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Management of Environmental Life Cycle Impact Assessment of a Photovoltaic Power Plant on the Atmosphere, Water, and Soil Environment

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Abstract: Photovoltaic power plants are considered to be environmentally friendly solutions to the production of electricity. Solar energy conversion does not release toxic compounds into the environment. However, the construction of solar power plant components (photovoltaic modules, sup-porting structure, inverter station, electrical installation) is extremely consumptive of energy and materials. Massive volumes of minerals, fossil fuels, and electricity are consumed during the manufacturing process. Efficient management of energy and environmental resources seems to be critical for national policy. It is crucial to admit that the post-consumer management of the components of a photovoltaic power plant is connected with a certain quantity of energy and matter and a negative impact on the natural environment. A life cycle assessment was carried out on a real 2 MW photovoltaic power plant located in the northern part of Poland. The analysis was carried out applying the ReCiPe 2016 model and the Life Cycle Assessment (LCA) approach. The impact of the examined renewable energy system was evaluated using 22 impact categories and 3 emission areas (air, water, soil). Life Cycle Assessment analysis was carried out for 2 post-consumer development scenarios (landfill and recycling). The examination of the collected results reveals that photovoltaic modules are the element causing the most negative environmental repercussions connected to the release of dangerous compounds into the atmosphere. Post-consumer development in the form of recycling would provide major environmental benefits and reduce detrimental environmental consequences across the whole life cycle of the photovoltaic power plant. The obtained research results enabled the formulation of pro-environmental recommendations aimed at the long-term development of the life cycle of solar power plants.

Keywords: energy; energy management; life cycle assessment (LCA); management; photovoltaic power plant; ReCiPe 2016; renewable energy sources; resource management

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1. Introduction

1.1. Background

Every year, the demand for electricity in all countries of the world will continue to grow (Figure 1) [1]. The traditional method of generating electricity degrades the quality of the environment. To combat climate change, energy must come from more and more sustainable sources, with lower levels of toxic substances emitted into the natural environment. Environmental actions are thus associated with the creation of additional so-called "green" or "clean" energy. Natural processes provide renewable energy. It can be solar energy, water energy, wind energy, geothermal energy, or bioenergy [2–5].

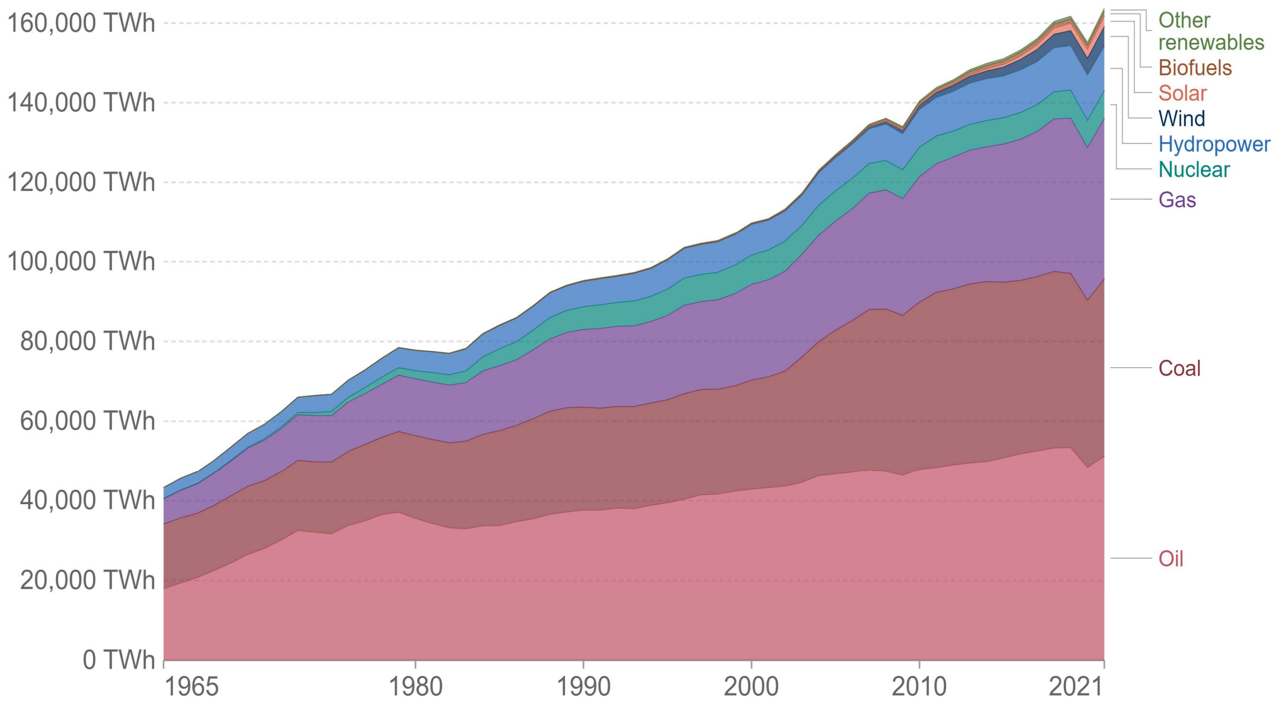

Figure 1. Energy consumption by source, World [1].

Energy and environmental management are critical components of a country's energy policy. Its implementation results in less media consumption; the management process is one of the many strategies to reduce energy and water use. Because global energy consumption is unavoidable and constantly increasing, steps must be taken to assure its reasonable usage [6,7].

Effective management of energy and mineral resources has become an essential and inseparable component of practically every aspect of our lives. Its rise in popularity is intimately tied to the global economic crisis. The negative consequences of the crisis can be reduced by introducing cost-cutting programs, which are closely related to wise and effective management [7,8].

The constant development of renewable energy sources in Poland and around the world encourages an increase in interest and investment in renewable energy sources. Today, photovoltaic installations are the most common. Solar radiation is used to create power in these installations. However, the life cycle of these types of technical systems is linked to a certain level of energy and matter consumption [9–11].

Changes in economic conditions and social expectations require that, in addition to building, production, and operating aspects, environmental protection objectives be considered in the life cycles of technical objects. Maintaining the current model of operation will prevent the introduction of positive changes in environmental quality as the current model is irrational in terms of sustainable development and consists of producing and selling products, generating waste, and depositing it in the environment. The development and implementation of actions targeted at the ecological, energy, and economic optimization of technological facilities aims to transform the management model into one that is as close to a closed circulation of energy and matter as possible. This would allow for greater efficiency in the use of raw material resources while minimizing negative environmental repercussions [2,8,12–14].

Currently, the life cycle of energy facilities (including renewable energy) is being assessed. Its control should be exercised from the beginning of the cycle, i.e., the formulation of the need, through the end, i.e., post-consumer development. This procedure enables the evaluation of interactions (both positive and negative) between the environment and the technical object. As a result, for the analysis, one of the most extensively used Life Cycle

Assessment (LCA) methods was chosen. This method allows for the investigation of a technical object's complete life cycle, beginning with design and ending with post-consumer development. LCA analyzes include:

- evaluation of environmental issues in the context of design, production, operation, and development, based on analyses of energy consumption and matter, as well as the occurrence of detrimental effects on the environment in the form of chemical compound and waste emissions;
- evaluation of the interaction between the technical facility and the environment, taking into account the facility's positive and negative environmental impact;
- evaluation of the possibilities of eliminating or decreasing the negative impact of a technological object's life cycle on the environment [15,16]

1.2. Literature Review

There are no studies in the international literature that use the relatively new ReCi-Pe 2016 approach to completing life cycle analyses of solar power facilities. Most research focuses solely on the impact of power plant life cycles on Global Warming Potential (GWP), ignoring other negative impacts on environmental quality and human health, as well as the depletion of raw material resources. These items also require detailed analysis, particularly in the context of sustainable energy system development.

In the case of LCA analyses for photovoltaic systems, the subject of their research is typically into the various types of materials from which PV modules are constructed. The most analyses were devoted to silicon-based elements, for example: Alsema [17], Frankl and others [18], Fthenakis and Kim [19], and Dones and Frischknecht [20]; Kato and others [21] studied the life cycle of single-crystalline silicon, sc-Si modules. On the other hand, the analyses conducted by Alsema [17], Fthenakis and Alsema [22], Fthenakis and Kim [19], Dones and Frischknecht [20], Ito and others [23,24], Kato and others [21], Nomura and others [25], and Oliver and Jackson [26] were based on multi-crystalline silicon, mc-Si. Alsema [17], Ito and others [23], and Kato and others [21] studied amorphous-silicon, a-Si. However, there are no studies in the world literature on the assessment of the life cycle of solar systems that use the ReCiPe 2016 technique. The majority of the research is focused on calculating CO2 and other greenhouse gas emissions [17–31].

The latest research includes research related to photovoltaic systems. Research concerns include Greenhouse Emissions [31], LCA of an Integrated PV-ACAES System [32], Comparison of Environmental Impact Assessment Methods [5] and the LCA-concerned wind farm power plant Sobaszek [13].

As previously stated, other repercussions that affect ecosystem quality, pose a threat to human health, and intensify the depletion of raw material resources are frequently overlooked.

1.3. Research Contribution

There is limited research on the life cycle of photovoltaic power facilities in the worldwide literature. However, in Poland, analyses employing the LCA methodology are still uncommon. The article attempts to outline the local perspective on the topic of the environmental impact of the chosen renewable energy source. As a result, an existing photovoltaic power plant—a 2 MW photovoltaic power plant in northern Poland—was examined. By keeping a local viewpoint, the author hoped to attract attention to a larger issue and contribute to raising public understanding of the environmental consequences of the renewable energy source's life cycle.

Main contribution of this research:

1. A local viewpoint on the environmental impact of the chosen renewable energy source.
2. An examination of existing solar power plants.
3. An increase in public awareness of the environmental consequences of the renewable energy source's life cycle.
4. Use of the ReCiPe 2016 model.

5. Assessment of the impact on the environment of the photovoltaic power plant in the life cycle.
6. Analysis of air, soil, and water emissions.

Eco-technology is an understandable combination of the technical operation of machines, devices, and technical facilities, including photovoltaic installations, with the need for continuous protection, improvement, shaping, positive progress, and development of both the human environment, such as soil, water, air, animals, plants, urban areas, rural areas, and the Earth, and raw materials, such as construction materials, elements, machines, devices, individual tools, or entire industries [33].

