Review paper

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ENVIRONMENT AND MATERIALS FOR RENEWABLE ENERGY SOURCES

Marija Nikolić

Ministry of Spatial Planning, Construction and Ecology, Banja Luka, Republic of Srpska

* Corresponding author: m.nikolic@mgr.vladars.rs

Abstract: According to Ember (2024), over 40% of global electricity was generated from clean sources, with solar power as the fastest growing and most significant new energy contributor. This paper explores the link between the materials used in solar power systems and their environmental impact, within the framework of the Green Agenda for the Western Balkans 2050.

Through a life cycle analysis of photovoltaic (PV) systems, key materials (silicon, glass, aluminum, copper, lithium, polymers) are assessed for their recyclability and ecological impact, compared to fossil fuel sources. Special focus is placed on the environmental advantages of decentralized solar systems - such as air quality preservation, transmission efficiency, and reduced land degradation- relative to conventional infrastructure.

The paper emphasizes the role of circular economy principles in managing solar panel waste, advocating for robust take-back and recycling programs. When properly designed and located outside sensitive habitats, solar energy is arguably the most sustainable form of electricity production in the 21st century.

The conclusion highlights the importance of sustainable material use in achieving energy and climate goals, urging Western Balkan countries to accelerate the adoption of renewable energy technologies and align with EU environmental policies.

Keywords: renewable energy, photovoltaic systems, materials, environmental protection, green transition.

1. INTRODUCTION

Over the past decade, the energy sector has undergone substantial transformations driven by the global need to reduce greenhouse gas emissions and preserve the environment. One of the key elements of this transition is the intensified development of renewable energy sources, with solar energy assuming a central role in the future energy landscape due to technological advances and declining costs.

According to Ember (2024), more than 40 percent of global electricity generation now comes from clean energy sources, and solar power represents the fastest-growing source of electricity in the world. Its technological advantages and widespread availability make it highly suitable for applications in urban, industrial, and rural areas, particularly within decentralized energy systems, thereby contributing to energy security, resilience, and inclusiveness across the globe.

However, the increasing deployment of photovoltaic (PV) systems also raises important questions regarding the sustainability of the materials used in their construction, as well as their environmental impact throughout the entire life cycle, from manufacturing and operation to end-of-life management. In the era of the circular economy, the handling of waste arising from decommissioned or aged PV modules is becoming an increasingly urgent issue. This requires careful analysis and the development of strategies for proper collection, recycling, or reuse of components while minimizing environmental impact.

In this context, the purpose of this paper is to analyze the relationship between the materials used in the solar industry and environmental protection, with a particular focus on identifying the most sustainable solutions in design, material innovation, and alignment with strategic directions for sustainable development.

According to the Energy Strategy of the Republic of Srpska until 2035, renewable energy sources (RES) play a key role in the future energy mix. The document projects an increase in the share of RES in electricity production from around 36 percent in 2015 to more than 50 percent by 2035. The most substantial growth is expected in the solar and wind sectors, owing to technological advancements and resource availability. The strategy also emphasizes the need to enhance energy efficiency, reduce dependence on fossil fuels, and introduce advanced and smart energy systems. The adoption of modern technologies, including advanced PV modules, as well as improvements in domestic capacities for the production and installation of solar systems, have been identified as priorities for creating new jobs, advancing the green economy, and strengthening energy independence. The strategy additionally highlights the need for a clearer regulatory framework that will ensure sustainable management of solar infrastructure at the end of its service life, including recycling and reuse of components.

The research presented in this paper is therefore directly aligned with the vision and goals of the energy policy of the Republic of Srpska and may significantly contribute to improved strategic planning, policy development, and the promotion of sustainable solutions in the field of renewable energy sources.

2. MATERIALS IN PHOTOVOLTAIC SYSTEMS

Photovoltaic (PV) systems consist of several components, among which the most significant are PV modules (solar panels), supporting structures, electrical installations, current conversion devices (inverters), and energy storage systems. The materials used in manufacturing these components play a crucial role in determining their total environmental impact and potential influence on human health.

