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THE ROLE OF RECYCLING IN THE SUSTAINABLE LIFE CYCLE OF PHOTOVOLTAIC POWER SYSTEMS: APPROACHES TO EFFICIENT RESOURCE USE AND LOCAL ENERGY MANAGEMENT

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Abstract:
The rapid expansion of photovoltaic (PV) power plants across the globe has intensified concerns about their environmental impacts and the extensive use of resources throughout their life cycle. Overcoming these challenges is crucial for advancing sustainable energy systems and improving community energy management. This study employs the life cycle assessment (LCA) approach to evaluate the environmental performance of PV power plants, focusing particularly on recycling as an end-of-life management strategy. The assessment examines the major stages of the PV life cycle and identifies module manufacturing, together with the consumption of fossil fuels and mineral resources, as the phases generating the greatest environmental burden. The results indicate that recycling lowers water usage and lessens adverse effects on human health compared with landfill-based disposal options. Recovering valuable materials also contributes to lowering the economic costs of raw material extraction while supporting the principles of a circular economy. Overall, the study demonstrates that recycling should be viewed not merely as a waste treatment solution, but as an essential component of the sustainable life cycle of PV power plants, enhancing resource efficiency and reinforcing the resilience of community energy systems.

Key words: life cycle assessment (LCA); photovoltaic power plant; ReCiPe 2016; renewable energy sources; sustainable development management

INTRODUCTION

The law now in effect in Poland defines sustainable development as socio-economic development that integrates economic, social, and environmental activities while maintaining ecological balance to meet societal requirements [1, 2]. Ensuring the National Power System (KSE) operates safely, providing the cheapest electricity possible, making the best use of primary energy resources, and protecting the environment by reducing CO_2 emissions and other harmful substances are all requirements for the sustainable development of the electricity sector [1, 3, 4]. Only when the three primary pillars of sustainable development – the environment, the economy, and society – are satisfied can it be achieved [5]. The environment is considered as all ecological factors connected to guaranteeing its best possible quality, reducing emissions of waste and dangerous chemicals into the environment, and minimizing the energy and material consumption of manufacturing, operation, and post-consumer disposal activities [6]. The economy is defined as the efficient operation of the National Power System (KSE) and the guarantee that the methods and technology used are not only safe for the environment but also provide financial gains and serve as a basis for future economic growth. Conversely, society is defined as the acceptability of a certain electrical source by the general populace [1, 7]. Historical occurrences highlight

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the potential consequences to national security associated with a strong reliance on foreign fossil fuel sources. An essential component of a country's economic growth is energy. Resource-rich nations' reliance on energy income emphasizes how crucial it is to protect this priceless resource. For nations that produce energy, safeguarding the security of energy resources is a primary national security concern. Energy concerns have a significant impact on the present geopolitical environment, hence energy regulation is essential to enhancing national security [8, 9, 10]. Management of sustainable development entails overseeing all operations to safeguard the environment and its resources. Maintaining human well-being via a variety of endeavors is one of its objectives. The management of sustainable development is founded on social, economic, and environmental factors. These sectors must all grow without impeding one another's progress. Although it could take longer than conventional management, this approach is more sustainable and safe [11, 12, 13]. Recent scenario-based research on the Polish power system confirms that photovoltaics and wind energy are currently the main drivers of renewable energy development in Poland, although their further integration requires grid modernisation, energy storage, system flexibility and stable regulatory conditions [14].

LITERATURE REVIEW

One important method for evaluating the environmental effect of photovoltaic (PV) systems is life-cycle analysis (LCA). The majority of research concentrate on evaluating the materials used to make photovoltaic modules, especially silicon, including amorphous silicon (a-Si), multicrystalline silicon (mc-Si), and monocrystalline silicon (sc-Si) technologies. Previous in-depth research on sc-Si modules has been conducted in several studies [15, 16, 17, 18, 19]. Further studies have also addressed related PV technologies and life-cycle aspects [17, 20, 21, 22, 23, 24]. Modern solar technologies, such as organic and perovskite cells, which frequently use transparent graphene electrodes, have been included in the analysis's scope in recent years [25, 26]. Additionally, there is a growing interest in energy efficiency studies [27], flexible PV panels, silicon cells in different configurations [28, 29], and the use of PV panels in textiles. LCA is a useful technique for examining small parts, such individual modules or components, but it may not be as applicable to larger-scale evaluations, like those of complete PV power plants [30]. In order to provide a more thorough and sustainable evaluation of renewable energy systems, it is necessary to further standardize life cycle assessment (LCA) methodologies and integrate environmental, economic, and social considerations [31]. In addition, the selection of renewable energy sources in industrial applications may require a multi-criteria approach that combines technical, economic and environmental criteria; such an approach has already been proposed for Polish industrial conditions [32, 33]. From an operational management perspective, energy efficiency may also be improved by production scheduling supported by FlexSim simulation and by integrating renewable energy sources into production systems [34].