In this article, the main objective of the research was the environmental assessment of the impact on the environment of the photovoltaic power plant in the life cycle, specifically, emissions to the atmosphere, soil, and water, using the ReCiPe 2016 model.

2. Materials and Methods

2.1. Object and Plan of Analysis

The clear specification of the target of analysis was the first step in identifying the research problem. The study's focus was a solar power plant with a capacity of 2 MW. The relationships occurring within the study item, on the other hand, were the subject of the analyses, as were the relationships between the considered object and its surroundings.

The identification of locations with the highest level of detrimental environmental impact plays the most important role in the sustainable life cycle of machinery, equipment, and renewable energy installations. Each stage of the life cycle, particularly the specificity of the processes that occur in it, necessitates a unique strategy. This is the fundamental assumption of the LCT–Life Cycle Thinking standard, which takes into account changes within its separate stages. LCA (Life Cycle Assessment) is the most commonly utilized tool in environmental life cycle analyses of technical goods. Identification of the processes occurring in their individual stages, defined by the highest level of negative (or positive) consequences, would enable long-term management of the tested solar power plant's life cycle (LCM–Life Cycle Management) [34].

The ISO 14000 standard defines the LCA structure as four essential components: aim and scope definition, analysis of the set of inputs and outputs–LCI (Life Cycle Inventory), effect assessment–LCIA (Life Cycle effect Assessment), and result interpretation. In general, LCA analysis entails determining and quantifying the potential environmental effects of a given product's performance of a certain function. The function, functional unit, and reference stream are crucial in the LCA technique. The functional unit is the quantitative effect of a product system that is used as a reference unit in life cycle analysis studies (for example, the quantity of energy generated by a solar power plant during its full life cycle in MWh). The reference stream, on the other hand, is defined as the measure of outputs or processes in a specific product system that are required to complete the function specified by the functional unit. Figure 2 depicts a graphical representation of the basic steps of LCA analysis [35].

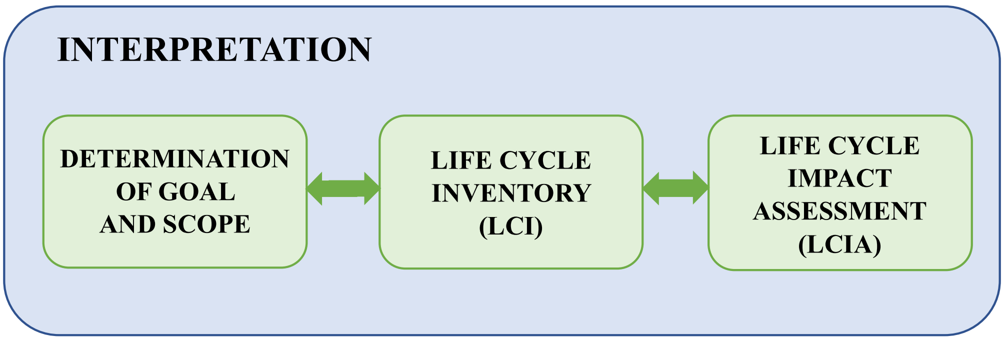

Figure 2. Graphic diagram showing the main stages of LCA analysis. Own elaboration based on [26].

The model utilized during the LCIA was ReCiPe 2016. The ReCiPe methodology determines indicators for 22 impact categories and 3 impact locations. The impact category indicators focus on specific environmental problems, whereas the impact area indicators illustrate the impact on the environment at three higher levels of aggregation. In comparison to other models, ReCiPe 2016 contains the most comprehensive set of impact categories. ReCiPe 2016 is an enhancement to the ReCiPe 2008 model as well as previously utilized models such as Eco-indicator 99. In contrast to the previous version, ReCiPe 2016 considers not only local but also global elements affecting the area of Europe, and thus it performs extremely well in the cycle analysis of the existence of renewable energy technical facilities [36].

The publication process began with a survey of the literature in the research topic. Section 2.2 presented the justification for pursuing the topic mentioned in the title. It also includes the primary research problem. The appropriateness of the choice of analyses was estimated using the LCA (Life Cycle Assessment) method. Section 2.3 contains the second phase of the LCI (Life Cycle Inventory) investigation. LCI enabled a complete examination of the structure of the tested solar power plant, determining the percentage share of individual elements and materials. The required simulation analyses were performed with the SimaPro 9.4.0 software and the ReCiPe 2016 calculation process. This stage's progression is detailed in Section 2.4. The investigation concluded with the interpretation of the acquired results (described in Section 2.5). The acquired results are reported in Section 3, and their interpretation is detailed in Section 4 [37].

2.2. Determination of Goals and Scope

The first stage of the LCA analysis is determining the aim and scope of the investigation. The most crucial decisions that define the overall assessment of the impact on the environment are made during this stage. The analysis's goal was to conduct an environmental assessment of the photovoltaic power plant's influence on the environment throughout its life cycle, with a focus on three areas of impact: air (atmosphere), soil, and water.

LCA is a process used to assess the potential for environmental hazards. Their identification is achieved by quantifying the amount of matter and energy utilized, as well as waste released into the environment, and then assessing the impact of these processes on the natural environment's quality, human health, and raw material depletion. The analyses span a product's complete life cycle, beginning with the extraction of raw materials required for production and continuing through production and distribution procedures to post-consumer management. This means that using the LCA method when designing renewable energy technological facilities allows for more efficient management of matter and energy over their entire life cycle, which translates to, among other things, lower consumption for production purposes and wider use in recycling processes [38].

The LCA method is helpful in:

- ○ assessment of potential environmental improvements for renewable energy technological installations at various stages of their life cycle;
- ○ making particular, critical decisions in government, non-government groups, and industry;
- ○ marketing [34].

This method estimates the interaction of a technical object with its surroundings. P. Hofstetter believes that three distinct zones should be distinguished in LCA investigations:

- ○ technosphere: denotes the technical system (e.g., production, transportation), where uncertainty is low and most measurements can be confirmed and repeated.
- ○ ecosphere: defined as the ecological mechanism.
- ○ value domain: defined by subjective choices, encompasses the influence, allocation, and modeling of the natural environment [34].

The system boundaries, data quality standards, functional unit, and effect categories are all part of the LCA analysis area. The great majority of processes that occur or will occur within the assessed life cycle of a solar power plant occur or will occur in Europe. Because the companies who contributed the data have a very strong position in the entire European market, the geographical scope of the analyses is Europe. A photovoltaic power plant has an estimated lifespan of 20–25 years. In the analysis, the cut-off level will be 0.01%. This means that the accuracy of the reported results will be compromised since compounds emitted during the life cycle with an impact level less than 0.01% of the overall impact will be excluded. The results of the analysis will be used primarily to describe the current reality (retrospective analysis), but also to construct more environmentally friendly solutions (prospective analysis).

A traditional LCA approach will be carried out in accordance with the ISO 14040 and ISO 14044 standards. The data utilized in the investigation came directly from the manufacturers or were retrieved from the SimaPro program databases. Function and functional unit are particularly important in LCA analysis methodologies. The process of generating power is the primary function of the facility under consideration. This indicates that the installed capacity of 2 MW should be considered a working unit. The assessment's energy-ecological (energy-environmental) aspects include 22 impact categories related to the ReCiPe 2016 model. The test results will be further grouped, and three emission zones will be specified: air, soil, and water.

2.3. LCI (Life Cycle Inventory)

The second stage of LCA is the analysis of the set of inputs and outputs. The Life Cycle Inventory (LCI) describes the system structure of a particular technical object. Material and energy streams connect all processes that occur during the life cycle of a solar power plant. All acquired data will be assigned to unit processes, which will subsequently be validated based on energy and mass balance. The magnitude (value) of the inputs must equal the magnitude (value) of the outputs. Inputs will include the primary materials, auxiliary materials, and water requirements. Outputs, on the other hand, will include the primary product as well as pollutants. Information on critical operations was gathered directly from material and component makers. Data on processes and materials with a lower influence on the natural environment, on the other hand, will be retrieved from the SimaPro 9.4.0 software's databases.

The overall weight of the evaluated photovoltaic power plant's plastics, materials, and elements is around 300,000 kg. Photovoltaic modules account for approximately 62% of the total weight of the facility (approximately 47% of the weight of the photovoltaic panels is solar glass and approximately 45% is aluminum). The supporting structures account for approximately 21% of the total weight of the analyzed technical object (most of which is made of steel), the inverter station accounts for approximately 15% of the weight of the object (its elements are primarily made of steel, which accounts for approximately 38% of the total weight), and the electrical installation accounts for approximately 2% of the total mass (based primarily on copper). Table 1 and Figure 3 provide the comprehensive list of materials, while Table 2 and Figure 4 reveal the list of photovoltaic power plant elements.

Table 1. Bill of materials of the analyzed photovoltaic power plant [investor's data].

Bill of Materials		
Material Name	**Mass**	**Unit**
Aluminum	85,120	kg
Steel	82,000	kg
Solar glass	79,230	kg
Copper	5000	kg
Others	9264	kg

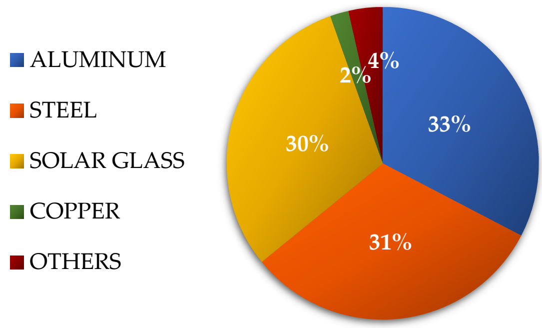

Figure 3. Percentage division of the mass of materials of the considered photovoltaic power plant [investor's data].

Table 2. List of elements of the analyzed photovoltaic power plant [investor's data].

