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Energy Waste as a Side-Effect of Photovoltaic Development: Net Impact of Photovoltaics on CO_2 Emissions in European Union Countries

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Abstract: Decarbonization policies are being implemented in all EU countries where renewable energy is being developed. One of the main energy sources used for this purpose is photovoltaic energy. However, the development of photovoltaics does not only mean environmental benefits in the form of green energy and thus a reduction in greenhouse gas emissions from fossil fuel energy production, but also energy waste. The development of photovoltaics generates energy waste, some of which cannot be recovered, which in turn has a negative impact on gas emissions. The aim of this article is to analyse the amount of energy waste from photovoltaics in European Union countries and the net impact of photovoltaics on greenhouse gas emissions. Data sources are Eurostat and Our World In Data. The analysis will be carried out for the majority of EU countries, excluding the smallest countries whose data may distort the overall results. The analysis should show the overall impact of PV in the countries analysed and the changes over the period studied. The results will also indicate whether the impact of PV on decarbonization is similar across the EU countries analysed, or whether there are clusters of countries due to the impact of PV, or a negative impact in some of them.

Keywords: energy waste; photovoltaic development; renewable energy sources (RES); industries; European Union countries; CO_2 emissions

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Academic Editor: Jin-Li Hu

Received: 7 November 2024
Revised: 18 December 2024
Accepted: 26 December 2024
Published: 28 December 2024

Citation: Gajdzik, B.; Wolniak, R.; Nagaj, R.; Žuromskaitė-Nagaj, B.; Grebski, W. Energy Waste as a Side-Effect of Photovoltaic Development: Net Impact of Photovoltaics on CO_2 Emissions in European Union Countries. *Energies* **2025**, *18*, 78. https://doi.org/10.3390/en18010078

1. Introduction

Rapid industrialisation in both developed and emerging countries, rising oil and gas prices, and the intensification of government actions aimed at reducing the share of fossil fuels in energy sources are key determinants for industries that will drive the expansion of the global market. National energy policies are moving towards a radical reduction in CO_2 emissions. The European Union has set a target to reduce greenhouse gas (GHG) emissions by 80–95% below 1990 levels by 2050, naming this key directive the “Net Zero” Strategy [1]. In the process of decarbonizing economies, emphasis is placed on reducing CO_2 emissions from “black” energy, derived from coal. The European Green Deal is the one to significantly reduce greenhouse gas emissions by 2050. The European Commission has prepared a set of legislative proposals whose implementation should contribute to zero-carbon economies and industries with a roadmap for a competitive low-carbon Europe by 2050 (COM2011) [2].

The planned changes must be radical to achieve the EU's goal of becoming climate-neutral by 2050, which is why they are referred to as "deep decarbonization". Many industries will need to replace their current production technologies with new ones, such as the steel industry [3], while others will have to cease production entirely, for example, coal mining for power plants [4–6]. The energy and heating industries are undergoing the largest transformations in their history, moving towards renewable energy sources (RES) [7]. Households are increasingly participating in the energy market as prosumers [8,9], with energy cooperatives emerging as one of their organisational forms [10,11]. Every organisation and individual will be impacted by "deep decarbonization" changes. The challenges of decarbonization are numerous, encompassing political and public hurdles [12], and, most critically, social and economic issues [13].

The "deep decarbonization" policy is closely tied to global, regional, and local energy policies. Contemporary energy policy represents a transformation focused on activities related to the production of energy predominantly from renewable sources. For many years, countries have promoted RES as a strategic (primary) energy source. In this energy strategy, wind and solar power plants, as well as biomass-based plants, hold greater importance than other sources. These plants must operate at the maximum level that the system can accommodate to be efficient. Other energy sources are used as secondary options but remain crucial for energy diversification (such as nuclear power, hydroelectric plants, as well as biogas and biomethane) [14–16]. In the energy transition, governments recommend enhancing the flexibility of power systems [17] and the energy efficiency of economies and industries [18,19]. One of the most pressing issues in the contemporary world is the need to further increase energy production while considering the impact of new capacities and solutions on the ecosystem. The green energy market is experiencing significant growth in technology development. Green energy sources are those that employ green technologies. The size of the green energy market was valued at $102.6 billion in 2022, and the sector is expected to grow from $112.4 billion in 2023 to $234.12 billion by 2032, demonstrating a compound annual growth rate (CAGR) of 9.60% over the forecast period (2023–2032) [20]. However, despite their long lifespans new green energy technologies age, raising challenges around recycling, recovery of rare elements, and the management of non-recyclable waste flow between regions, which may exacerbate environmental problems [21,22].

