the majority of PV capacity installed only recently and with a finite lifespan, Ukraine will soon face significant volumes of decommissioned PV modules requiring processing, utilization, or reuse. The article highlights the urgency of developing a robust PV module recycling sector, as current practices involve landfilling most components. A comprehensive analysis of Ukraine's PV module park, conducted as part of the EU-funded Retrieve project, represents a crucial first step towards effective PV waste management, aligning with Ukraine's energy strategy and commitments under the Paris Agreement on climate change.

1 Introduction

The rapid development of solar and wind energy in 2023 made it possible to reach 30% of electricity generation from renewable energy sources in the global electricity balance. Accordingly, as of 2023, solar energy produces 5.5% of the world's total electricity production, which already allows for a significant reduction in greenhouse gas emissions from the global energy sector (in 2023, the level of emissions was 12% lower than the peak in 2007) [1].

The total generation capacity of photovoltaic (PV) systems is growing extremely fast. According to the International Energy Agency (IEA), in 2023, the global installed capacity of solar PV systems reached 1624 GW, compared to 40 GW in 2010 [2]. At the COP28 climate change conference in Dubai, more than 130 national governments, including the European Union, agreed to work together to triple the world's installed renewable energy capacity to at least 11,000 GW by 2030 [3]. However, this rapid growth of PV systems also leads to an increase in the number of decommissioned PV modules, which creates a new

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problem of their accumulation in the form of e-waste (for OECD countries alone, 29 million tons of PV waste is projected to accumulate by 2058 [4]). On the other hand, producing new photovoltaic modules requires, in addition to high-purity silicon, a sufficiently large number of materials, such as silver, indium, and bismuth, which are difficult to obtain quickly [5,6]. The solution to this problem is to apply circular economy approaches to used or damaged PV modules by transforming them into new, more efficient ones [7], given that 95% of the materials of existing PV modules are suitable for further processing and use [8].

2 Methodology

Data were aggregated from various sources, including a survey of PV owners in Ukraine, importers and installers of photovoltaic panels and related equipment, open analytics of government services and energy companies, and other publicly available sources. The study employed quantitative and qualitative analysis techniques to process and interpret the collected data reflecting the actual situation in Ukraine.

3 Results

Ukraine's average annual solar energy potential among European countries is relatively high - 1235 kWh/m^2- much higher than, for example, Poland - 1080 kWh/m^2 and Germany - 1000 kWh/m^2 [9]. Accordingly, a solar photovoltaic power plant can operate efficiently for about nine months from March to November in the southern regions of Ukraine and seven months from April to October in the northern areas.

Solar energy, in terms of developing photovoltaic power plants, is a relatively new industry in Ukraine, actively developing only in the last ten years. Accordingly, 2010 is considered as the point of active growth (Fig. 1). At the same time, the pace of its development is extremely high compared to other sectors of the Ukrainian economy. Thus, by the end of 2021, solar energy in Ukraine accounted for more than 5% of total electricity production. Ukraine ranks 8th in terms of the total installed capacity of photovoltaic power plants in Europe (8062 MW) as of 2022, and compared to 2021, it has lost one position due to damage to part of the installed capacity because of hostilities and collateral damage effects [10].