2.1 Silicon

Silicon is the primary semiconductor material used in solar cells, especially in monocrystalline and polycrystalline panels, which dominate the global market. Its advantages include stability, high efficiency, and long service life. However, the production of high-purity silicon is energy intensive and requires controlled processing conditions, presenting certain environmental challenges.

2.2 Glass

The front surface of most PV modules is covered with tempered, high-transparency glass. Glass provides mechanical protection and contributes to module longevity. It is fully recyclable, making it a favorable material within the circular economy model.

2.3 Aluminum

Aluminum is commonly used for PV module frames and mounting structures. Its low weight, corrosion resistance, and recyclability position it among the more environmentally acceptable materials, especially when sourced from recycled inputs.

2.4 Copper

Copper is used in wiring and internal electrical components. Although more expensive than some other metals, its electrical conductivity and durability are essential for overall system efficiency. Copper is also highly recyclable.

2.5 Lithium and other battery components

In systems equipped with energy storage, particularly those using lithium-ion batteries, materials such as lithium, cobalt, nickel, and graphite play a major role. These materials carry considerable environmental and social burdens due to mining practices and processing methods, necessitating responsible resource management and the development of alternative technologies.

2.6 Polymers

Polymeric materials are used for encapsulating solar cells and providing insulation. While they improve water resistance and mechanical stability, most polymers are difficult to recycle, posing challenges at the end-of-life stage.

2.7 Nanomaterials

Nanomaterials represent a new generation of engineered materials increasingly explored in photovoltaic applications due to their exceptional optical, electronic, and mechanical properties. Nanostructured layers can significantly improve light absorption, reduce reflection, and enhance the energy conversion efficiency of solar cells. Their use is particularly relevant in thin-film and perovskite PV modules, where they enable better control of photon flow and enhanced thermal stability. According to the publication *Nanomaterials and Energy* by D. Mirjanić (ASARS, 2021), (Д. Мирјанић, *Наноматеријали и енергија*, АНУРС, Бања Лука 2021) the importance of nanoengineering lies in its potential to reduce material costs and improve recyclability, making nanomaterials highly suitable in the context of the circular economy and sustainable development of the solar industry.

3. LIFE CYCLE AND ENVIRONMENTAL IMPACT

Life Cycle Assessment (LCA) is a key tool used to evaluate the overall environmental impact of photovoltaic (PV) systems. The objective of the LCA methodology is to encompass all stages of a product's life cycle, from raw material extraction, component manufacturing, transportation, installation, and use, to end-of-life disposal or recycling. Such analysis enables decision-makers, engineers, and researchers to identify critical points with the highest environmental impact and propose mitigation measures.

Given the widespread application of solar energy within the global energy transition, integrating LCA analyses into PV project planning and development has become an essential component of environmentally responsible management.

3.1 Material production and processing

The extraction and processing of key materials used in PV systems, such as mono- and polycrystalline silicon, aluminum, copper, and lithium, represent the most energy-intensive phase in terms of consumption and emissions. The production of high-purity silicon (accounting for 80–90 percent of the global PV module market) requires arc furnaces and chemical processing, both of which are energy intensive and often reliant on fossil fuels, significantly increasing the carbon footprint of the early life-cycle phase.

Mining and processing of copper and lithium, used in wiring, conductors, and energy storage batteries, may lead to land degradation, groundwater contamination, and biodiversity loss. This phase is consistently identified as critical in LCA studies, motivating increased interest in alternative, more environmentally friendly materials and technologies, such as perovskite PV modules and recycled aluminum.

3.2 Use and operation

The operational phase of PV systems is the most environmentally efficient. During electricity generation, PV systems produce no direct CO_2 emissions, require no water consumption, release no air pollutants, and generate no noise. These qualities make them suitable for both urban and rural environments and for installation on existing structures (such as rooftops), reducing the need for additional land use.

The average service life of PV modules ranges from 25 to 30 years, with many continuing to operate beyond the rated lifespan but at reduced efficiency. The Energy Payback Time (EPBT), defined as the time required for a PV system to generate the amount of energy used to produce it, typically ranges from 1.5 to 3 years. This means that, over its lifetime, a PV system produces 8 to 20 times more energy than was consumed in its manufacturing, one of the technology's most significant advantages.