List of Elements		
Name of the Element	**Mass**	**Unit**
Photovoltaic modules	161,100	kg
Supporting structure	53,320	kg
Inverter station	40,000	kg
Electrical installation	6194	kg

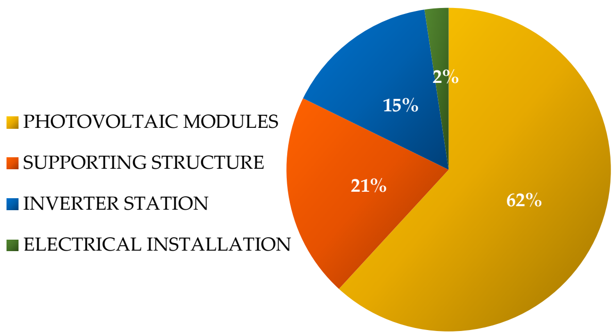

Figure 4. Percentage division of the elements of the considered photovoltaic power plant [investor's data].

2.4. LCIA (Life Cycle Impact Assessment)

The third step of the LCA study, i.e., LCIA (Life Cycle Impact Assessment), is critical when estimating the environmental impact of a photovoltaic power plant's life cycle. All methodological variations across LCA techniques are mostly related to the LCIA phase, which includes both necessary and optional aspects. The following aspects are required: impact categories, category indicators, categorization, and characterization. Normalizing, grouping, and weighing are optional aspects. When performing analyses, the order of mandatory items is carefully established and must be followed. However, the user should decide whether or not to use the optional elements. SimaPro 9.4.0 software (Pré Sustainability, LE Amersfoort, The Netherlands) will be used for the analyses. The ReCiPe 2016 model will be used to evaluate a solar power plant's life cycle. Figure 5 depicts a graphical representation of the required and optional LCIA elements [34].

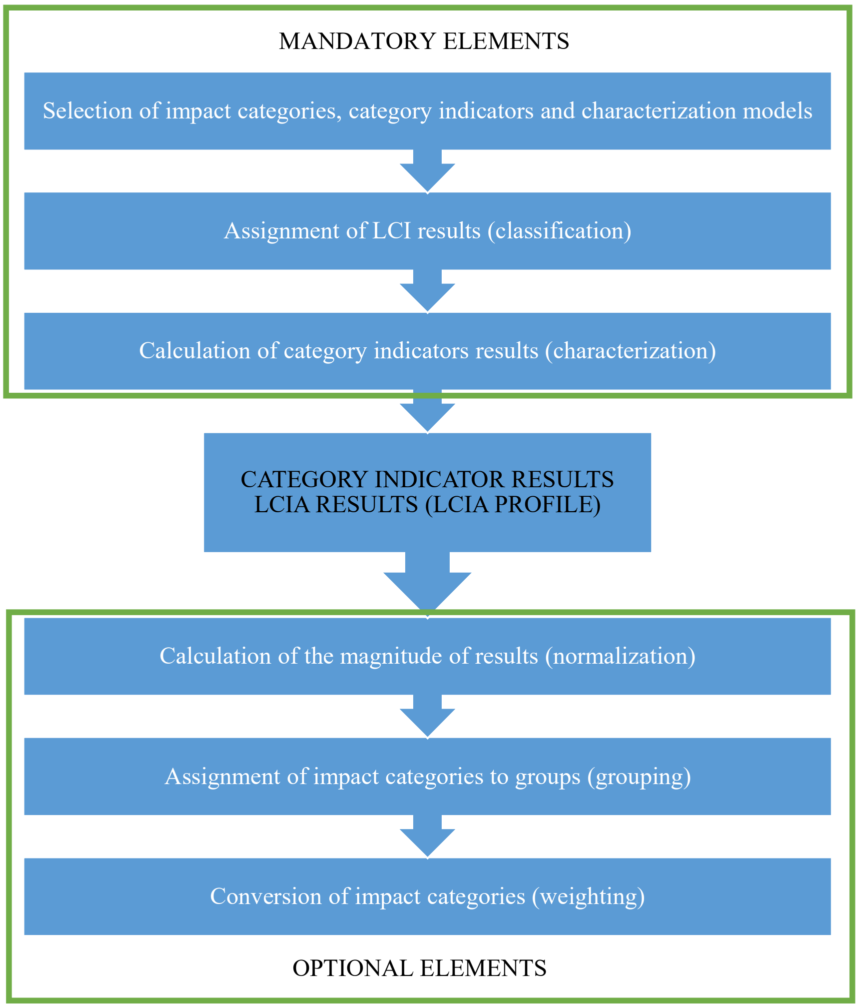

Figure 5. Graphic diagram of mandatory and optional LCIA elements. Elaboration by the authors based on [39].

LCI results are classified by allocating them to certain effect categories. This process can be automated with the use of appropriate, specialized software. The SimaPro 9.4.0 program will be used for categorization, which automatically allocates LCI results to individual impact categories based on a list of compounds from the program's calculating methods and databases. The techniques of characterizing and turning LCI results into impact category indicators are quite complex. Technically, they consist of translating the LCI results by proper characterization factors and displaying them as relative shares in each of the effect categories. The ReCiPe 2016 approach will be the primary calculating procedure employed in this analysis [34].

Normalization is the process of calculating the size of category indicator scores in relation to reference data. It is used to assess the relative relevance of index results relating to a specific location, such as Poland, Europe, or a person. Furthermore, normalization can be used to prepare LCIA results for later operations, such as weighing. The SimaPro program will be used to evaluate normalization as part of the investigation. This is the stage required for subsequent ones, such as grouping and weighing. There are several methods and preferences for valuing the effect categories. Some may be more essential than others, depending on the goal and scope of the analysis. They can be classified based on the amount of emission or the scale (global, local) [34].

Grouping occurs in the ReCiPe 2016 approach when the findings of 22 impact category indicators are summed up into 3 regions of impact and before final aggregation to the total effect indicator [34].

Weighting is the process of determining and providing a level of relevance, i.e., a weighting factor, to individual effect categories and multiplying them by non-normalized indicator values. The weighting stage should be carried out using a comprehensive, internationally accepted set of weighting criteria defined for all impact categories. By carrying out the weighing process, it is possible to receive results in Pt (environmental points). One thousand environmental points (1000 Pt) equals the environmental impact of one European person in one year. SimaPro 9.4.0 software will be used to complete grouping and weighting during life cycle analyses of a photovoltaic power plant [34].

2.5. Interpretation

The final stage of the LCA technique is the interpretation of the acquired results. The results of the LCI or LCIA are summarized, analyzed, and remarked on in the phase that concludes a series of previously specified actions. The interpretation stage serves as the foundation for drawing conclusions and summarizing judgments taken in accordance with the purpose and scope that were previously stated. The following can be noted at this stage:

- prioritization of threats,
- analysis of potentially dangerous elements,
- defining methods of minimizing risks,
- inclusion of amendments,
- presentation of further actions [15,40].

On the one hand, the interpretation is the final stage of the LCA analysis (the fourth stage), yet it is still present in each of the three prior stages of the procedure (defining the goal and scope, LCI, and LCIA). The major goal of the interpretation is to analyze the results and verify them in light of the previously specified purpose and scope of the research. This point will be implemented in Chapters 3 and 4 of this article.

3. Results

Tables 3 and 4 detailed the results of grouping and weighing the environmental consequences of the examined photovoltaic power plant's life cycle in terms of emissions to the atmosphere, water, and soil environment. The ReCiPe 2016 model's impact categories are all included. Two methods of post-consumer management of plastics, materials, and components were also considered: landfill and recycling. The effect categories with the highest level of negative influence on the atmospheric environment were found to be Fine particle matter production (3.62×10^4 Pt–landfill) and Global warming, Category of human health impact (2.52×10^4 Pt–landfill). In terms of influence on the aquatic environment, the Human carcinogenic toxicity impact category (1.60×10^4 Pt–landfill) and Human non-carcinogenic toxicity impact category (4.03×10^4 Pt–landfill) had the highest unfavorable consequences. The soil environment was the last emission region studied. Human carcinogenic toxicity effect category (1.98×10^2 Pt–landfill) and Human non-carcinogenic toxicity impact category (1.07×10^2 Pt–landfill) had the highest level of negative effects in this regard, similar to the aquatic environment.

The usage of recycled plastics, materials, and elements from the examined photovoltaic power plant would allow for a reduction in the size of negative environmental consequences in the emission areas considered. This is especially obvious in the effect category of emissions to the aquatic environment (-1.69×10^5 Pt). Figure 6 depicts the total values of a solar power plant's life cycle impact, taking into account the type of post-consumer management strategy (landfill, recycling) in terms of emissions to the atmosphere, water, and soil environments. It demonstrates the critical significance of recycling in reducing the negative environmental implications of water discharges.

Table 3. Grouping and weighing the consequences for the environment during the life cycle of the analyzed photovoltaic power plant in terms of emissions to the atmosphere, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and elements (landfill) [unit: Pt] (authors' research).

No.	Element of a Technical Object	Photovoltaic Power Plant		
	Waste Scenario	Landfill		
	Emission Area	Air	Water	Soil
	Impact Category			
1	Global warming, Human health	2.52×10^4	X	-6.70×10^{-1}
2	Global warming, Terrestrial ecosystems	1.23×10^3	X	-3.28×10^{-2}
3	Global warming, Freshwater ecosystems	3.36×10^{-2}	X	-8.96×10^{-7}
4	Stratospheric ozone depletion	7.74×10^0	X	X
5	Ionizing radiation	5.20×10^1	3.31×10^{-1}	X
6	Ozone formation, Human health	6.02×10^1	X	X
7	Fine particulate matter formation	3.62×10^4	X	X
8	Ozone formation, Terrestrial ecosystems	1.41×10^2	X	X
9	Terrestrial acidification	5.04×10^2	X	X
10	Freshwater eutrophication	X	2.02×10^2	1.36×10^{-2}
11	Marine eutrophication	X	1.10×10^{-1}	2.05×10^{-6}
12	Terrestrial ecotoxicity	1.13×10^2	5.27×10^{-6}	3.89×10^{-3}
13	Freshwater ecotoxicity	5.40×10^{-2}	7.51×10^1	7.54×10^{-3}
14	Marine ecotoxicity	4.28×10^{-1}	1.57×10^1	1.02×10^{-3}
15	Human carcinogenic toxicity	4.32×10^2	1.60×10^4	1.98×10^2
16	Human non-carcinogenic toxicity	3.14×10^3	4.03×10^4	1.07×10^2
17	Land use	X	X	X
18	Mineral resource scarcity	X	X	X
19	Fossil resource scarcity	X	X	X
20	Water consumption, Human health	X	-1.92×10^5	X
21	Water consumption, Terrestrial ecosystem	X	-1.98×10^4	X
22	Water consumption, Aquatic ecosystems	X	-1.40×10^0	X
	TOTAL	$\mathbf{6.70 \times 10^4}$	$\mathbf{-1.55 \times 10^5}$	$\mathbf{3.04 \times 10^2}$