RESEARCH CONTRIBUTION

Reducing adverse environmental consequences, boosting beneficial effects, cutting costs, raising economic rewards, and spreading awareness of renewable energy sources are the cornerstones of the sustainable development of renewable energy systems [35]. A literature study served as the first step in the publication preparation process, enabling the core research challenge to be formulated and the topic selection to be justified. Life-cycle analysis was done to evaluate the methodology's validity (LCA). A thorough examination of the structure of the solar power plant under study, accounting for the percentage contribution of various parts and materials, was made possible by the LCI stage. The ReCiPe 2016 calculation process and SimaPro 9.4.0 software were used to perform appropriate simulations, and the results were meticulously recorded. An explanation of the findings was provided at the end of the study. Evaluating the safety of natural resources and their potential for recovery through recycling procedures was the primary objective of the study. Recent evidence from a recycling facility also shows that structured process-improvement methods can reduce rework, water and detergent consumption,

which supports the need to treat recycling not only as an end-of-life option but also as a managed efficiency process [36].

MATERIALS AND METHODS

Finding regions with the greatest degree of negative environmental effect is crucial to the sustainable life cycle of renewable energy machinery, devices, and installations. Every stage of the life cycle, and especially the distinct processes that take place within it, requires a different strategy [37]. This principle forms the basis of the Life Cycle Thinking (LCT) standard, which takes into account variations occurring at each phase of the life cycle. Among the available approaches, LCA (Life Cycle Assessment) is the most widely used tool in environmental life cycle studies of technological facilities [38, 39]. Identifying activities occurring within particular life cycle phases that may generate negative or positive impacts enables sustainable life cycle management (LCM) of photovoltaic (PV) power plants [40, 41, 42, 43]. The social dimension constitutes the final component of sustainable development. Even if a solar power plant is economically viable and has limited environmental impact, its location may still encounter strong social opposition. Such reluctance among local communities may result from numerous factors, including cultural norms or insufficient public awareness. Therefore, increasing public awareness through educational initiatives and social campaigns is essential for ensuring the long-term sustainability of photovoltaic systems [40, 41, 42, 43]. In recent years, lifecycle management (LCM) has proven to be an effective strategy in this regard [44]. The most frequently applied LCM strategies include market expansion strategies aimed at increasing sales during patent protection periods, brand protection strategies designed to extend the product's market presence without generic competition, market protection strategies against competitors' actions intended to reduce sales, and strategies focused on extending the product lifecycle by shortening development and time-to-market processes [45].

The ISO 14000 standard outlines the four fundamental phases of life cycle assessment (LCA) analysis: identifying the goal and scope of the research, evaluating environmental effects (LCIA), analyzing the life cycle inventory (LCI), and interpreting the findings [46]. LCA generally entails determining and measuring the possible environmental effects connected to a particular product's functioning. In LCA, the ideas of function, functional unit, and reference flow are very crucial [47, 48]. A functional unit, such as the quantity of energy generated by a solar power plant during its whole life cycle, given in MWh, is a quantifiable impact of a product system's operation and is used as a reference unit in life cycle studies. In contrast, a reference flow shows the number of outputs or processes in a particular product system required to carry out the function specified by the functional unit. Figure 1 shows a graphical depiction of the fundamental phases of life cycle assessment.

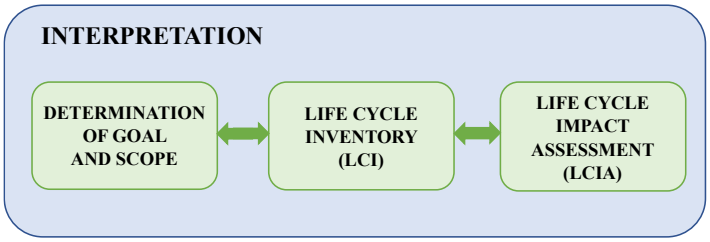


Fig. 1 Graphic diagram showing the main stages of LCA analysis

Alt text: *The graphic diagram presents the main stages of the Life Cycle Assessment (LCA) analysis. It illustrates the sequence of steps involved in evaluating the environmental impacts of a product or process.*

Source: own elaboration based on [3].

LCM can be applied by all types of businesses and organizations as a management strategy to improve sustainability performance. Its primary objective is to support more sustainable value chain management, and it can be implemented by both large and small enterprises [49]. Throughout a product's lifespan, LCM enables the organization, evaluation, supervision, and continuous improvement of product-related data and activities [50]. One of the tools used in life cycle impact assessment (LCIA) is the

ReCiPe 2016 model (Figure 2). It was originally developed in 2008 through collaboration between the Netherlands National Institute for Public Health and the Environment (RIVM), Radboud University Nijmegen, Leiden University, and PRé Sustainability, the creators of the SimaPro software [51].