3.3 End of life: disposal and recycling

At the end of their service life, PV modules become part of the rapidly growing waste stream of electrical and electronic equipment (e-waste), requiring specialized management. Although more than 80 percent of PV module components (glass, aluminum, copper) can be effectively recycled, substantial technological and logistical barriers remain. Challenges often arise in separating and processing polymers, thin films, and certain toxic materials such as cadmium or lead (present in some module types), whose improper disposal may contaminate the environment.

According to the International Renewable Energy Agency (IRENA), global PV waste could exceed 78 million tonnes by 2050. This trend represents both a challenge and an opportunity: the development of collection, recycling, and reuse systems for PV components may create new jobs, support the circular economy, and significantly reduce reliance on primary raw materials.

3.4 Comparison with traditional energy sources

A comparative life-cycle analysis of PV systems with traditional energy sources such as coal, fuel oil, and natural gas clearly demonstrates the environmental superiority of solar energy. While coal-fired power plants may emit more than 900 g CO_2 per kWh, PV systems typically generate fewer than 50 g CO_2 per kWh over their entire life cycle, including the manufacturing stage.

Furthermore, PV systems do not require water for cooling and emit no sulfur dioxide (SO_2), nitrogen oxides (NO_x), or heavy metals, all of which are associated with acid rain and ecosystem degradation. Despite certain environmental burdens during the manufacturing phase, solar energy remains one of the cleanest and most environmentally acceptable energy options available today.

4. ADVANTAGES OF DECENTRALIZED SOLAR SYSTEMS

Decentralized solar systems are a key component of the ongoing transition toward sustainable, efficient, and climate-neutral energy models. They enable electricity production close to the end user, reducing dependence on centralized grids, increasing system resilience, and strengthening the involvement of local communities in energy management.

According to pilot projects conducted in the Republic of Srpska (unpublished), decentralized PV installations installed on public buildings in three municipalities have reduced monthly electricity costs by up to 38 percent, with investment payback periods ranging from 6 to 8 years. Users also reported increased control over energy expenditures and enhanced energy security during periods of market instability.

4.1 Reduction of transmission losses

By generating electricity close to the point of consumption (Figure 1: Example of a solar power plant on rooftops of homes, schools, and hospitals), transmission losses, which in conventional systems may reach 6–8 percent, are practically eliminated. In an internal energy-efficiency analysis of an industrial zone in Banja Luka (2024), the transition to a hybrid model reduced total technical losses by 5.7 percent compared to the previous year. This improvement also contributed to increased grid stability, particularly during peak-demand periods.

4.2 Reduction of Emissions and Improvement of Air Quality

Eliminating the combustion of fossil fuels means that decentralized solar systems produce no direct CO_2, SO_2, or NO_x emissions, nor particulate matter associated with respiratory diseases. In Bosnia and Herzegovina, as well as across Central and Eastern Europe, winter peaks in suspended particulate matter (PM pollution) are largely linked to the combustion of solid fuels in households. Increasing the share of solar PV systems in electricity generation has been shown to reduce SO_2, NO_x, and PM emissions by displacing generation from fossil fuel power plants, which yields measurable public health benefits. Therefore, the local expansion of PV installations is expected to contribute to im-

Figure 1. *Appearance of a Solar Power Plant*

proved air quality, particularly during the heating season, while simultaneously lowering energy costs for households.

4.3 Minimal Physical Impact on Land

Unlike large hydropower plants or wind farms, rooftop solar PV systems do not require additional land area. In rural regions where the preservation of agricultural and forest land is essential, this advantage enables the parallel development of the energy and agricultural sectors. As a result, soil degradation, habitat fragmentation, and the loss of agricultural land are avoided. The International Renewable Energy Agency (IRENA) emphasizes that this characteristic is one of the key advantages of rooftop installations compared to centralized solar farms or parks, as it allows energy development without competing for space. Furthermore, the implementation of agrivoltaics (dual land use) has demonstrated that placing solar panels above arable land can even improve the microclimate and reduce evaporation, thereby contributing to soil fertility conservation and sustainable agriculture.