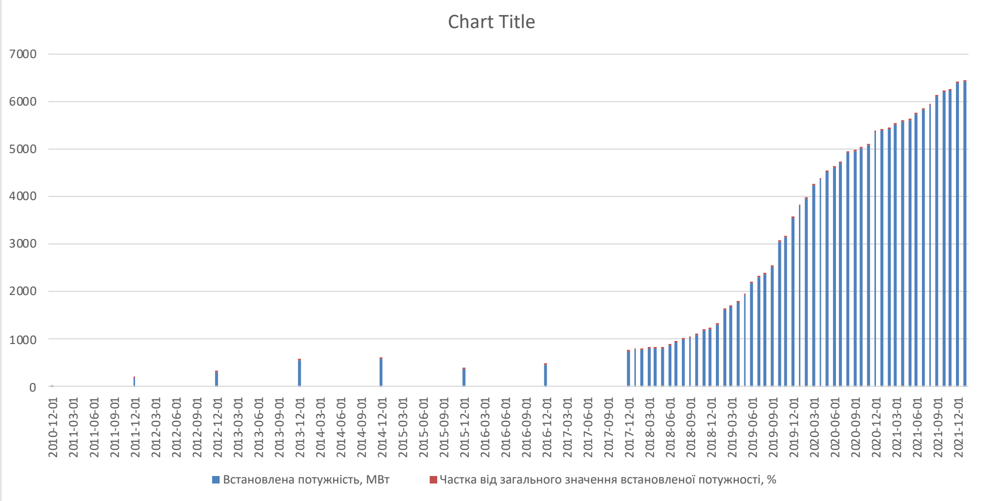

Fig. 1. Installed capacity growth rates of photovoltaic power plants in Ukraine.

The entire territory of Ukraine is suitable for the location of photovoltaic power plants. The most favorable regions for this are the southern regions (Odesa, Mykolaiv, Kherson, Zaporizhzhia, and part of Donetsk region, Crimean peninsula), where more than 60% of industrial PV power plants (PVPPs) are currently concentrated [11] (Fig. 2).

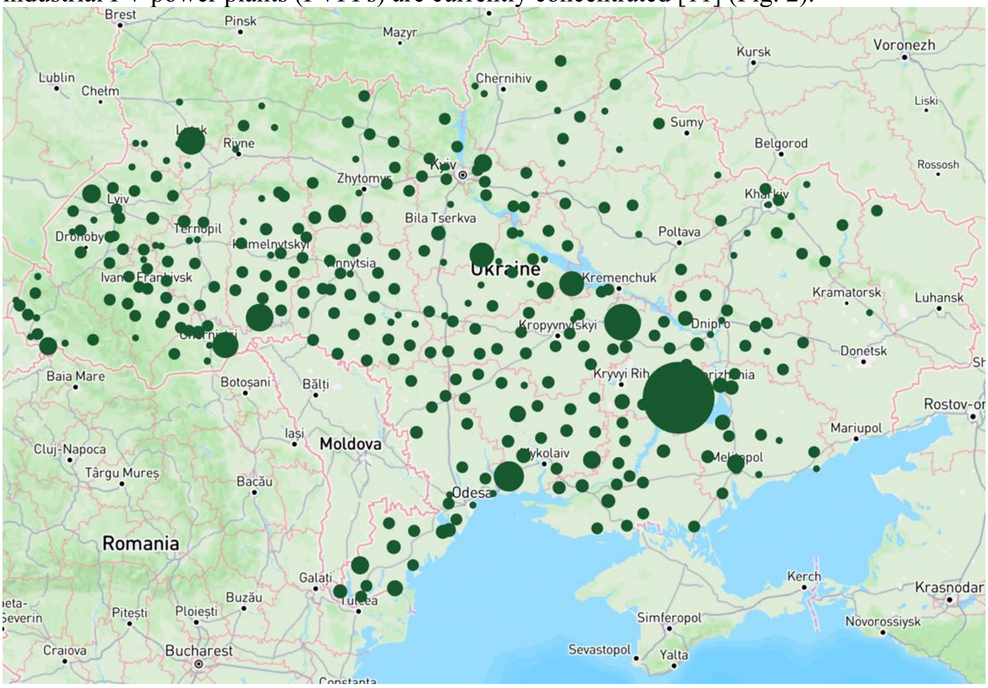

Fig. 2. Density of photovoltaic stations on the territory of Ukraine.