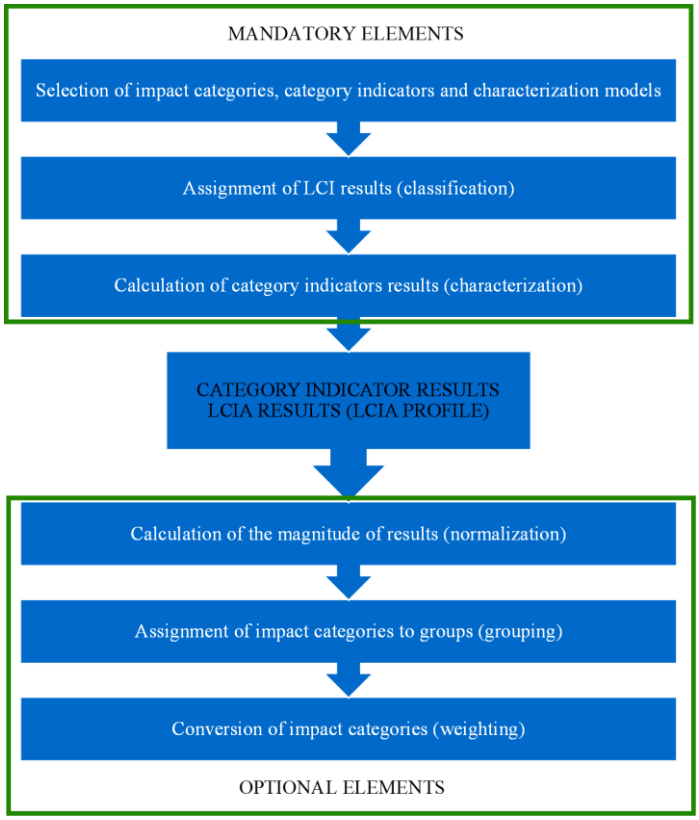


Fig. 2 Graphic diagram of mandatory and optional LCIA elements
Alt text: *The figure illustrates the mandatory and optional elements included in Life Cycle Impact Assessment (LCIA). It provides an overview of the assessment framework and its components.*
Source: own elaboration based on [55].

The model converts life cycle inventory data into indicator values representing potential environmental impacts across different impact categories [52]. ReCiPe includes indicators for three impact areas and 22 impact categories. The impact categories address specific environmental issues, whereas the broader impact areas represent more aggregated levels of environmental consequences. Compared with other models, ReCiPe 2016 offers one of the most comprehensive sets of impact categories. It expands and improves upon the 2008 version as well as earlier models such as Eco-indicator 99. Unlike its predecessor, ReCiPe 2016 considers both local and global factors affecting the European region, making it particularly suitable for life cycle assessments of technical renewable energy infrastructure [53]. The managerial interpretation of LCM is also consistent with recent studies on EU Taxonomy implementation and ESG maturity, which emphasise that environmental objectives must be translated into organisational competencies, process data and practical decision-support tools [54].
The study focuses on a 2 MW photovoltaic power plant located in northern Poland. Based on eight years of operation, the installation is capable of producing between 1900 and 2200 MWh of electricity annually. About 300,000 kg of materials, supplies, and components make up the tested solar power plant (Figure 3).

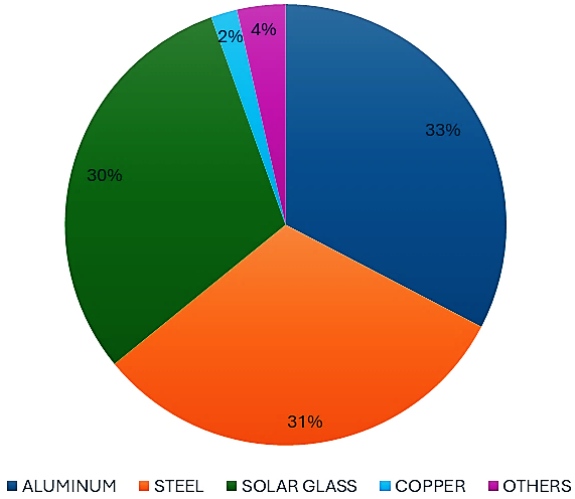


Fig. 3 Percentage distribution of component mass in the tested photovoltaic power plant (investor data)
Due to weather-related variations, annual electricity generation may fluctuate by approximately 10%. Consequently, the average annual electricity production of the power plant was estimated at 2000 MWh.
Alt text: *The Figure presents the percentage distribution of component mass in the tested photovoltaic power plant. It shows the contribution of each component to the total system mass.*

RESULTS

The findings of describing the environmental effects brought about by the life cycle of the examined solar power plant are compiled in Table 1.