This paper focuses on solar energy produced using photovoltaic (PV) technology and its decarbonization impact on the economy through CO_2 emission reductions. This transformation, however, has drawbacks, one of which is energy loss. A reason for these losses is the underestimation of renewable energy capacity, which translates to financial losses. Additionally, there are issues with energy storage access, preventing individual energy producers and consumers from using potential energy [23]. Furthermore, energy is needed to transport and process photovoltaic waste (segregated into main waste streams such as base and special metals, other metals, and non-metallic waste, including glass). Among this waste are rare elements, whose scarcity necessitates recovery from photovoltaic cells [24–26]. While PV recycling issues might seem distant, PV technologies already in use have a lifespan of 25–40 years [27]. Beyond energy market structural factors, PV efficiency contributes to energy loss. PV technology is continually improved to minimise energy losses. For instance, in March 2022, the Indian solar panel manufacturer Gautam Solar (New Delhi, India) introduced G-2X monocrystalline solar modules, ideal for rooftop and ground-mounted solar power plants as they generate energy from both the front and back of the module, adding 10–30% more power. The combined front and back module efficiency reaches up to 25.72% [20]. Due to the innovation and ongoing enhancement of

PV technology, the share of solar energy in RES has grown, reaching a global level of 5.52% in 2023, compared to 0.15% in 2010 [28]. However, based on reports from countries where coal and nuclear energy dominate, renewable energy losses are anticipated. By 2040, as much as 70 TWh of renewable energy will remain unused, partly due to the priority given to electricity generated in nuclear plants, cogeneration, and coal and gas units operating at technical minimums over renewable sources [23]. So far, the literature has also dealt with the environmental issue of photovoltaic panels. Schlömer [29] analysed technologies used in different sectors of the economy and assessed their technical efficiency in production, mainly in terms of costs, including the environmental costs associated with comparing the CO_2 emission levels of different generation technologies, including photovoltaic panels. However, this was a purely technical analysis, focused on comparing technologies in terms of emission levels and which technologies are the most emission intensive. Guo et al. [30] conducted a review of the status of the use of emissions of silicon-based solid waste, related to the PV industry. In their work, they identified the advantages of developing the PV industry, and the risks and challenges it faces. They based their analysis on the example of China. However, they did not undertake analyses related to the overall impact on the economy and, moreover, the analysis is only based on the example of one country. Another interesting work on this topic was that developed by Riahi et al. [31]. They carried out a technical study on the recycling of photovoltaic waste and proposed a more efficient way of recycling this waste. In this work, however, the authors focused only on a narrow area of the issue related to PV panels, namely, the waste itself. However, the overall impact of PV energy production on environmental emissions, including the benefits of energy production through this technology, was not analysed.

As discussed above, the literature commonly analyses photovoltaic development, primarily from a technical perspective, specifically assessing which PV technologies are more productive. The International Energy Agency also regularly publishes reports on the development prospects of photovoltaic power systems in the world's largest economies, including trends in the PV industry [32]. Additionally, the carbon footprint of solar panels has been analysed, examining CO_2 emissions associated with energy manufacturing [33]. Moreover, the literature indicates that PV panels are not entirely environmentally neutral, as they generate waste that must be recycled [34], and waste incineration also contributes to the carbon footprint [35,36]. Although PV-generated energy is green, it should be remembered that some CO_2 is emitted during manufacturing [29]. Therefore, a holistic analysis of the environmental impact of PV panels and the solar energy they produce, including the two types of environmental costs associated with producing solar energy from PV, is warranted. Nagaj et al. [37] analysed the impact of deep decarbonization policy on the level of greenhouse gas emissions in the European Union. This policy will benefit not only the industrial sectors, but each of us. People are even integrating to meet new challenges, and energy cooperatives are examples of this, in which people share energy from PV and store it [38].

An analysis of the use of PV panels for energy production and the net environmental impact on the economy, and thus whether there is an impact on social welfare in the European countries where green energy promotion processes are most advanced, has not yet been analysed in the literature. This paper addresses this research gap by conducting such an analysis.

The purpose of this article is to analyse the net impact of photovoltaics on CO_2 emissions in European Union countries, considering the impact of generated and disposed energy waste. Data sources include Eurostat, the Energy Institute's Statistical Review of World Energy, and Our World in Data. The analysis will cover most EU countries, excluding the smallest ones, for which comprehensive data are unavailable, as including them could distort the study's overall results. The analysis should reveal the comprehensive circular economy impact of photovoltaics in the countries studied. The results will also indicate whether the carbon footprint of PV waste is significant from the perspective of the decarbonization impact of solar energy production from PV. The analysis should show whether photovoltaics in the circular economy of all EU countries studied similarly influence decarbonization processes or even have a negative impact.