The largest photovoltaic solar power plant in Ukraine and the third largest and most potent in Europe is the Nikopol PVPP. The Nikopol PVPP covers 400 hectares and is located on the territory of a former manganese ore quarry. The land is of low value and unsuitable for agriculture. The plant consists of 750 thousand photovoltaic modules with a total capacity of 246 MW and 80 inverter stations with power transformers and switchgear (Fig. 3).

Fig. 3. Nikopol photovoltaic power plant, the largest in Ukraine (DTEK, 2021. https://dtek.com/en/media-center/photo/nikopol-spp/1700747560/).

The most efficient photovoltaic power plant, where the generation is 40% higher with the help of biaxial trackers compared to average Ukrainian PV power plants (where PV modules are fixed statically), is the 2.5 MW tracker PV power plant Solar Park Pidhorodne. This station uses a dynamic two-row system with a vertical arrangement of 20 PV modules (Fig.4).

Fig. 4. The most efficient tracker photovoltaic station «Solar Park Pidhorodne» (2021 year).

Photovoltaic power plants in Ukraine are the most popular type of renewable energy sources (RES), like wind, hydro, and bioelectric power plants. They share close to 75% of all RES facilities. Since February 24, 2022, Ukrainian energy facilities have been under constant missile and drone attacks and have withstood hundreds of Russian strikes. At least 13% of industrial solar power plants have been destroyed or damaged, and under certain security conditions, these PV modules need to be refabricated and/or utilized. According to the Solar Energy Association of Ukraine, 62 industrial solar power plants with a total installed capacity of more than 950 MW are now in the occupied territories. This needs to consider a significant number of small domestic PVPPs (with a capacity of up to 30 kW). The territory of Ukraine, free from the aggressor, is currently a location for more than 5900 MW of industrial PVPPs and more than 1200 MW of small domestic PVPPs, which also suffer significant losses because of hostilities.

As a result of the war, the role of photovoltaic power plants has changed from a "green transition" and decarbonization to an essential tool for energy security and grid resilience in the face of the destruction of classical maneuverable generation facilities. Solar energy is a part of the unified energy system of Ukraine, so without its stable operation, the effective functioning of the economy is impossible.

Analysis of the fleet of photovoltaic modules of Ukrainian PV power plants.

In 2004-2009, 40-50% of the world's solar silicon production was concentrated in Ukraine. Ukraine had a closed cycle of the photovoltaic output. The Zaporizhzhia Semiconductor Plant Joint Stock Company produced polysilicon. This is the most capital-intensive and complex part of the solar energy technology chain. Apart from Ukraine, only Germany and Norway made the primary raw materials. Notably, production in Zaporizhzhia was restored from scratch and reached 2.2 thousand tons of polysilicon per year. Capital investments exceeded 450 million euros. Ukrainian enterprises mainly sell their products in European markets.

In 2009-2010, China put into operation new production facilities in the solar energy sector, resulting in European manufacturers of solar cells and photovoltaic modules losing the market and Ukrainian plants cutting back on producing semiconductor raw materials and photovoltaic modules. Due to the economic crisis, the EU has reduced subsidies for renewable energy. In addition, since 2010, Chinese photovoltaic modules have been imported to Ukraine on a massive scale, both legally and illegally. Most Ukrainian producers of semiconductor materials for photovoltaics could not compete with China and were forced to close or re-profile. Ukraine's largest enterprise, Pillar, which grew silicon and sold silicon wafers abroad, had two factories in Spain and suspended operations in August 2018. As of mid-2024, the largest Ukrainian manufacturers of photovoltaic modules - PJSC Quasar, Prolog Semicore LLC, and KNESS PV are not operating. Accordingly, development in the direction of PV module recycling may become a "new lease of life" for these production facilities.

Given that 98% of the capacity was installed after 2010, 90% was installed after 2018. Given that the average lifetime of PV modules is about 25-30 years, it can be assumed that in 2035-2048, Ukraine will have a significant amount of decommissioned PV modules that will need to be recycled.