Table 1
Characterization of the consequences of the life cycle of the analyzed photovoltaic power plant for the environment in the area of 22 impact categories of the ReCiPe 2016 model, taking into account the method of post-consumer management of materials, components and elements

No	Element of a Technical Object	Photovoltaic Power Plant		Unit
	Waste Scenario	Landfill	Recycling	
	Impact Category			
1	Global warming, human health	1.51×10^{0}	4.97×10^{-1}	DALY
2	Global warming, terrestrial ecosystems	4.55×10^{-3}	1.50×10^{-3}	species/year
3	Global warming, freshwater ecosystems	1.24×10^{-7}	4.09×10^{-8}	species/year
4	Stratospheric ozone depletion	4.64×10^{-4}	2.72×10^{-4}	DALY
5	Ionizing radiation	3.13×10^{-3}	8.83×10^{-4}	DALY
6	Ozone formation, human health	3.61×10^{-3}	1.89×10^{-3}	DALY
7	Fine particulate matter formation	2.17×10^{0}	1.01×10^{0}	DALY
8	Ozone formation, terrestrial ecosystems	5.23×10^{-4}	2.74×10^{-4}	species/year
9	Terrestrial acidification	1.86×10^{-3}	9.04×10^{-4}	species/year
10	Freshwater eutrophication	7.47×10^{-4}	5.53×10^{-4}	species/year
11	Marine eutrophication	4.09×10^{-7}	2.95×10^{-7}	species/year
12	Terrestrial ecotoxicity	4.16×10^{-4}	3.30×10^{-4}	species/year
13	Freshwater ecotoxicity	2.78×10^{-4}	2.42×10^{-4}	species/year
14	Marine ecotoxicity	5.97×10^{-5}	5.21×10^{-5}	species/year
15	Human carcinogenic toxicity	9.96×10^{-1}	5.00×10^{-1}	DALY
16	Human non-carcinogenic toxicity	2.62×10^{0}	2.23×10^{0}	DALY
17	Land use	3.85×10^{-4}	2.69×10^{-4}	species/year
18	Mineral resource scarcity	5.55×10^{4}	4.53×10^{4}	USD
19	Fossil resource scarcity	1.22×10^{5}	5.67×10^{4}	USD
20	Water consumption, human health	4.24×10^{1}	-1.88×10^{1}	DALY
21	Water consumption, terrestrial ecosystem	2.58×10^{-1}	-1.14×10^{-1}	species/year
22	Water consumption, aquatic ecosystems	1.16×10^{-5}	-5.10×10^{-6}	species/year

Every effect category found in the ReCiPe 2016 model was taken into account. Both recycling and landfill disposal were taken into consideration as post-consumer management scenarios for plastics, materials, and components. The group that included processes that depleted water had the greatest detrimental impact on human health among those identified (4.24 x 10^1 DALY during the life cycle with landfill disposal). When it came to recycling as a post-consumer management strategy, the same category also had the most positive impact in this area (-1.88 x 10^1 DALY). The category including mechanisms generating water depletion impacting terrestrial ecosystems had the highest level of harmful influence on environmental quality when it came to the technical facility under study (2.58 x 10^{-1} species/year). Once more, if recycling were selected as the post-consumer management option, this group would benefit the most in this respect (-1.14 x 10^{-1} DALY). These findings demonstrate the serious effects of human activity on the quality of drinking water and the growing global problem of diminishing supplies. In turn, the depletion of raw materials is linked to rising costs for extracting a unit of a particular resource, in addition to its obvious environmental effects. Processes linked to the depletion of fossil fuel resources (USD 1.22 x 10^5) result in higher monetary expenses than processes related to the depletion of mineral resources (USD 5.55 x 10^4) throughout the life cycle of the solar power plant under examination. However, in both situations, recycling as a post-consumer management strategy would enable a reduction in these costs throughout the technical object's life cycle, as the recovered materials, components, and materials would be reused rather than irretrievably lost (storage).
The findings of describing the environmental effects brought about by the life cycle of the examined solar power plant are compiled in Table 2.

Table 2

Characterization of the consequences for the environment of the life cycle of the analyzed photovoltaic power plant in the area of processes causing depletion of water resources, affecting human health (ReCiPe 2016 model), taking into account the method of post-consumer management of materials, materials and components

No	Element of a Technical Object	Photovoltaic Power Plant		Unit
	Waste Scenario	Landfill	Recycling	
	Impact Category			
1	Water	-1.14×10^1	-1.14×10^1	DALY
2	Water, cooling, unspecified natural origin	1.29×10^{-2}	8.82×10^{-2}	DALY
3	Water, lake	7.23×10^{-4}	1.06×10^{-3}	DALY
4	Water, river	1.98×10^{-2}	1.57×10^{-2}	DALY
5	Water, turbine use, unspecified natural origin	5.37×10^1	-7.48×10^0	DALY
6	Water, unspecified natural origin	3.49×10^{-2}	3.43×10^{-2}	DALY
7	Water, well	3.72×10^{-3}	1.21×10^{-3}	DALY
8	Remaining substances	1.06×10^{-2}	2.86×10^{-3}	DALY
TOTAL		**4.24×10^1**	**-1.88×10^1**	**DALY**

In the ReCiPe 2016 model, consideration was given to the processes that directly affect human health and deplete water supplies. Recycling and landfill disposal were the two post-consumer disposal options for plastics, materials, and components that were taken into consideration. The use of water in turbines (not only for producing electricity but also for cooling processes) had the greatest detrimental effect on human health among the substances that were found to have an impact on human health (5.37 x 10^1 DALY for the life cycle with landfill disposal). The solar power plant's life cycle with recycling disposal had the greatest beneficial effect on water resources. During the whole life cycle, recycling lowers water use (-1.14 x 10^1 DALY). The total values of the impact of a solar power plant's life cycle, accounting for post-consumer management practices (recycling, storage), in the field of activities that deplete water resources and have an influence on human health, are shown in Figure 4.