In the Netherlands, approximately ten agrivoltaic installations are currently being implemented (as of March 2024), enabling the joint use of land for energy production and agriculture, particularly under conditions of limited available land area. (Source: Agrivoltaic Project in the Netherlands, Innovation Origins, 2024)

4.4 Energy Independence and Resilience

Decentralized systems are particularly valuable in the context of climate change and increasingly frequent extreme weather events. Systems equipped with battery storage or hybrid support allow facilities to operate even during grid outages. In the pilot project implemented at a school in Prijedor, the installation of a solar system with an 18 kWh battery enabled uninterrupted teaching during two supply interruptions in February 2024. Such interventions directly enhance community resilience.

5. CIRCULAR ECONOMY AND PV SYSTEM WASTE MANAGEMENT

The growing use of solar energy also brings an increasing responsibility for managing the waste generated at the end of the lifecycle of photovoltaic (PV) systems. Global PV waste is expected to exceed 70 million tons by 2050, with a significant share coming from developing countries that currently lack adequate management mechanisms. For this reason, integrating circular economy principles into the solar sector has become a key imperative for sustainable development.

5.1 Circular Economy Principles in the Solar Sector

The circular economy aims to extend the lifespan of products and materials through reuse, repair, remanufacturing, and recycling. In the context of PV systems, this includes:

– Designing modules suitable for disassembly

– Using non-toxic and recyclable components (silicon, glass, aluminum)

– Reducing reliance on difficult-to-process polymers and lead-based soldering

Figure 2. *Illustration of Agrivoltaics and Development Practices in the Netherlands*

5.2 Challenges in PV Module Recycling

Although glass and aluminum can be relatively easily recovered, the greatest technological challenge lies in separating thin layers of silicon, polymers, and soldered components. These processes require expensive equipment and chemical treatment that are not yet commercially widespread, particularly in the Western Balkans region.

5.3 Need for Institutional Frameworks

To implement circular economy principles in the solar sector, it is necessary to analyze existing differences between the EU and the Western Balkans. A comparative analysis (Table 1) of the European Union and the Western Balkans shows significant differences in institutional capacity for managing PV system waste. While the European Union has well-developed institutional and technological mechanisms for PV waste management, the Western Balkan countries are largely in the early stages of establishing similar frameworks.

Table 1. *Comparative Analysis of Institutional Capacities for PV Waste Management*

Category	EU	Western Balkans
Legal framework for PV waste	Yes (WEEE Directive)	Partial / No
Mandatory recycling	Yes	No
Specialized organizations	PV Cycle, national agencies	None
Recycling capacities	Developed	Insufficient
EPR policy (producer responsibility)	Yes	Emerging
PV system registry	Exists	Does not exist

Note: This analysis is the author's work, based on a comparative review of official European sources (the WEEE Directive, reports from the European Environment Agency – EEA, IRENA, PV Cycle) and assessments of the current situation in the Western Balkan countries, including the Republic of Srpska.

6. STRATEGIC FRAMEWORK OF THE REPUBLIC OF SRPSKA: CLIMATE AND ENERGY POLICY

The Republic of Srpska, as part of the broader energy transition process in the Western Balkans, has defined a series of strategic documents aimed at aligning with the European Union's climate goals and promoting the use of renewable energy sources, including solar energy.

6.1 Energy Strategy of the Republic of Srpska until 2035

This document serves as a framework for the development of the energy sector, with an emphasis on:

– increasing the share of renewable sources in total electricity production,
– improving energy efficiency,
– strengthening decentralized production, and
– encouraging investment in small and medium-sized solar systems.

According to projections, solar energy is expected to constitute a significant portion of newly installed capacity by 2035. The introduction of more flexible regulatory measures and subsidies plays a key role in achieving this goal.

6.2 Climate Change Adaptation Strategy

The Republic of Srpska recognizes climate change as one of the greatest threats to long-term development. The strategy prioritizes:

– reducing greenhouse gas emissions,
– improving the resilience of energy infrastructure,
– public education, and
– enhancing monitoring and reporting of emissions.

Solar energy, as a low-emission technology with significant potential for local application, represents a direct response to climate challenges.

6.3 Green Agenda for the Western Balkans

In line with the "Green Agenda" adopted by the European Commission for the region, the integration of the Republic of Srpska's strategies with goals such as:

– decarbonization of the economy,

– introduction of a circular economy,
– biodiversity protection, and
– increased investment in clean technologies, is anticipated.