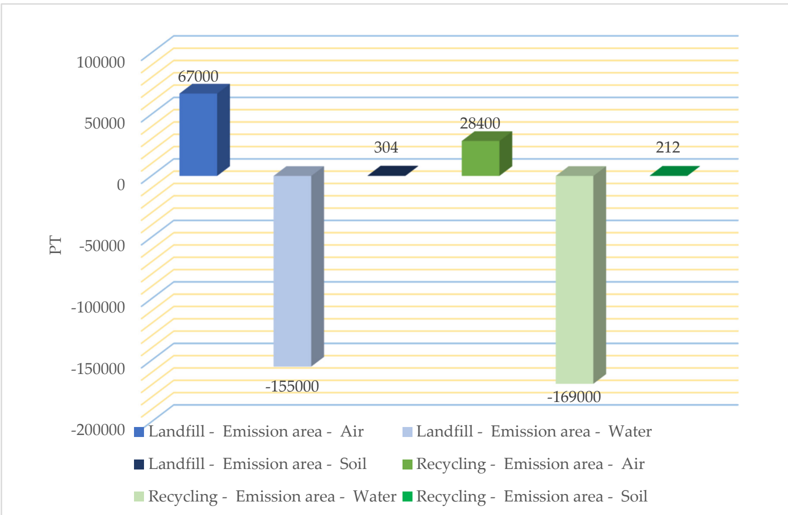

Figure 6. Grouping and weighting of the total consequences for the environment during the life cycle of the analyzed photovoltaic power plant in terms of emissions to the atmosphere, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and elements [unit: Pt] (authors' research).

Table 4. Grouping and weighing the consequences for the environment during the life cycle of the analyzed photovoltaic power plant, in terms of emissions to the atmosphere, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and elements (recycling) [unit: Pt] (authors' research).

No.	Element of a Technical Object	Photovoltaic Power Plant		
	Waste Scenario	Recycling		
	Emission Area / Impact Category	Air	Water	Soil
1	Global warming, Human health	8.29×10^{3}	X	-6.55×10^{-1}
2	Global warming, Terrestrial ecosystems	4.05×10^{2}	X	-3.21×10^{-2}
3	Global warming, Freshwater ecosystems	1.11×10^{-2}	X	-8.76×10^{-7}
4	Stratospheric ozone depletion	4.54×10^{0}	X	X
5	Ionizing radiation	1.45×10^{1}	2.90×10^{-1}	X
6	Ozone formation, Human health	3.14×10^{1}	X	X
7	Fine particulate matter formation	1.68×10^{4}	X	X
8	Ozone formation, Terrestrial ecosystems	7.43×10^{1}	X	X
9	Terrestrial acidification	2.45×10^{2}	X	X
10	Freshwater eutrophication	X	1.49×10^{2}	1.14×10^{-2}
11	Marine eutrophication	X	7.95×10^{-2}	2.05×10^{-6}
12	Terrestrial ecotoxicity	8.94×10^{1}	4.04×10^{-6}	3.81×10^{-4}
13	Freshwater ecotoxicity	4.58×10^{-2}	6.55×10^{1}	5.41×10^{-3}
14	Marine ecotoxicity	3.37×10^{-1}	1.37×10^{1}	6.94×10^{-4}
15	Human carcinogenic toxicity	3.10×10^{2}	6.19×10^{3}	1.12×10^{2}
16	Human non-carcinogenic toxicity	2.19×10^{3}	3.50×10^{4}	1.01×10^{2}
17	Land use	X	X	X
18	Mineral resource scarcity	X	X	X
19	Fossil resource scarcity	X	X	X
20	Water consumption, Human health	X	-1.91×10^{5}	X
21	Water consumption, Terrestrial ecosystem	X	-1.97×10^{4}	X
22	Water consumption, Aquatic ecosystems	X	-1.37×10^{0}	X
	TOTAL	$\mathbf{2.84 \times 10^{4}}$	$\mathbf{-1.69 \times 10^{5}}$	$\mathbf{2.12 \times 10^{2}}$

Tables 5 and 6 describe the findings of grouping and weighting the environmental repercussions of the life cycle of the examined photovoltaic power plant's supporting structure in terms of emissions to the atmosphere, water, and soil. The ReCiPe 2016 model's impact categories were all taken into account. Two post-consumer development scenarios were considered once more. The Global warming, Human health impact (2.09×10^{3} Pt–landfill), and Fine particulate matter creation impact categories (1.76×10^{3} Pt–landfill) had the highest amount of negative impact on the atmospheric environment. In terms of influence on the aquatic environment, the Human carcinogenic toxicity impact category (2.70×10^{3} Pt–landfill) and Human non-carcinogenic toxicity impact category (2.13×10^{3} Pt–landfill) had the most severe results. The soil environment was the last emission region studied. Human carcinogenic toxicity impact category (8.32×10^{-1} Pt–landfill) and Human non-carcinogenic toxicity impact category (1.11×10^{0} Pt–landfill) had the highest level of negative effects in this regard, similar to the aquatic environment. The use of recycling techniques for plastics, materials, and components of the examined solar power plant would allow for a reduction in the size of negative environmental repercussions in the emission areas considered, particularly in terms of emissions to the water environment (-2.66×10^2 Pt). Figure 7 depicts the entire life cycle effect values of the solar power plant's supporting structure, taking into account the type of post-consumer treatment (landfill, recycling) in terms of emissions to the atmosphere, water, and soil environments. There is a particularly high level of destructive environmental implications in the area of emissions to the atmosphere.

Table 5. Grouping and weighing the consequences for the environment during the life cycle of the supporting structure of the analyzed photovoltaic power plant in terms of emissions to the atmosphere, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and components (landfill) [unit: Pt] (authors' research).

No.	Element of a Technical Object	Supporting Structure		
	Waste Scenario	Landfill		
	Emission Area	Air	Water	Soil
	Impact Category			
1	Global warming, Human health	2.09×10^3	X	-4.34×10^{-2}
2	Global warming, Terrestrial ecosystems	1.02×10^2	X	-2.13×10^{-3}
3	Global warming, Freshwater ecosystems	2.80×10^{-3}	X	-5.81×10^{-8}
4	Stratospheric ozone depletion	1.69×10^{-1}	X	X
5	Ionizing radiation	2.69×10^{-1}	1.22×10^{-3}	X
6	Ozone formation, Human health	3.75×10^0	X	X
7	Fine particulate matter formation	1.76×10^3	X	X
8	Ozone formation, Terrestrial ecosystems	9.29×10^0	X	X
9	Terrestrial acidification	1.42×10^1	X	X
10	Freshwater eutrophication	X	2.97×10^1	6.23×10^{-4}
11	Marine eutrophication	X	2.15×10^{-2}	1.02×10^{-7}
12	Terrestrial ecotoxicity	4.73×10^{-1}	3.02×10^{-7}	7.57×10^{-6}
13	Freshwater ecotoxicity	7.04×10^{-4}	5.39×10^0	1.32×10^{-4}
14	Marine ecotoxicity	2.47×10^{-3}	1.09×10^0	1.91×10^{-5}
15	Human carcinogenic toxicity	3.97×10^0	2.70×10^3	8.32×10^{-1}
16	Human non-carcinogenic toxicity	1.53×10^1	2.13×10^3	1.11×10^0
17	Land use	X	X	X
18	Mineral resource scarcity	X	X	X
19	Fossil resource scarcity	X	X	X
20	Water consumption, Human health	X	-2.87×10^3	X
21	Water consumption, Terrestrial ecosystem	X	-3.05×10^2	X
22	Water consumption, Aquatic ecosystems	X	-5.65×10^{-2}	X
	TOTAL	$\mathbf{4.00 \times 10^3}$	$\mathbf{1.69 \times 10^3}$	$\mathbf{1.90 \times 10^0}$

Table 6. Grouping and weighing the consequences for the environment during the life cycle of the supporting structure of the analyzed photovoltaic power plant in terms of emissions to the atmospheric, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and components (recycling) [unit: Pt] (authors' research).

No.	Element of a Technical Object	Supporting Structure		
	Waste Scenario	Recycling		
	Emission Area	Air	Water	Soil
	Impact Category			
1	Global warming, Human health	1.49×10^{3}	X	-4.34×10^{-2}
2	Global warming, Terrestrial ecosystems	7.28×10^{1}	X	-2.13×10^{-3}
3	Global warming, Freshwater ecosystems	1.99×10^{-3}	X	-5.81×10^{-8}
4	Stratospheric ozone depletion	1.47×10^{-1}	X	X
5	Ionizing radiation	2.21×10^{-1}	1.10×10^{-3}	X
6	Ozone formation, Human health	3.70×10^{0}	X	X
7	Fine particulate matter formation	1.75×10^{3}	X	X
8	Ozone formation, Terrestrial ecosystems	9.17×10^{0}	X	X
9	Terrestrial acidification	1.40×10^{1}	X	X
10	Freshwater eutrophication	X	8.75×10^{0}	6.21×10^{-4}
11	Marine eutrophication	X	1.21×10^{-3}	1.02×10^{-7}
12	Terrestrial ecotoxicity	4.70×10^{-1}	3.00×10^{-7}	7.53×10^{-6}
13	Freshwater ecotoxicity	7.03×10^{-4}	1.08×10^{0}	1.26×10^{-4}
14	Marine ecotoxicity	2.46×10^{-3}	2.30×10^{-1}	1.83×10^{-5}
15	Human carcinogenic toxicity	3.92×10^{0}	2.65×10^{3}	6.20×10^{-1}
16	Human non-carcinogenic toxicity	1.51×10^{1}	2.49×10^{2}	1.10×10^{0}
17	Land use	X	X	X
18	Mineral resource scarcity	X	X	X
19	Fossil resource scarcity	X	X	X
20	Water consumption, Human health	X	-2.87×10^{3}	X
21	Water consumption, Terrestrial ecosystem	X	-3.05×10^{2}	X
22	Water consumption, Aquatic ecosystems	X	-5.65×10^{-2}	X
	TOTAL	$\mathbf{3.36 \times 10^{3}}$	$\mathbf{-2.66 \times 10^{2}}$	$\mathbf{1.68 \times 10^{0}}$

Tables 7 and 8 present the findings of grouping and weighting the environmental repercussions of the life cycle of solar panels from the investigated photovoltaic power plant in terms of emissions to the atmosphere, water, and soil. All effect categories of the ReCiPe 2016 model were considered. Similarly, two post-consumer development scenarios were considered: landfill and recycling. Global warming, Human health impact category (1.24×10^{4} Pt–landfill), and Fine particulate matter formation impact category (1.32×10^{4} Pt–landfill) had the highest level of negative impact on the atmospheric environment (similarly to supporting structures). In terms of influence on the aquatic environment, the Human carcinogenic toxicity impact category (6.39×10^{3} Pt–landfill) and Human non-carcinogenic toxicity impact category (9.64×10^{3} Pt–landfill) had the most severe results. The soil environment was the last emission region studied. Human carcinogenic toxicity impact category (5.47×10^{1} Pt–landfill) and Human non-carcinogenic toxicity impact category (7.41×10^{0} Pt–landfill) had the highest level of negative effects in this regard, similar to the aquatic environment.