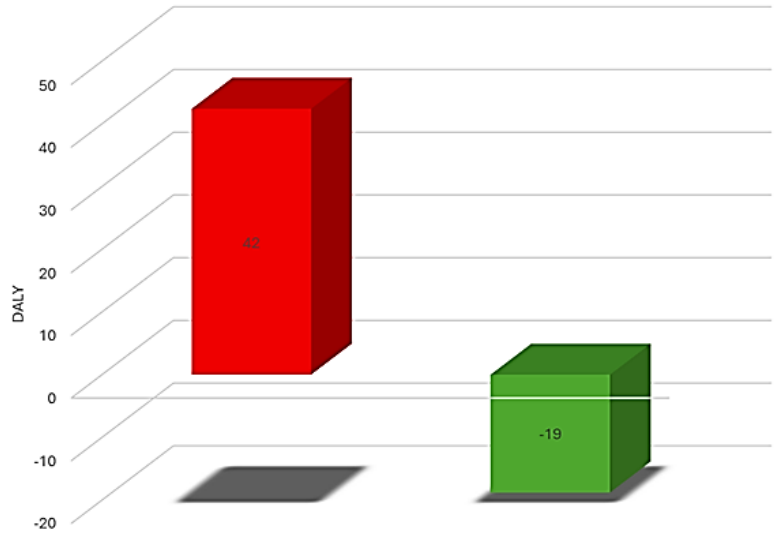


Fig. 4 Characterization of the overall consequences of the life cycle of the analyzed photovoltaic power plant for the environment in the area of processes causing depletion of water resources and affecting human health (ReCiPe 2016 model), taking into account the method of post-consumer management of materials, components and elements (RED – landfill, GREEN – recycling)

Alt text: *The figure presents the characterization of the environmental impacts of the analyzed photovoltaic power plant over its life cycle using the ReCiPe 2016 model. It compares landfill and recycling scenarios in terms of water resource depletion and human health impacts.*

The findings of describing the environmental effects brought about by the life cycle of the examined solar power plant are compiled in Table 3.

Table 3

Characterizing the consequences of the life cycle of the analyzed photovoltaic power plant for the environment, in the area of the impact of processes causing depletion of water resources, affecting terrestrial ecosystems (ReCiPe 2016 model), taking into account the method of post-consumer management of materials, materials and elements

No	Element of a Technical Object		Photovoltaic Power Plant	
	Waste Scenario		Landfill	Recycling
	Substance	Emission Area		
1	Water	Water	-7.26×10^{-2}	-7.25×10^{-2}
2	Water, cooling, unspecified natural origin	Raw materials	8.45×10^{-4}	6.01×10^{-4}
3	Water, lake	Raw materials	4.39×10^{-6}	6.44×10^{-6}
4	Water, river	Raw materials	1.20×10^{-4}	9.71×10^{-5}
5	Water, turbine use, unspecified natural origin	Raw materials	3.29×10^{-1}	-4.29×10^{-2}
6	Water, unspecified natural origin	Raw materials	2.15×10^{-4}	2.10×10^{-4}
7	Water, well	Raw materials	2.28×10^{-5}	2.09×10^{-5}
8	Remaining substances	x	8.58×10^{-5}	3.78×10^{-5}
TOTAL			**2.58×10^{-1}**	**-1.14×10^{-1}**

Source: own research (unit: species/year).

In the ReCiPe 2016 model, the mechanisms that impact terrestrial ecosystems and deplete water supplies were considered. Recycling and landfilling were two additional post-use management possibilities that were taken into account. The usage of water in turbines had the most detrimental effects on terrestrial ecosystems out of all the compounds that were shown to have an influence (3.29×10^{-1} species/year throughout the life cycle including landfill management). The life cycle with recycling management showed the most improvement. The detrimental effects on the environment in the examined area are greatly decreased by this process (-7.25×10^{-2} species/year). The data obtained once again

demonstrate the growing global concern about the depletion of drinking water supplies and the substantial influence of human activities on their quality. The overall values of the impact of a solar power plant's life cycle, including for post-consumer management practices (recycling, storage), in the field of activities that deplete water resources and influence terrestrial ecosystems, are shown in Figure 5.