In addition to the planned decommissioning of PV modules that are technically outdated and imperfect, the need to recycle PV modules at Ukrainian power plants is caused by the following reasons:

- Occurrence of PV defects at the stage of PV installation (the percentage of such PV defects can only be determined based on a questionnaire);
- PV defects during PV operation (a typical problem for Ukrainian PV power plants is low-quality PV modules with a short service life and high degradation;
- Complete destruction of the PV system due to fire or natural disaster;

- Destruction of PV power plants due to hostilities (Figs. 5, 6).

Fig. 5. Destroyed solar power plant (22 MW) of Solar Generation in Mykolaiv region. (Photo by Stanislav Ignatiev, 2022. «Soling 1» PV power plant https://www.prostir.ua/?news=vde-heneratsiji-v-umovah-vijny-vidnovyty-rozstrilyane-zberehty-vtsilile).

Fig. 6. Photovoltaic power plant (4.45 MW) Alternative Energy Sorcés Solar in Kharkiv region (Photo by Stanislav Ignatiev, 2022. «Merefa» PV power plant. https://www.epravda.com.ua/publications/2023/05/24/700431/).

The decision to dispose of a PV module should be based on determining the presence of defects in the module and their impact on the PV module's operation. The analysis of PV module damage shows that different PV modules (by manufacturer) have the same defects. These defects are as follows: damage to the cell (breakdown of the semiconductor junction, burnout of the cell); damage to the busbar (deterioration of contact at the point where the cell is connected to the busbar and corrosion of the conductive material); damage to the terminal – junction box; damage to the aluminum frame (corrosion of aluminum, bending of the frame, drying out and cracking of the sealant and seals); damage to the protective glass (cracking, abrasive effect of dust in the air on the transparency of the glass). Considering the experience of PV module operation and the detection of defects in them, a PV module defect diagram was built (Fig. 7).

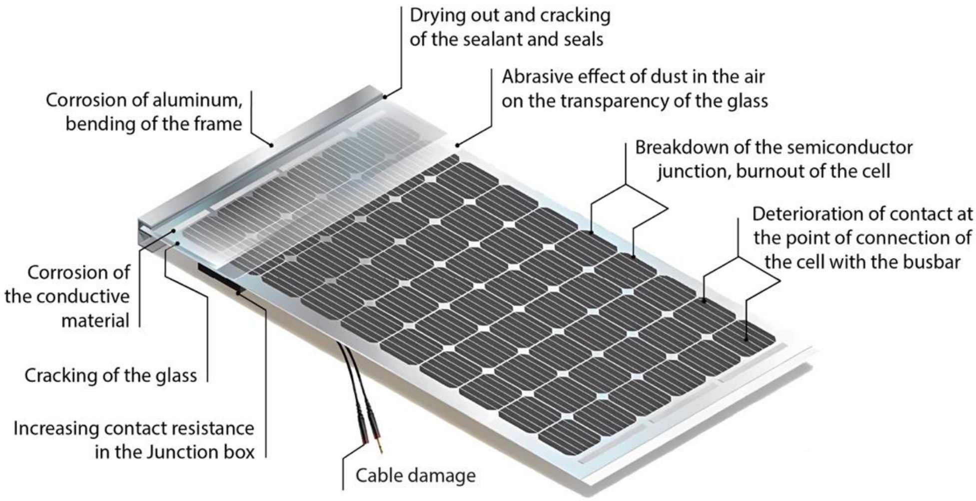

Fig. 7. Defect diagram of a photovoltaic module.

PV module defects lead to a deterioration of the PV module and a decrease in the generated electricity. Not every detected fault has the same impact on the technical condition of the PV module. If the effects of one defect are currently insignificant, it can lead to a severe problem in the near or far future.

Currently, methods and software systems are being developed to determine the residual life of PV modules based on the results of technical diagnostics. This will allow for determining the further suitability of PV modules and the feasibility of their replacement [2]. However, the problem is that modules from different manufacturers have different production technologies and design features. During further research, it is necessary to collect statistics on the defectiveness of PV modules and, on this basis, to formulate uniform criteria for their rejection.