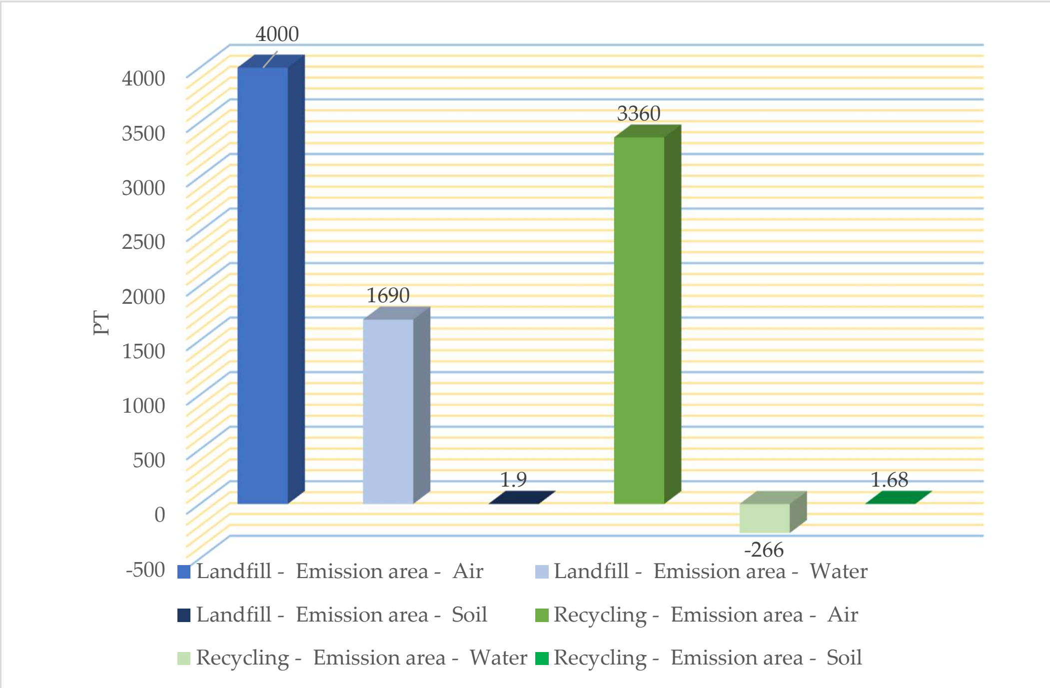

Figure 7. Grouping and weighting of the total consequences for the environment of the life cycle of the supporting structure of the analyzed photovoltaic power plant in terms of emissions to the atmospheric, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and elements [unit: Pt] (authors' research).

The use of recycling procedures for plastics, materials, and elements from the assessed photovoltaic power plant would allow for a reduction in the negative environmental repercussions in the emission areas considered, particularly emissions to the water environment (-1.33×10^3 Pt). Figure 8 depicts the total values of the life cycle impact of photovoltaic panels in a photovoltaic power plant, taking into account the kind of post-consumer management (landfill, recycling) in terms of emissions to the atmosphere, water, and soil environments. There is a particularly high level of detrimental environmental implications in the area of emissions to the atmosphere.

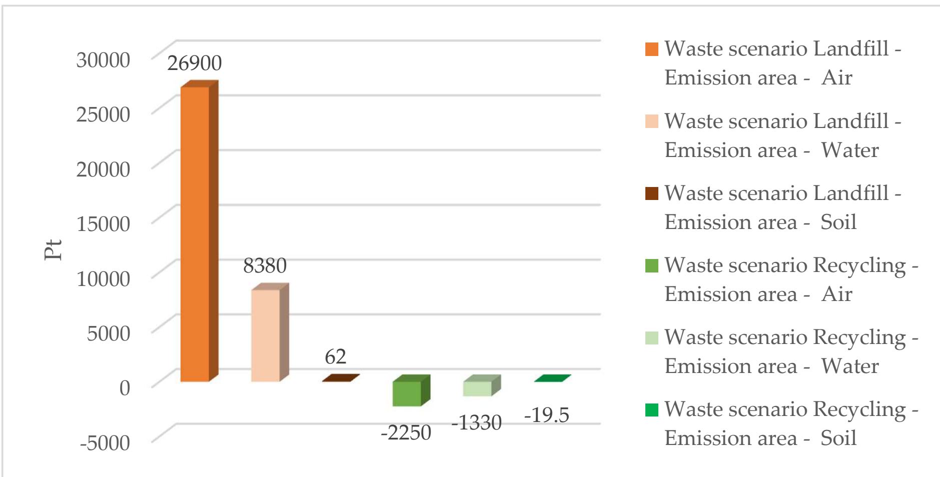

Figure 8. Grouping and weighting of the total consequences for the area surrounding the analyzed photovoltaic power plant during the life cycle of its photovoltaic panels in terms of emissions to the atmospheric, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials, materials and components [unit: Pt] (authors' research).

Table 7. Grouping and weighting of the total consequences for the environment of the life cycle of the solar panels of the analyzed photovoltaic power plant in terms of emissions to the atmospheric, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and elements (landfill) [unit: Pt] (authors' research).

No.	Element of a Technical Object	Photovoltaic Panels		
	Waste Scenario	Landfill		
	Emission Area / Impact Category	Air	Water	Soil
1	Global warming, Human health	1.24×10^4	X	-1.03×10^{-1}
2	Global warming, Terrestrial ecosystems	6.07×10^2	X	-5.05×10^{-3}
3	Global warming, Freshwater ecosystems	1.66×10^{-2}	X	-1.38×10^{-7}
4	Stratospheric ozone depletion	2.39×10^0	X	X
5	Ionizing radiation	2.39×10^1	3.16×10^{-2}	X
6	Ozone formation, Human health	2.42×10^1	X	X
7	Fine particulate matter formation	1.32×10^4	X	X
8	Ozone formation, Terrestrial ecosystems	5.66×10^1	X	X
9	Terrestrial acidification	1.84×10^2	X	X
10	Freshwater eutrophication	X	7.78×10^1	2.88×10^{-3}
11	Marine eutrophication	X	3.62×10^{-2}	1.15×10^{-7}
12	Terrestrial ecotoxicity	8.93×10^0	1.90×10^{-6}	3.79×10^{-3}
13	Freshwater ecotoxicity	5.33×10^{-3}	2.52×10^1	2.52×10^{-3}
14	Marine ecotoxicity	4.00×10^{-2}	5.69×10^0	3.29×10^{-4}
15	Human carcinogenic toxicity	7.77×10^1	6.39×10^3	5.47×10^1
16	Human non-carcinogenic toxicity	3.18×10^2	9.64×10^3	7.41×10^0
17	Land use	X	X	X
18	Mineral resource scarcity	X	X	X
19	Fossil resource scarcity	X	X	X
20	Water consumption, Human health	X	-7.03×10^3	X
21	Water consumption, Terrestrial ecosystem	X	-7.31×10^2	X
22	Water consumption, Aquatic ecosystems	X	-1.57×10^{-1}	X
TOTAL		$\mathbf{2.69 \times 10^4}$	$\mathbf{8.38 \times 10^3}$	$\mathbf{6.20 \times 10^1}$

Tables 9 and 10 summarize the results of grouping and weighing the consequences for the area surrounding of the analyzed photovoltaic power plant during the life cycle of its inverter station in terms of emissions to the atmospheric, water, and soil environments. All impact categories of the ReCiPe 2016 model were taken into account. Similarly, two scenarios of post-consumer development were taken into account: landfill and recycling. Among the identified impact categories, the highest level of negative impact on the atmospheric environment (as was the case for supporting structures and photovoltaic panels) were the Fine particulate matter formation impact (1.80×10^4 Pt–landfill) and Global warming, Human health impact categories (1.03×10^4 Pt–landfill). Regarding the impact on the aquatic environment, the most negative consequences were recorded for Human carcinogenic toxicity impact (6.74×10^3 Pt–landfill) and Human non-carcinogenic toxicity impact categories (2.68×10^4 Pt–landfill). The last analyzed emission area was the soil environment. Similarly, the highest level of harmful impacts in this respect were characterized by Human carcinogenic toxicity impact (1.42×10^2 Pt–landfill) and Human non-carcinogenic toxicity impact categories (9.81×10^1 Pt–landfill).

Table 8. Grouping and weighting of the total consequences for the environment of the life cycle of the solar panels of the analyzed photovoltaic power plant in terms of emissions to the atmospheric, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials, materials and elements (recycling) [unit: Pt] (authors' research).