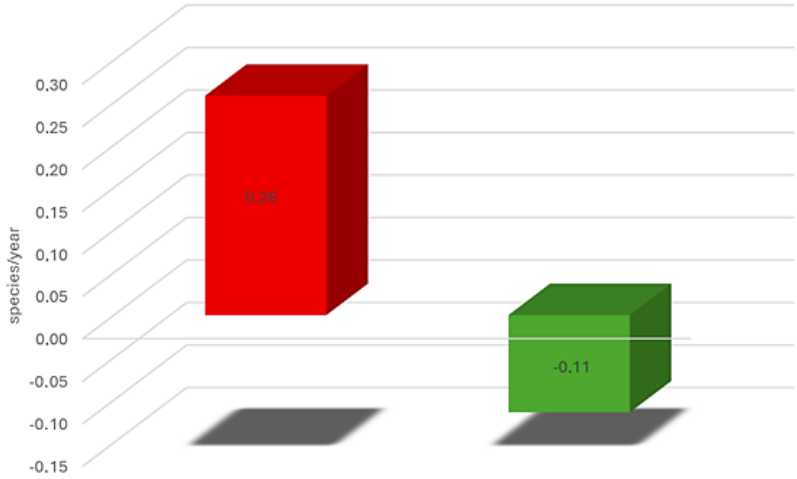


Fig. 5 Characterizing the overall consequences of the life cycle of the analyzed photovoltaic power plant for the environment, in the area of the impact of processes causing depletion of water resources, affecting terrestrial ecosystems (ReCiPe 2016 model), taking into account the method of post-consumer management of materials, materials and elements (RED – landfill, GREEN – recycling)

Alt text: *The figure shows the overall life cycle impacts of the analyzed photovoltaic power plant on water resources and terrestrial ecosystems. The results are presented for two end-of-life scenarios: landfill (red) and recycling (green).*

The findings of describing the environmental effects brought about by the life cycle of the examined solar power plant are compiled in Table 4. In the ReCiPe 2016 model, emissions of chemicals that impact terrestrial ecosystems and cause global warming were considered.

Table 4

Characterizing the consequences of the life cycle of the analyzed photovoltaic power plant for the environment, in the area of the impact of processes causing depletion of water resources, affecting terrestrial ecosystems (ReCiPe 2016 model), taking into account the method of post-consumer management of materials, materials and elements

No	Element of a Technical Object		Photovoltaic Power Plant	
	Waste Scenario		Landfill	Recycling
	Substance	Emission Area		
1	Carbon dioxide, fossil	Air	3.45×10^{-3}	1.18×10^{-3}
2	Carbon dioxide, land transformation	Air	1.00×10^{-5}	9.97×10^{-6}
3	Dinitrogen monoxide	Air	5.35×10^{-5}	3.31×10^{-5}
4	Ethane, haxafluoro-, HFC-116	Air	5.62×10^{-5}	-2.63×10^{-5}
5	Hydrocarbons, chlorinated	Air	1.20×10^{-7}	4.16×10^{-8}
6	Methane, biogenic	Air	3.17×10^{-4}	2.35×10^{-4}
7	Methane, chlorodifluoro-, HCFC-22	Air	2.81×10^{-7}	4.52×10^{-7}
8	Methane, dichlorodifluoro-, CFC-12	Air	2.37×10^{-7}	2.37×10^{-7}
9	Methane, fossil	Air	3.03×10^{-4}	1.60×10^{-4}
10	Methane, tetrafluoro-, CFC-14	Air	3.02×10^{-4}	-1.41×10^{45}
11	Sulfur hexafluoride	Air	5.30×10^{-5}	4.47×10^{-5}
12	Remaining substances	x	5.75×10^{-7}	2.00×10^{-8}
TOTAL			**4.55×10^{-3}**	**1.50×10^{-3}**

Source: own research (unit: species/year).

Recycling and landfill disposal were two other post-use management possibilities that were taken into account. Carbon dioxide emissions from fossil fuels had the greatest detrimental effect on terrestrial ecosystems out of all the pollutants that were found to have an effect (3.45 10-3 species/year during the life cycle with landfill disposal). The life cycle with recycling disposal showed the greatest positive impact. Among other things, the recycling process lowers the amount of methane released into the environment (-1.41 10^{-4} species/year). Carbon dioxide is referenced far more often than methane, which is likewise categorized as a greenhouse gas. Nevertheless, it is an environmentally harmful chemical molecule. One ton of methane has an impact on the climate that is around 85 times larger than one ton of CO_2 over its first 20 years in the atmosphere. Agriculture and the energy sector are the two main suppliers of methane. The main sources of methane emissions from the energy sector are the extraction, transportation, and storage of fossil fuels like coal, oil, and natural gas. In Europe, Poland is the country that emits the most methane from fossil fuels. People's air is significantly contaminated by methane. As a result, conditions like emphysema and asthma may develop. Over the next 20 years, worldwide methane emissions should be cut by about 50%, according to recent reports from the Intergovernmental Panel on Climate Change (IPCC). The importance of the energy sector in this respect is underlined, but no specific reduction measures are described. The rapid phase-out of fossil fuels and the prevention of methane leaks from closed mines and abandoned gas or oil wells appear to be the main solutions. Thus, the acquired results demonstrate how human activity significantly contributes to global warming and lowers air quality. Recycling as a post-consumer management strategy, however, would lower these emissions over the course of the technological facility's life cycle because recovered materials, components, and materials would be reused rather than irretrievably destroyed (landfilled). Considering post-consumer management (landfilling, recycling), Figure 6 shows the cumulative impact values of the photovoltaic power plant's life cycle in terms of emissions of compounds that influence terrestrial ecosystems and cause global warming.