The following research questions (RQs) were adopted in the paper:

RQ1: Is the overall environmental impact of the consumption of solar PV in the circular economy in EU countries positive?

RQ2: Is the environmental role (CO_2 emissions) of waste from photovoltaic (PV) panels in EU countries significant?

RQ3: Does solar energy in all EU countries play a positive decarbonizing role in the amount of CO_2 emitted?

The contribution of this paper to science arises from two reasons. First, a comprehensive analysis of the circular economy impact of PV panels will be conducted. This analysis will be inclusive of such an impact, which has not been previously undertaken for economies. The authors will propose a model for conducting such an analysis. This paper fills this research gap by performing such an analysis. Ultimately, this paper methodologically addresses the debate on whether, on balance, greenhouse gas emissions will decrease, considering the recycling issues of solar panels in the sustainable development of EU economies. Second, the analysis will be conducted for all European Union countries. Excluding the point mentioned above, the analysis of the impact of PV development is most often found in the literature or reports only for the largest economies in the world. This paper will analyse the impact on the countries of the European Union. In addition to the contribution of this paper to the literature indicated above, the novelty of this paper also stems from the application of the Kaldor–Hicks criterion to the analysis of changes in social welfare in European Union economies as measured by the level of the net environmental effect resulting from the use of PV for energy production.

Ultimately, this paper methodologically answers the debate on whether, on balance, greenhouse gas emissions will decrease, considering the recycling problems of solar panels in the sustainable development of EU economies.

The structure of the paper is as follows. After the background of the analysis, the methodology of measurement will be presented, followed by the results of the analysis. A discussion will follow, and the paper will conclude with the final conclusions.

2. Background of Analysis

Photovoltaic technology is increasingly being used worldwide. Year by year, photovoltaic systems are taking a larger share in the EU energy mix. In 2021, photovoltaic electricity production in the EU accounted for 5.5% of the gross electricity production in the EU [39]. In the coming decades, further growth is expected in the solar energy sector, driven by both large-scale installations and increased self-consumption based on rooftop photovoltaic systems. The Global Solar PV Market report indicates that the global PV market will reach a value of USD 223.3 billion by 2027. This growth will be driven by the increasing demand for renewable energy in line with the Deep Decarbonization policy. The green transition process is affecting key regions worldwide. The global threshold of 1000 GW of installed capacity is ready to be reached and surpassed, with Asia leading the global growth trend. In the EU, the solar power production capacity continues to grow, and according to Solar Power Europe, it reached 259.99 GW in 2023 [40]. Under the European Green Deal and the RE Power EU plan, solar power is a building block of the EU's transition to cleaner energy. The European energy strategy aims to deliver over

320 GW of photovoltaic energy by 2025 and nearly 600 GW by 2030 [41]. Moreover, the EU funds many solar cell projects, such as the PERTPV project, in which perovskite-based materials were used to build a new type of solar cell. The European Union is also striving to increase the production of PV cells. China is currently the largest producer. The key directions for the development of the PV market in the EU are outlined in documents available on the website of the European Commission [40]. The review of the Renewable Energy Directive sets a binding target for renewable energy, according to which, by 2030, it should account for at least 42.5% of Europe's energy mix [42].

PV technology is considered pro-development, and its advantage is the provision of "green" energy. Although minimising greenhouse gas emissions is important, the environmental impact of this technology can be influenced by various factors. These will vary depending on the type of technology, the scale of the plant, the location, as well as the type and quantity of materials used. PV technologies are crucial for future energy supply, which is why the estimated scale at which they must operate is immense and requires significant amounts of materials and space per unit of energy produced. Moreover, scientists also warn that the increasing amount of waste from the green technology sector may impose significant environmental and economic burdens on future generations. When these PV technologies reach the end of their lifespan, new types of waste are also generated. For example, many waste facilities in the EU incinerate part of a solar PV panel's mass, which can contain elements such as silver, copper, and silicon. Based on studies carried out in the United States, these materials can represent around two-thirds of the total monetary value of the materials making up the silicon PV cell. Solar panels offer many advantages as a clean and renewable energy source, suitable for various scales of implementation. Challenges such as the intermittency of solar energy production, initial costs, land-use consequences, the need to store excess energy, production costs, and the recycling of panels highlight the need for thoughtful planning and technological innovation to maximise benefits while eliminating limitations.