No.	Element of a Technical Object	Photovoltaic Panels		
	Waste Scenario	Recycling		
	Emission Area / Impact Category	Air	Water	Soil
1	Global warming, Human health	-1.56×10^{3}	X	-1.03×10^{-1}
2	Global warming, Terrestrial ecosystems	-7.65×10^{1}	X	-5.05×10^{-3}
3	Global warming, Freshwater ecosystems	-2.09×10^{-3}	X	-1.38×10^{-7}
4	Stratospheric ozone depletion	-5.21×10^{-2}	X	X
5	Ionizing radiation	-8.33×10^{0}	-3.48×10^{-3}	X
6	Ozone formation, Human health	1.41×10^{0}	X	X
7	Fine particulate matter formation	-9.06×10^{2}	X	X
8	Ozone formation, Terrestrial ecosystems	3.36×10^{0}	X	X
9	Terrestrial acidification	-1.05×10^{1}	X	X
10	Freshwater eutrophication	X	5.66×10^{1}	4.23×10^{-4}
11	Marine eutrophication	X	3.48×10^{-2}	1.15×10^{-7}
12	Terrestrial ecotoxicity	4.33×10^{0}	9.82×10^{-7}	3.21×10^{-4}
13	Freshwater ecotoxicity	2.04×10^{-3}	2.32×10^{1}	8.16×10^{-5}
14	Marine ecotoxicity	1.76×10^{-2}	5.25×10^{0}	-4.78×10^{-5}
15	Human carcinogenic toxicity	4.55×10^{1}	-1.96×10^{3}	-1.96×10^{1}
16	Human non-carcinogenic toxicity	2.52×10^{2}	8.31×10^{3}	2.22×10^{-1}
17	Land use	X	X	X
18	Mineral resource scarcity	X	X	X
19	Fossil resource scarcity	X	X	X
20	Water consumption, Human health	X	-7.03×10^{3}	X
21	Water consumption, Terrestrial ecosystem	X	-7.31×10^{2}	X
22	Water consumption, Aquatic ecosystems	X	-1.57×10^{-1}	X
	TOTAL	$\mathbf{-2.25 \times 10^{3}}$	$\mathbf{-1.33 \times 10^{3}}$	$\mathbf{-1.95 \times 10^{1}}$

The use of recycling processes for plastics, materials, and elements of the analyzed photovoltaic power plant would allow for the reduction of negative environmental consequences in the considered emission areas, particularly emissions to the water environment (-1.68×10^{5} Pt). Figure 9 shows the total life cycle impact values of the inverter station of the photovoltaic power plant, taking into account the form of post-consumer management (landfill, recycling) in terms of emissions to the atmospheric, water, and soil environments. It shows the significant role of recycling in minimizing the destructive environmental consequences in terms of water emissions.

Table 9. Grouping and weighing the consequences for the area surrounding the analyzed photovoltaic power plant during the life cycle of its inverter station in terms of emissions to the atmospheric, water and soil environment (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and elements (landfill) [unit: Pt] (authors' research).

No.	Element of a Technical Object	Inverter Station		
	Waste Scenario	Landfill		
	Emission Area	Air	Water	Soil
	Impact Category			
1	Global warming, Human health	1.03×10^{4}	X	-5.09×10^{-1}
2	Global warming, Terrestrial ecosystems	5.02×10^{2}	X	-2.49×10^{-2}
3	Global warming, Freshwater ecosystems	1.37×10^{-2}	X	-6.80×10^{-7}
4	Stratospheric ozone depletion	4.80×10^{0}	X	X
5	Ionizing radiation	2.74×10^{1}	2.97×10^{-1}	X
6	Ozone formation, Human health	2.98×10^{1}	X	X
7	Fine particulate matter formation	1.80×10^{4}	X	X
8	Ozone formation, Terrestrial ecosystems	6.96×10^{1}	X	X
9	Terrestrial acidification	2.70×10^{2}	X	X
10	Freshwater eutrophication	X	8.75×10^{1}	1.00×10^{-2}
11	Marine eutrophication	X	4.97×10^{-2}	1.83×10^{-6}
12	Terrestrial ecotoxicity	8.52×10^{1}	2.90×10^{-6}	6.07×10^{-5}
13	Freshwater ecotoxicity	4.25×10^{-2}	4.22×10^{1}	4.84×10^{-3}
14	Marine ecotoxicity	3.12×10^{-1}	8.46×10^{0}	6.66×10^{-4}
15	Human carcinogenic toxicity	2.65×10^{2}	6.74×10^{3}	1.42×10^{2}
16	Human non-carcinogenic toxicity	1.91×10^{3}	2.68×10^{4}	9.81×10^{1}
17	Land use	X	X	X
18	Mineral resource scarcity	X	X	X
19	Fossil resource scarcity	X	X	X
20	Water consumption, Human health	X	-1.81×10^{5}	X
21	Water consumption, Terrestrial ecosystem	X	-1.87×10^{4}	X
22	Water consumption, Aquatic ecosystems	X	-1.16×10^{0}	X
	TOTAL	$\mathbf{3.15 \times 10^{4}}$	$\mathbf{-1.66 \times 10^{5}}$	$\mathbf{2.40 \times 10^{2}}$

Tables 11 and 12 describe the findings of grouping and weighting the consequences during the life cycle of the electrical installation at the examined solar power plant in terms of emissions to the atmosphere, water, and soil environments. All effect categories of the ReCiPe 2016 model were considered. Similarly, two post-consumer development scenarios were considered: landfill and recycling. Among the identified impact categories, the Fine particulate matter formation impact (3.25×10^{3} Pt–landfill) and Global warming, Human health impact categories (3.65×10^{2} Pt–landfill) had the highest level of negative impact on the atmospheric environment (as was the case for other photovoltaic power plant units). In terms of influence on the aquatic environment, the Human carcinogenic toxicity impact (1.59×10^{2} Pt–landfill) and Human non-carcinogenic toxicity impact categories (1.76×10^{3} Pt–landfill) had the most severe results. The soil environment was the last emission region studied. The Human carcinogenic toxicity impact (5.61×10^{-1} Pt–landfill) and Human non-carcinogenic toxicity impact categories (2.57×10^{-1} Pt–landfill) had the highest level of negative effects in this regard, similar to the aquatic environment.

Table 10. Grouping and weighing the consequences for the areas surroundings the analyzed photovoltaic power plant during the life cycle of its inverter station in terms emissions to the atmospheric, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and elements (recycling) [unit: Pt] (authors' research).

No.	Element of a Technical Object	Inverter Station		
	Waste Scenario	Recycling		
	Emission Area / Impact Category	Air	Water	Soil
1	Global warming, Human health	8.36×10^{3}	X	-5.09×10^{-1}
2	Global warming, Terrestrial ecosystems	4.09×10^{2}	X	-2.49×10^{-2}
3	Global warming, Freshwater ecosystems	1.12×10^{-2}	X	-6.80×10^{-7}
4	Stratospheric ozone depletion	4.44×10^{0}	X	X
5	Ionizing radiation	2.26×10^{1}	2.92×10^{-1}	X
6	Ozone formation, Human health	2.63×10^{1}	X	X
7	Fine particulate matter formation	1.59×10^{4}	X	X
8	Ozone formation, Terrestrial ecosystems	6.17×10^{1}	X	X
9	Terrestrial acidification	2.41×10^{2}	X	X
10	Freshwater eutrophication	X	8.41×10^{1}	1.04×10^{-2}
11	Marine eutrophication	X	4.35×10^{-2}	1.83×10^{-6}
12	Terrestrial ecotoxicity	8.45×10^{1}	2.76×10^{-6}	5.21×10^{-5}
13	Freshwater ecotoxicity	4.30×10^{-2}	4.12×10^{1}	5.20×10^{-3}
14	Marine ecotoxicity	3.16×10^{-1}	8.26×10^{0}	7.23×10^{-4}
15	Human carcinogenic toxicity	2.60×10^{2}	5.50×10^{3}	1.31×10^{2}
16	Human non-carcinogenic toxicity	1.92×10^{3}	2.64×10^{4}	9.92×10^{1}
17	Land use	X	X	X
18	Mineral resource scarcity	X	X	X
19	Fossil resource scarcity	X	X	X
20	Water consumption, Human health	X	-1.81×10^{5}	X
21	Water consumption, Terrestrial ecosystem	X	-1.87×10^{4}	X
22	Water consumption, Aquatic ecosystems	X	-1.16×10^{0}	X
	TOTAL	$\mathbf{2.73 \times 10^{4}}$	$\mathbf{-1.68 \times 10^{5}}$	$\mathbf{2.30 \times 10^{2}}$

The use of recycling processes for plastics, materials, and elements of the analyzed photovoltaic power plant would allow for a reduction in the of negative environmental consequences in the considered emission areas, particularly in terms of emissions to the water environment (-5.01×10^{0} Pt). Figure 10 depicts the entire life cycle effect values of a solar power plant's electrical installation, taking into account the type of post-consumer management (landfill, recycling) in terms of emissions to the atmosphere, water, and soil environments. There is a particularly high level of detrimental environmental implications in the area of emissions to the atmosphere.

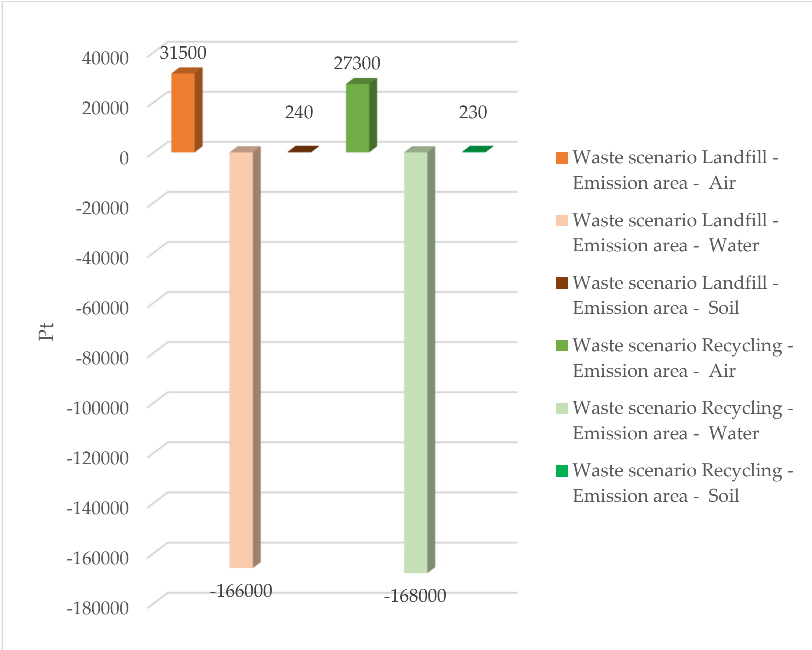

Figure 9. Grouping and weighting of the total consequences for the areas surroundings other analyzed photovoltaic power plant during the life cycle of its inverter station in terms of emissions to the atmospheric, water and soil environment (ReCiPe 2016 model), taking into account the method of post-consumer management of materials, materials and components [unit: Pt] (authors' research).