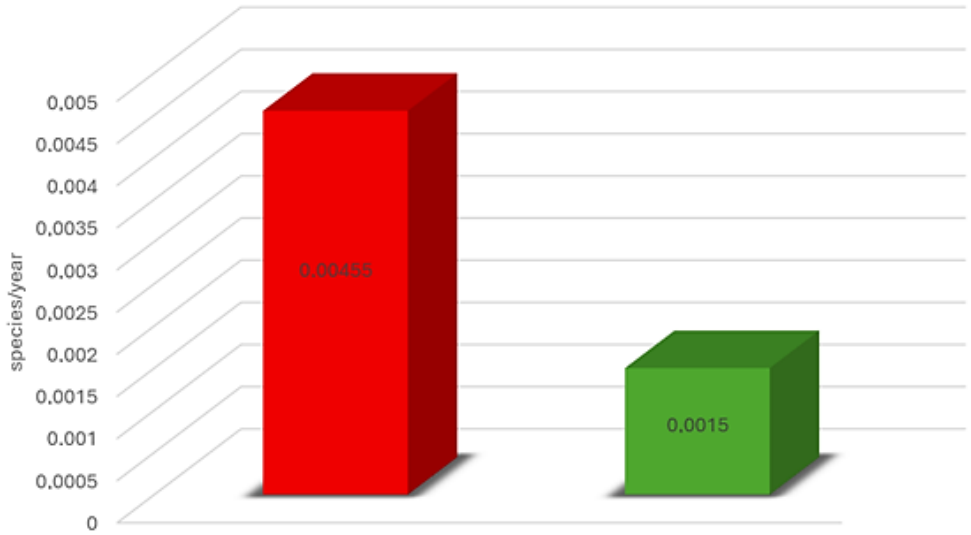


Fig. 6 Characterization of the overall consequences for the environment of the life cycle of the analyzed photovoltaic power plant, in the area of emissions of substances causing global warming, affecting terrestrial ecosystems (ReCiPe 2016 model), taking into account the method of post-consumer management of materials, materials and elements (RED – landfill, GREEN – recycling)

Alt text: *The figure presents the environmental impacts of the analyzed photovoltaic power plant over its life cycle using the ReCiPe 2016 model. It compares landfill and recycling scenarios in terms of global warming emissions and their effects on terrestrial ecosystems.*

The findings of describing the environmental effects brought about by the life cycle of the examined solar power plant are compiled in Table 5.

Table 5

Characterization of the consequences for the environment of the life cycle of the analyzed photovoltaic power plant, in the area of emissions of substances causing soil acidification (ReCiPe 2016 model), taking into account the method of post-consumer management of materials, materials and elements

No	Element of a Technical Object		Photovoltaic Power Plant	
	Waste Scenario		Landfill	Recycling
	Substance	Emission Area		
1	Ammonia	Air	4.47×10^{-5}	2.69×10^{-5}
2	Nitrogen oxides	Air	2.92×10^{-4}	1.51×10^{-4}
3	Solfur dioxide	Air	1.51×10^{-3}	7.07×10^{-4}
4	Sulfur oxides	Air	6.60×10^{-7}	6.60×10^{-7}
5	Sulfur trioxide	Air	1.86×10^{-5}	1.86×10^{-5}
6	Sulfuric acid	Air	3.84×10^{-7}	3.91×10^{-7}
7	Remaining substances	x	2.38×10^{-8}	6.28×10^{-7}
	TOTAL		**1.68×10^{-3}**	**9.04×10^{-4}**

Source: own research (unit: species/year).

In the ReCiPe 2016 model, emissions of compounds that impact terrestrial ecosystems and cause soil acidification were considered. Both recycling and landfill disposal were taken into consideration as post-consumer management scenarios for plastics, materials, and components. Sulfur dioxide has the most detrimental effects on terrestrial ecosystems of all the compounds that have been detected; it causes a number of detrimental environmental effects (1.51 x 10^{-3} species/year throughout the life cycle with landfill disposal). The solar power plant's life cycle with recycling disposal showed the greatest positive impact. Recycling lessens the atmospheric emissions of sulfur dioxide and, as a result, its detrimental acidifying effects on the environment (7.07 x 10^{-4} species/year). Because recovered materials, materials, and components would be reused, recycling as a post-consumer management strategy would lower these emissions over the course of the technical facility under study's life cycle. In terms of emissions of compounds that cause soil acidification, Figure 7 shows the cumulative impact values of the solar plant's life cycle, accounting for post-consumer management (landfill, recycling).