According to various estimates, almost 40% of photovoltaic power plants in southern Ukraine have been damaged, accumulating large volumes of damaged photovoltaic modules. Thus, the issue of legislative regulation of the PV utilization process and the search for the most efficient recycling technologies to implement a closed-loop economy model is already acute.

According to a study by the International Renewable Energy Agency (IRENA), each MW of installed solar photovoltaic capacity can generate about 60-78 tons of waste by the end of its lifetime. Based on this, Ukraine will accumulate about 60 thousand tons of PV module waste by 2035. By 2048, this number will increase to 500 thousand tons, which emphasizes the urgency of developing a strong PV module recycling sector, as most of the materials can be recycled or reused instead of being dumped in a landfill. The material consumption of one standard crystalline module in tons (t) per megawatt (MW) is estimated at 46.4 t/MW of glass, 8.6 t/MW of plastic, 7.5 t/MW of aluminum, 4.6 t/MW of copper, 4 t/MW of silicon, and 0.02 t/MW of silver.

There are no PV module recycling facilities in Ukraine, and there are no special requirements for their disposal. As a rule, only the aluminum frames of PV modules are involved in further processing. At the same time, all other components that are difficult to separate are buried at an industrial waste dump.

Taking into account this situation and the already installed significant capacities of PV power plants in Ukraine, it is promising to conduct research on the PV module fleet and their condition, with the prospect of their further deep utilization by obtaining not just PV

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components but also new PV modules with improved characteristics based on the products of processing. Accordingly, the first step towards the "correct" management of PV waste in Ukraine should be a thorough analysis of the PV module fleet's design, manufacturing technology, and type. For the first time in Ukraine, such research was conducted by scientists at King Danylo University as part of the Retrieve project.

The data obtained from the study allow us to analyze in detail the characteristics of PV modules operated in Ukraine. For example, the distribution between monocrystalline (68%) and polycrystalline (32%) PV modules for Ukrainian PV power plants can be determined, or the percentage distribution can be determined by the unit capacity of PV modules (Fig.8).

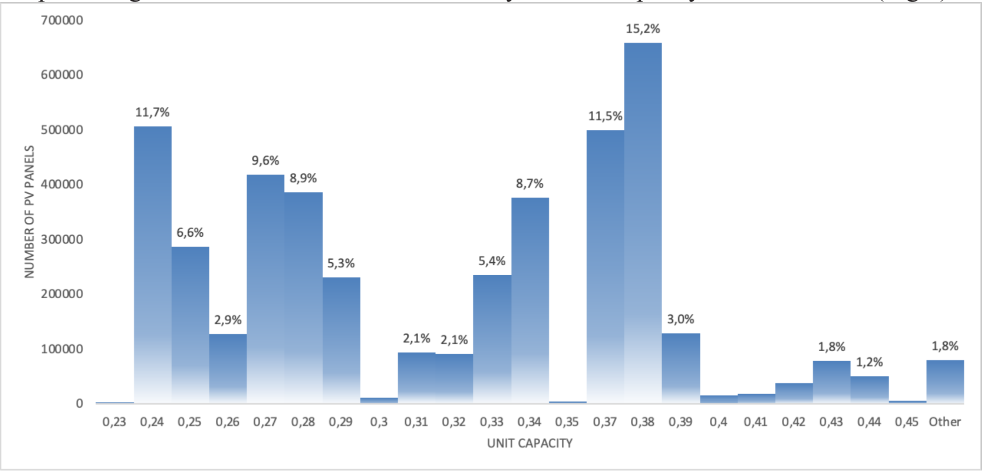

Fig. 8. Percentage distribution of installed PV modules by unit capacity.