Table 13 highlights the findings of grouping and weighing the environmental consequences induced by the life cycle of the examined solar power plant in the areas of emissions to the atmosphere, water, and soil environments (ReCiPe 2016 model). Two post-consumer management scenarios for plastics, materials, and components were also considered: landfill and recycling. The highest level of negative environmental consequences was observed among the assessed impacts in the domain of impact on human health in terms of emissions to the atmosphere (6.51×10^4 Pt–landfill). In the case of recycling as a form of post-consumer management, the highest level of positive impact (-1.52×10^5 Pt) was in the area of human health in terms of emissions to water. Recycling as a kind of post-consumer management would allow for the reduction of hazardous emissions during the whole life cycle of the evaluated technological object. Figures 11 and 12 show the total values of the analyzed photovoltaic power plant's life cycle impact, taking into account the type of post-consumer management (landfill, recycling) as well as emission areas (atmospheric, water, and soil environments) and impact areas (human health, ecosystem, raw material resources). Recycling plays a key role in avoiding the detrimental environmental effects of emissions to water, both in terms of impact on human health and ecosystem quality.

Table 11. Grouping and weighing the consequences for the areas surrounding the analyzed photovoltaic power plant during the life cycle of its electrical installation in terms of emissions to the atmospheric, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and elements (landfill) [unit: Pt] (authors' research).

No.	Element of a Technical Object	Electrical Installation		
	Waste Scenario	Landfill		
	Emission Area	Air	Water	Soil
	Impact Category			
1	Global warming, Human health	3.65×10^{2}	X	-1.49×10^{-2}
2	Global warming, Terrestrial ecosystems	1.78×10^{1}	X	-7.27×10^{-4}
3	Global warming, Freshwater ecosystems	4.87×10^{-4}	X	-1.99×10^{-8}
4	Stratospheric ozone depletion	3.79×10^{-1}	X	X
5	Ionizing radiation	4.68×10^{-1}	1.25×10^{-3}	X
6	Ozone formation, Human health	2.49×10^{0}	X	X
7	Fine particulate matter formation	3.25×10^{3}	X	X
8	Ozone formation, Terrestrial ecosystems	5.84×10^{0}	X	X
9	Terrestrial acidification	3.61×10^{1}	X	X
10	Freshwater eutrophication	X	6.69×10^{0}	1.42×10^{-4}
11	Marine eutrophication	X	3.01×10^{-3}	4.51×10^{-9}
12	Terrestrial ecotoxicity	1.80×10^{1}	1.70×10^{-7}	3.16×10^{-5}
13	Freshwater ecotoxicity	5.42×10^{-3}	2.34×10^{0}	5.00×10^{-5}
14	Marine ecotoxicity	7.38×10^{-2}	4.52×10^{-1}	7.55×10^{-6}
15	Human carcinogenic toxicity	8.52×10^{1}	1.59×10^{2}	5.61×10^{-1}
16	Human non-carcinogenic toxicity	8.95×10^{2}	1.76×10^{3}	2.57×10^{-1}
17	Land use	X	X	X
18	Mineral resource scarcity	X	X	X
19	Fossil resource scarcity	X	X	X
20	Water consumption, Human health	X	-7.29×10^{2}	X
21	Water consumption, Terrestrial ecosystem	X	-7.95×10^{1}	X
22	Water consumption, Aquatic ecosystems	X	-2.27×10^{-2}	X
	TOTAL	$\mathbf{4.68 \times 10^{3}}$	$\mathbf{1.12 \times 10^{3}}$	$\mathbf{8.03 \times 10^{-1}}$

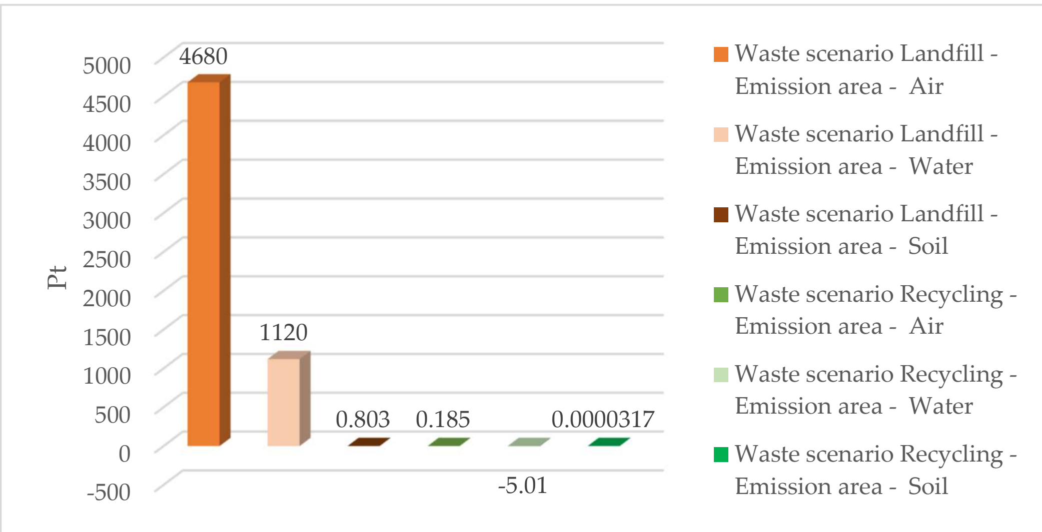

Figure 10. Grouping and weighting of the total consequences for the areas surrounding the analyzed photovoltaic power plant's electrical installation during its life cycle in terms of emissions to the atmospheric, water and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and components [unit: Pt] (authors' research).

Table 12. Grouping and weighing the consequences for the areas surrounding the analyzed photovoltaic power plant's electrical installation during its life cycle in terms of emissions to the atmospheric, water, and soil environments (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and elements (recycling) [unit: Pt] (authors' research).

No.	Element of a Technical Object	Electrical Installation		
	Waste Scenario	Recycling		
	Emission Area / Impact Category	Air	Water	Soil
1	Global warming, Human health	2.30×10^{0}	X	-9.37×10^{-5}
2	Global warming, Terrestrial ecosystems	1.12×10^{-1}	X	-4.57×10^{-6}
3	Global warming, Freshwater ecosystems	3.06×10^{-6}	X	-1.25×10^{-10}
4	Stratospheric ozone depletion	2.38×10^{-3}	X	X
5	Ionizing radiation	$2{,}94 \times 10^{-3}$	7.86×10^{-6}	X
6	Ozone formation, Human health	1.57×10^{-2}	X	X
7	Fine particulate matter formation	2.04×10^{1}	X	X
8	Ozone formation, Terrestrial ecosystems	3.67×10^{-2}	X	X
9	Terrestrial acidification	2.27×10^{-1}	X	X
10	Freshwater eutrophication	X	4.21×10^{-2}	8.93×10^{-7}
11	Marine eutrophication	X	1.89×10^{-5}	2.84×10^{-11}
12	Terrestrial ecotoxicity	1.13×10^{-1}	1.07×10^{-9}	1.99×10^{-7}
13	Freshwater ecotoxicity	3.41×10^{-5}	1.47×10^{-2}	3.14×10^{-7}
14	Marine ecotoxicity	4.64×10^{-4}	2.84×10^{-3}	4.75×10^{-8}
15	Human carcinogenic toxicity	5.36×10^{-1}	1.00×10^{-0}	3.53×10^{-3}
16	Human non-carcinogenic toxicity	5.63×10^{0}	1.11×10^{1}	1.62×10^{-3}
17	Land use	X	X	X
18	Mineral resource scarcity	X	X	X
19	Fossil resource scarcity	X	X	X
20	Water consumption, Human health	X	-4.58×10^{0}	X
21	Water consumption, Terrestrial ecosystem	X	-5.00×10^{-1}	X
22	Water consumption, Aquatic ecosystems	X	-1.43×10^{-4}	X
	TOTAL	$\mathbf{1.85 \times 10^{-1}}$	$\mathbf{-5.01 \times 10^{0}}$	$\mathbf{3.17 \times 10^{-5}}$

Table 13. Grouping and weighing the consequences for the environment during the life cycle of the analyzed photovoltaic power plant in terms of emissions to the atmospheric, water, and soil environments, taking into account the areas of impact (ReCiPe 2016 model) and the method of post-consumer management of materials and elements [unit: Pt] (authors' research).

Photovoltaic Power Plant				
Waste SCENARIO	Emission AREA	Impact Area		
		Human Health	Ecosystem	Material Resources
Landfill	Air	6.51×10^{4}	1.99×10^{3}	X
	Water	-1.35×10^{5}	-1.95×10^{4}	X
	Soil	3.05×10^{2}	-8.82×10^{-3}	X
Recycling	Air	2.76×10^{4}	8.14×10^{2}	X
	Water	-1.52×10^{5}	-2.03×10^{4}	X
	Soil	2.10×10^{2}	-1.53×10^{-2}	X

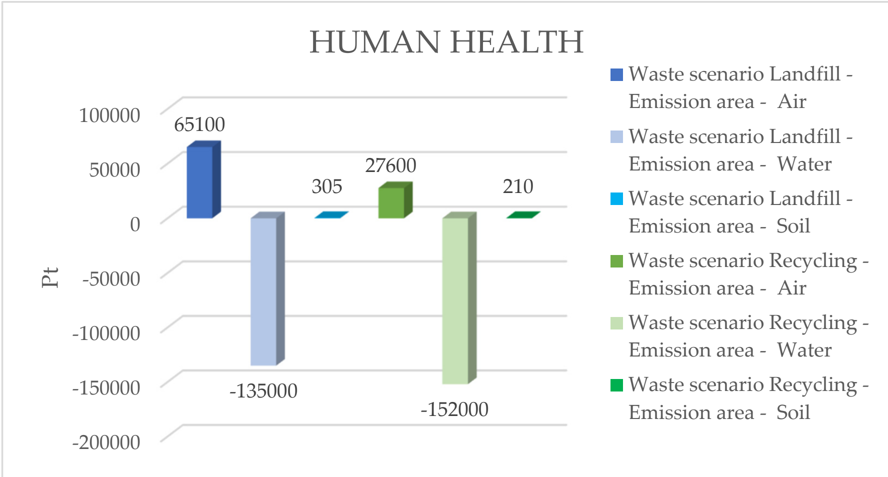

Figure 11. Grouping and weighting of the total consequences for the environment during the life cycle of the analyzed photovoltaic power plant in terms of impact on human health (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and elements [unit: Pt] (authors' research).