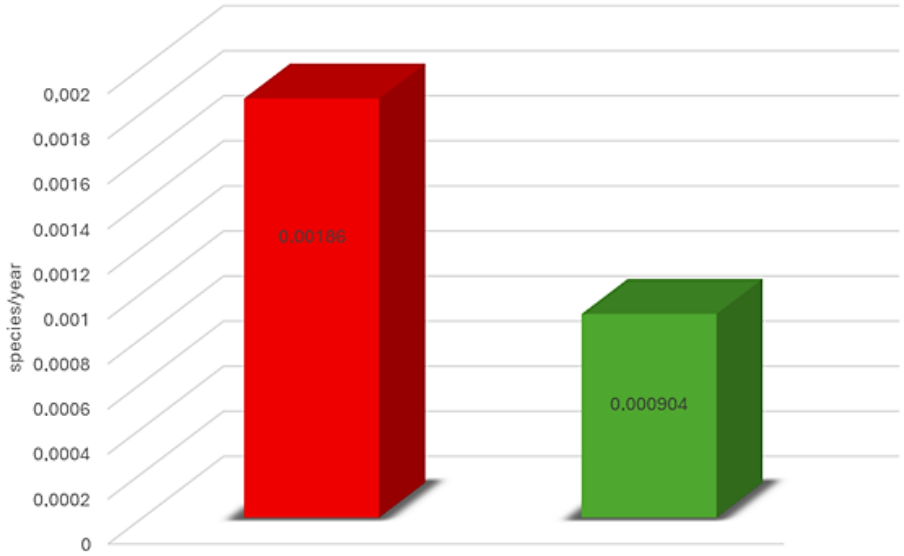


Fig. 7 Characterization of the overall consequences of the life cycle of the analyzed photovoltaic power plant for the environment, in the area of emissions of substances causing soil acidification (ReCiPe 2016 model), taking into account the method of post-consumer management of materials, materials and elements (RED – landfill, GREEN – recycling)

Alt text: *The figure presents the environmental impacts of the analyzed photovoltaic power plant over its life cycle using the ReCiPe 2016 model. It compares landfill and recycling scenarios in terms of emissions causing soil acidification.*

CONCLUSIONS

Units like DALYs and species/year are utilized at the endpoint level in the ReCiPe 2016 technique to evaluate the system's ultimate impact on ecosystems and human health.

Disability Adjusted Life Years are referred to as DALYs. The influence of the environment on human health is measured using this unit. The DALY value in life cycle assessments (LCA) shows the number of years of healthy life that might be lost as a result of radiation, pollution, climate change, or other environmental effects associated with a process or product's life cycle. The detrimental effect on human health increases with the DALY value.

Ecosystem effects are measured in species/year. It shows the possible loss of species during a specific time frame and is typically understood as the proportion of species that are at risk of going extinct in a particular year as a result of environmental effects. This unit makes it possible to evaluate how land use, eutrophication, acidification, and climate change affect ecosystem functioning. A higher species/year ratio denotes a higher risk of biodiversity loss and environmental damage.

These units are part of the so-called endpoint indicators, which allow the findings of the LCA study to be presented in a form that is easier to grasp and directly relates to the environmental repercussions for both humans and nature.

Recycling is a crucial tactic for reducing adverse effects on the environment and human health, according to a life-cycle analysis of the solar power plant that takes into account different post-consumer waste management scenarios (recycling vs. landfilling). Research findings from the ReCiPe 2016 model, in particular, show that material recovery has a major positive impact on air pollution, water consumption, and emissions of harmful chemicals.

For instance, when it came to water usage, the solar power plant's turbine operation procedures had the biggest detrimental effect on human health (4.24×10^{1} DALY in the landfill scenario). Significant improvements were made by using recycling as a waste management technique, which decreased this impact to -1.88×10^{1} DALY.

The findings also demonstrate the importance of recycling in lowering greenhouse gas emissions. Recycling significantly reduced methane emissions, which in turn lessened the impact on climate change from -1.41×10^{-4} species/year. The depletion of water and mineral resources also significantly increased expenses (USD 1.22×10^{5} for fossil fuels, for example). However, since recovered materials can be utilized again rather than being lost forever, recycling lowers these expenses.

The findings also demonstrate the gravity of the decline of water resources and how it affects terrestrial ecosystems. Comparing the recycling scenario to the landfill scenario, the environmental effect in terms of species loss decreased by about 50% (from -7.25×10^{-2} species/year to -3.29×10^{-1} species/year).

According to the investigation, recycling materials at every stage of a solar plant's life cycle offers quantifiable advantages for the environment and human health. The detrimental effects on human health and environmental quality are greatly lessened by cutting back on water use, pollution emissions, and the depletion of natural resources. Thus, putting into practice efficient recycling techniques is a big step in the direction of renewable energy's sustainable growth, particularly in light of the escalating problems of environmental degradation and global warming.

The updated literature also strengthens the practical implications of the study. The integration of PV and wind power in Poland requires system flexibility, storage and stable regulatory conditions [14], while the selection of renewable energy sources in industry should be supported by multi-criteria decision methods [50]. From the circular-economy perspective, the results are additionally consistent with current research showing that recycling processes can be improved through DMAIC-based management [36] and that waste-management eco-efficiency can be evaluated using quantitative approaches such as DEA [53, 56].

Only a few effect categories from the extensive ReCiPe 2016 analysis are covered by the research findings that are being presented. The scope of this research might be expanded to include other regions that could be impacted by hazardous pollution, or it could take a different strategy, similar as ReCiPe 2016.

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