4 Discussion

The study's results can be used to select or develop PV recycling technology to identify the leading manufacturers that dominate the panel fleet. Accordingly, we can distinguish the manufacturers that dominate among the installed PV systems (Longi Solar -17%, JA Solar - 16.5%, RISEN - 9.7%) (Fig. 9). More and more manufacturers are announcing the development of PV modules for easier recycling and reuse of materials. The top three manufacturers are actively researching and declaring that 90% of their module products are fully recycled and reused. Cooperation between PV module manufacturers and recycling companies plays a vital role here. Recycling technologies should be foreseen at the production stage, thereby minimizing the costs of recycling and reuse.

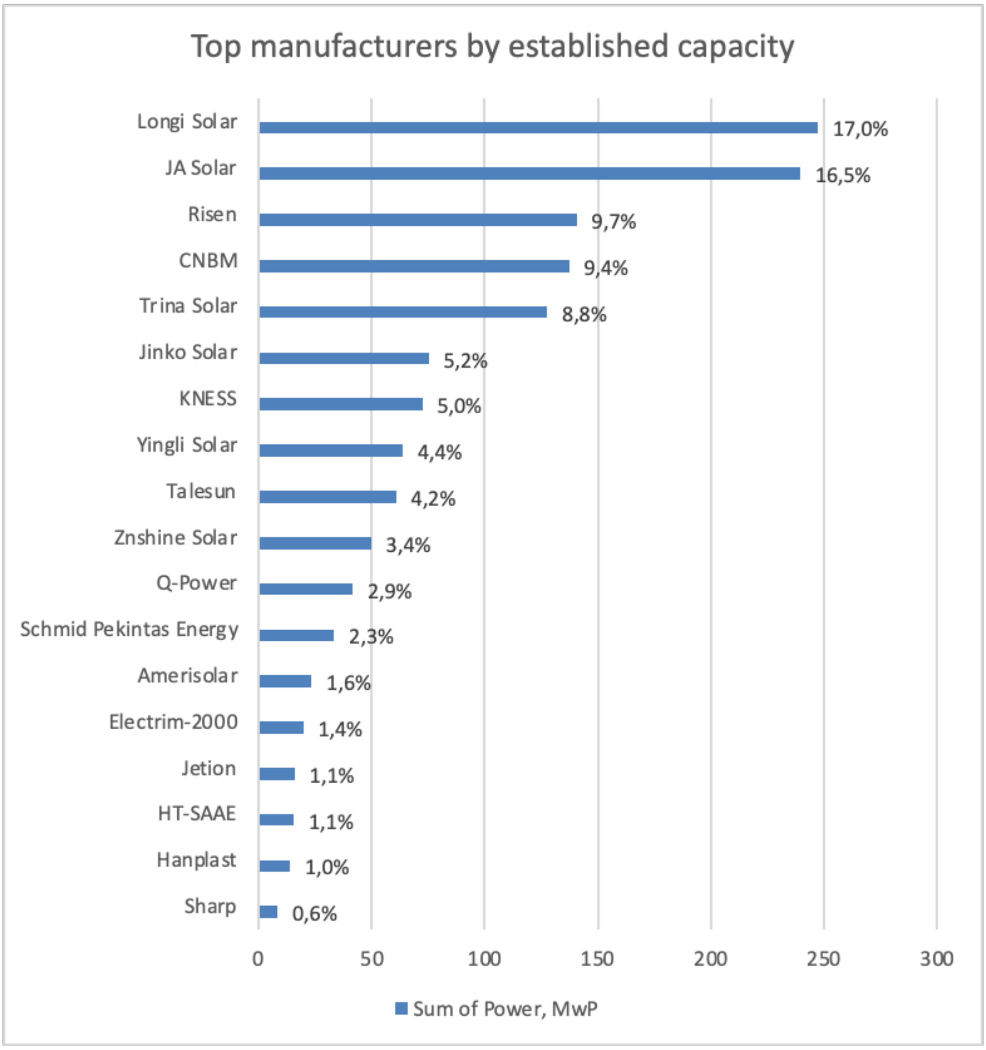

Fig. 9. Percentage distribution of installed PV modules by manufacturers

The life cycle of a photovoltaic module (Fig. 10) begins with sourcing raw materials, their processing, and the production of the module. As of today, all modules are imported to Ukraine, and there is no domestic production. Regular testing and maintenance are required during the operational phase to ensure optimal performance after installation.