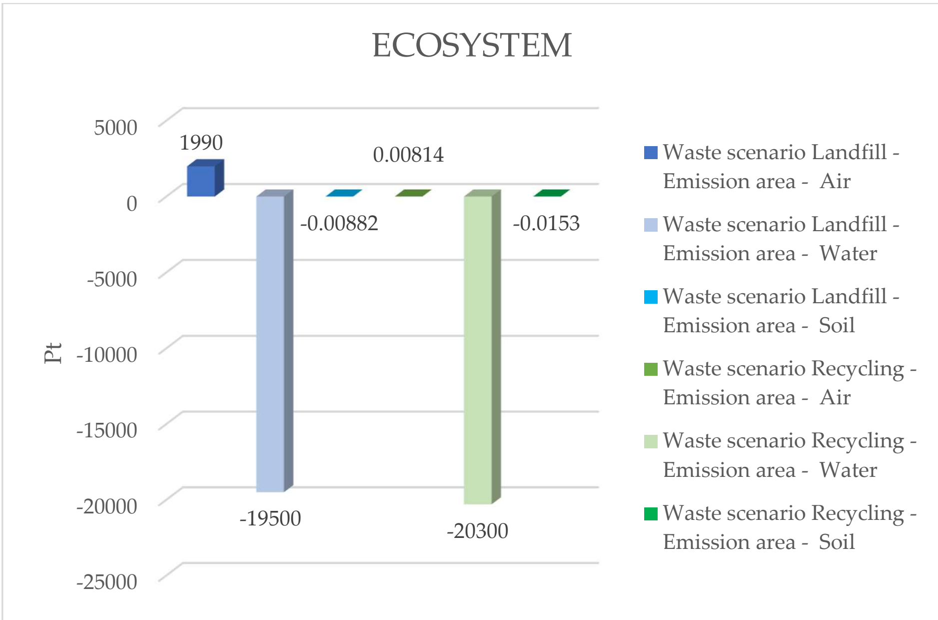

Figure 12. Grouping and weighting of the total consequences for the environment during the life cycle of the analyzed photovoltaic power plant in terms of impact on the ecosystem (ReCiPe 2016 model), taking into account the method of post-consumer management of materials and elements [unit: Pt] (authors' research).

Table 14 presents the findings of grouping and weighing the environmental implications of the separate components of the investigated photovoltaic power plant's life cycle. Two post-consumer development scenarios were considered: landfill and recycling. Furthermore, the findings were classified into three emission regions (atmospheric, water, and soil environments) and three effect areas (human health, ecosystem, and raw material resources). Among the identified impacts, the inverter station had the highest level of negative environmental consequences in terms of impact on human health and emissions to the atmosphere (3.05×10^4 Pt–landfill). In terms of emissions to the soil environment, the life cycle of solar panels (1.06×10^3 Pt–landfill) had the highest detrimental impact on the ecosystem. In the case of adopting recycling as a type of post-consumer management, an inverter station has the maximum level of beneficial impact (impact on human health: -1.51×10^5 Pt and ecosystem: -1.97×10^4 Pt in the area of emissions to water). Recycling would allow for a reduction in the amount of hazardous emissions during the whole life cycle of the evaluated technical product.

Table 14. Grouping and weighing the consequences for the environment during the life cycle of analyzed photovoltaic power plant's individual assemblies in terms of emissions to the atmospheric, waters and soil environments, taking into account the areas of impact (ReCiPe 2016 model) and the method of post-consumer management of materials and elements [unit: Pt] (authors' research).

		Supporting Structure		
Waste Scenario	**Emission Area**	**Impact Area**		
		Human Health	**Ecosystem**	**Material Resources**
Landfill	Air	3.88×10^3	1.26×10^2	X
	Water	1.96×10^3	-2.69×10^2	X
	Soil	1.90×10^0	-1.34×10^{-3}	X
Recycling	Air	3.26×10^3	9.65×10^1	X
	Water	3.42×10^1	-2.95×10^0	X
	Soil	1.67×10^0	-1.35×10^{-3}	X
		Photovoltaic Panels		
Waste Scenario	**Emission Area**	**Impact Area**		
		Human Health	**Ecosystem**	**Material Resources**
Landfill	Air	2.61×10^4	8.56×10^2	X
	Water	8.99×10^3	-6.23×10^2	X
	Soil	6.20×10^1	1.06×10^{-3}	X
Recycling	Air	-2.18×10^3	-7.93×10^1	X
	Water	-6.82×10^2	-6.46×10^2	X
	Soil	-1.95×10^1	-4.27×10^{-3}	X
		Inverter Station		
Waste Scenario	**Emission Area**	**Impact Area**		
		Human Health	**Ecosystem**	**Material Resources**
Landfill	Air	3.05×10^4	9.27×10^2	X
	Water	-1.47×10^5	-1.85×10^4	X
	Soil	2.40×10^2	-8.54×10^{-3}	X
Recycling	Air	2.65×10^4	7.96×10^2	X
	Water	-1.51×10^5	-1.97×10^4	X
	Soil	2.28×10^2	-9.34×10^{-3}	X
		Electrical Installation		
Waste Scenario	**Emission Area**	**Impact Area**		
		Human Health	**Ecosystem**	**Material Resources**
Landfill	Air	4.60×10^3	7.79×10^1	X
	Water	1.19×10^3	-7.00×10^1	X
	Soil	8.03×10^{-1}	-4.97×10^{-6}	X
Recycling	Air	2.89×10^1	4.90×10^{-1}	X
	Water	7.48×10^0	-4.40×10^{-1}	X
	Soil	5.05×10^{-3}	-3.13×10^{-4}	X

4. Summary and Discussion

4.1. Conclusions

The overarching purpose of sustainable development is to address humanity's needs while also considering future generations' demands. The socioeconomic growth of highly developed countries involves rapid social and economic development while simultaneously improving the population's quality of life and the environment. The concepts of life cycle thinking (LCT) and life cycle management (LCM) address these assumptions. Their application aims to reduce the environmental impact of activities associated with the production, operation, and post-consumer development of photovoltaic power plants. The Environmental Life Cycle Assessment (LCA) is the fundamental instrument for conducting analytical work in this domain since it allows for the quantification of potential consequences at each step [12,40,41].

The primary purpose of this study was met by assessing the life cycle of a solar power plant in terms of emissions to the environment, soil, and water. The analysis completed allows for the evaluation of the positive and negative impacts of the life cycle of the evaluated photovoltaic power plant.

The investigation covered three emission areas that are typical of the ReCiPe 2016 model (air, water, and soil).

- ➢ The highest level of harmful emissions to the atmosphere was recorded (life cycle with landfill storage of plastics, materials, and power plant components: 6.70×10^4 Pt).
- ➢ Among the impacts identified for power plant assemblies, the inverter station's life cycle had the highest level of negative environmental consequences in terms of impact on human health and emissions to the atmosphere (3.05×10^4 Pt life cycle with landfill management).
- ➢ In terms of emissions to the soil environment, the life cycle of solar panels (1.06×10^3 Pt–landfill) had the highest detrimental impact on the ecosystem.
- ➢ The highest level of adverse impact was reported in the area of influence on human health in terms of emissions to the atmosphere (6.51×10^4 Pt life cycle with landfill management) of the three evaluated areas of impact (human health, ecosystem, raw material resources).
- ➢ The use of recycling methods would allow for a reduction in harmful emissions in all areas evaluated.

Real-world case studies revealed that the life cycle of a photovoltaic power plant corresponds to the principles of sustainable development. However, it is vital to implement improvement methods targeted at limiting negative and boosting positive environmental impact.

A multi-faceted assessment of their life cycle based on LCA, LCC, and S-LCA can thus serve as the foundation for the sustainable development of photovoltaic power plants. In the long run, they allow for ongoing improvement, which is part of the contemporary, universal ways of assessing the quality of renewable energy technical items.

The studies closest to those presented in the article can be found in the "Assessment of the Life Cycle of a Wind and Photovoltaic Power Plant in the Context of Sustainable Development of Energy Systems" [37]. This enables some form of verification of the obtained results. The results have the same or very close order of magnitude. Because of the input data used in the research, the results will never be the same. However, in the case of poorly performed testing, the order of magnitude will be very similar or the same.

4.2. Main Recommendations

The LCA can be undertaken at any point in the life cycle and after it has been completed, allowing for the eco-design of innovative solutions in the field of solar systems with high installed capacity, among other things. The approach described also allows for the option of minimizing negative and enhancing positive effects in three areas of the studied technical product.

As part of the actions to sustainably improve the life cycle of photovoltaic power plants, it is suggested:

- changes in the construction of both entire working units and individual elements, allowing for easier separation of individual materials, not causing difficulties during identification during post-consumer management;
- taking economically effective measures aimed at reducing energy consumption, material consumption and harmful emissions of production processes;
- carrying out more pro-environmental works;
- popularizing the idea of testing and assessing the impact of photovoltaic power plants and other renewable energy systems throughout their entire life cycle.

4.3. Extending the Scope of Research

The scope of the study might be expanded to include other locations that may be impacted by harmful pollutants. Human health, ecosystems, and raw material resources, for example, can all be studied.

The ReCiPe 2016 model addresses 22 impact areas. Each of the 22 impact categories should be studied in the context of the overall solar power plant as well as its individual elements and assemblies in order to determine which factors, substances, or chemical compounds are the most harmful to the environment.

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