The implementation of mechanisms such as emissions trading systems and carbon taxation will further accelerate the transition to renewables, giving solar energy an even stronger strategic role.

7. CHALLENGES AND RECOMMENDATIONS

Despite the numerous advantages of solar energy, enhancing its sustainability requires overcoming several challenges. A key issue is the limited infrastructure for the collection and recycling of used PV modules, which may lead to the accumulation of electronic waste and environmental pollution. Additionally, the production of certain materials, particularly lithium, cobalt, and silicon, is associated with significant environmental and social costs, including water pollution and labor rights violations in exporting countries.

Insufficient application of eco-design in solar equipment manufacturing limits the ease of disassembly and recycling, while the lack of national programs and incentives for a circular economy slows progress in this direction. Furthermore, there is a need for greater public education, especially in rural areas, on the importance of decentralized renewable systems.

Recommendations:

– Establish a regulatory framework that obliges solar equipment manufacturers and importers to implement an Extended Producer Responsibility (EPR) system.

– Introduce financial incentives for eco-design, the use of recycled materials, and the development of local waste processing capacities.

– Invest in research and development of alternative, less harmful materials for energy storage and production.

– Align national strategies with the EU Green Agenda principles, supported by cross-border initiatives.

– Increase data availability and transparency regarding the life cycle of PV systems and their environmental impact.

– Educate local populations and technical staff to enable practical implementation of circular economy principles.

8. CONCLUSION

Solar energy represents one of the most important drivers of the transition to sustainable and climate-neutral energy systems. Through proper selection and management of materials, it is possible to significantly reduce the environmental impact of photovoltaic systems while simultaneously strengthening energy independence and economic development. Decentralized solar systems, based on circular economy and eco-design principles, offer solutions that are technologically, environmentally, and socially sustainable.

If the Republic of Srpska continues to develop its regulatory, institutional, and technical capacities in line with the Energy Strategy and the Green Agenda, solar energy could become a key pillar for achieving climate targets by 2050. A sustainable future requires a systemic approach, cross-sectoral collaboration, and continuous investment in innovation, education, and natural resource protection.

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ЖИВОТНА СРЕДИНА И МАТЕРИЈАЛИ ЗА ОБНОВЉИВЕ ИЗВОРЕ ЕНЕРГИЈЕ

Сажетак: Према извјештају организације Ember (2024), више од 40% глобалне електричне енергије произведено је из чистих извора, при чему је соларна енергија најбрже растући и најзначајнији нови извор струје у свијету. Овај рад разматра однос између материјала који се користе у изградњи соларних електрана и њиховог утицаја на заштиту животне средине у свијетлу Зелене агенде за Западни Балкан до 2050. године.

Кроз анализу циклуса животног вијека фотонапонских (PV) система, разматрају се врсте материјала (силицијум, стакло, алуминијум, бакар, литијум, полимери), њихова рециклабилност и еколошки утицај у односу на традиционалне изворе енергије. Посебна пажња посвећена је улози децентрализованих соларних система у очувању квалитета ваздуха, смањењу губитака у преносу енергије и очувању биодиверзитета — уз минималан физички утицај на земљиште у поређењу са другим инфраструктурним рјешењима.

У раду се такође анализира значај циркуларне економије у производњи и одлагању соларне опреме, те наглашава потреба за успостављањем система за скупљање и рециклажу PV модула, као једне од кључних мјера заштите животне средине. Соларна енергија, уколико се планира и изводи у складу са стандардима и регулативама (нпр. изван осјетљивих екосистема, са минималним пејзажним утицајем), представља најодрживији облик производње електричне енергије у XXI вијеку.

Закључује се да је избор и управљање материјалима за соларне електране кључан фактор у обезбјеђивању одрживог развоја и очувању животне средине, те да државе Западног Балкана морају убрзати усклађивање са ЕУ климатским циљевима кроз подршку зеленим технологијама и локалну производњу обновљиве енергије.

Кључне ријечи: обновљиви извори енергије, фотонапонски системи, материјали, заштита животне средине, зелена транзиција.

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