The modules can be dismantled at the end of their service life. This presents a choice: send to a landfill, collect for reuse, export for recycling, or process domestically to recover materials. Of course, landfill disposal is not a rational option due to material losses and potential pollution. Instead, collecting and recycling modules can conserve resources and support the growth of the domestic PV industry.

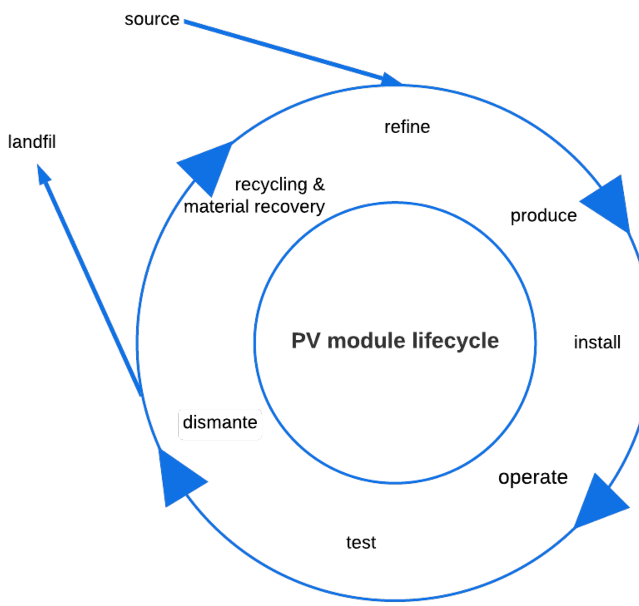

Fig. 10. PV module lifecycle.

Throughout the entire life cycle, minimizing emissions, reducing waste, and considering each stage's environmental impact is crucial. Circular practices, such as designing for recycling and extending the service life through maintenance, can help achieve these goals.

To enable a more circular PV industry in Ukraine, further research and investment are needed in areas such as recycling technologies, material recovery processes, and end-of-life management strategies.

As a result of the study, we see great potential for recovering the Ukrainian photovoltaic industry in the direction of PV recycling and circularity. Many barriers to the circular economy in the solar energy sector need to be identified, and standards and goals need to be created to interconnect all elements of the technological chain [12]. Thanks to the Retrieve project, we are conducting research in this area with EU partners with extensive experience and a high technological level.

5 Conclusions

Based on the time of commissioning of the primary capacities of Ukrainian PV power plants and the corresponding projected service life of PV modules, a significant problem of PV module utilization should have arisen in 2035-2040. However, active hostilities in the south and east of the country and the resulting destruction of robust PV power plants cause the accumulation of large volumes of damaged PV modules. Thus, the issue of legislative regulation of the PV utilization process and the search for the most efficient technologies for their processing to implement a closed-loop economy model is already acute.

The industry currently needs more research on addressing these issues sustainably and circularly. This progress requires stakeholders to be willing to take on the financial risks associated with investing in recycling infrastructure based on circular economy principles to minimize the adverse environmental effects.

Developing a comprehensive PV waste management policy is entirely consistent with Ukraine's energy strategy, which envisages an increase in the share of renewable energy to 25% by 2035 (currently 11%). The Paris Agreement on Climate Change is a significant incentive to find effective mechanisms for PV waste utilization. To fulfill its obligations, Ukraine needs to increase its share of renewables in electricity generation by 30%. It is clear that solar energy will be its main base based on the operation of photovoltaic modules.

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