The negative environmental impact of photovoltaic panels had not been the subject of discussion until their first batch was withdrawn (photovoltaic panels have a long lifespan of 25 to 40 years) [27]. Photovoltaic panels (PV) can pose a threat to the environment after the end of their operational life, in the form of significant waste [26]. This leads to a concerning situation due to the ambitious goals of the International Renewable Energy Agency, which predicts the launch of 8519 GW of photovoltaic installations by 2050, compared to 480 GW in 2018 [39], as all of these would have significant environmental costs after their operational life, corresponding to millions of tonnes of photovoltaic waste. Mahmoudi, Huda and Behnia [43] estimated the total waste stream to be around 25–28.5 million tonnes just for OECD countries, corresponding to a cumulative photovoltaic power capacity of only 250 GW. In the waste structure estimated at 25–28.5 million tonnes (MT), there are basic and special metals (4.58 MT) and other metals (2.37 MT), followed by non-metallic waste (25.69 MT), including glass and EVA, which make up 68% and 26%, respectively [43]. According to Mahmoudi et al. [43], not all countries meet the minimum level of photovoltaic waste, which is 20 kilotonnes (KT) between 2026 and 2027. When comparing the energy produced to the energy required for recycling in the life cycle, the average cost of electricity with photovoltaic recycling may be about 2% lower than without photovoltaic recycling [26]. The creation of the gross value of recovered waste materials, according to forecasts by Mahmoudi et al. [43], could amount to USD 36–42 billion. Such income could serve as an attractive incentive to engage many RES policy stakeholders in this activity. Based on this context, many studies have emerged worldwide presenting an assessment of photovoltaic industry waste in specific regions (Table 1).

Table 1. Regional PV wastes based on literature review.

Region/Country	Source	Description
India	Gautam, Shankar and Vrat (2021) [44]	Gautam, Shankar and Vrat (2021) assessed e-waste in India and estimated that from 2020 to 2047, about 2.95 billion tonnes of photovoltaic waste could be generated, which is equivalent in value to USD 645 trillion worth of precious metals, of which up to 70% (USD 452 trillion) could be recovered.
Australia	Mahmoudi, Huda and Behnia (2021) [43]	Mahmoudi, Huda and Behnia projected the amount of photovoltaic waste in Australia and estimated that recovery of PV materials will yield an income of around USD 1.2 billion.
United States	Domínguez and Geyer (2019) [45]	Domínguez and Geyer (2019) evaluated PV wastes at the main installations in the US. The estimated amount for this purpose is that 69.7 GW of large-scale PV projects can produce 9.8 metric tonnes of photovoltaic waste between 2030 and 2060. These have recoveries of 9.2 metric tonnes and a value of approximately USD 22 billion.
Mexico	Domínguez and Geyer (2019) [45]	Domínguez and Geyer also valued PV waste in Mexico and foresaw the generation of 1.2 million tonnes of PV waste. In addition, around 271 tonnes of recovered silver, 10 tonnes of recovered gold, 17 tonnes of recovered gallium, 10 tonnes of indium, 139 tonnes of cadmium, and 100 tonnes of tellurium could be recovered from such wastes.
Italy	Paiano (2015) [46]	Italy is the second largest country in the European Union by the general amount of installed photovoltaic capacity: in 2013, Italy's cumulative installed capacity reached more than 17,620 MW. The development of solar energy in Italy is presented by the author in this context, which discusses the use and recycling of PV technology.
Thailand	Faircloth, Wagner, Woodward, Rakkwamsuk and Gheewala (2019) [47]	Faircloth and Wagner estimated that the demand for silicon accumulated could be reduced through recycling of silicon. Additionally, none of the recycling processes was economically viable even though the cost of recycling was as low as USD 0.03 per kilogram.
China	Nieto-Morone et al. (2023) [48]	China also has some of the most ambitious goals such as 600 GW by 2030 as part of the National Energy and Climate Plans. Under the 14th Five-Year Plan, China is pursuing a larger target of 1.2 TW of solar and wind capacity up to 2030. From 2050 onwards, China will start generating significant photovoltaic waste since the panels wear out and reach the end of their lifecycle, which requires adequate waste management and recycling facilities.
Germany	Weckend, Wade and Heath (2016) [49]	With Germany among the leading countries in solar energy, the streams of PV waste are estimated to reach 3.5 million tonnes by 2050. Already, stringent European Union recycling regulations have Germany investing in technologies that recover critical materials from PV waste, including silicon, copper and silver. Recycling could provide Germany with a way to meet material scarcity and provide long-term sustainability for the transition to renewable energy.
Japan	IRENA International Renewable Energy Agency, (2016) [50].	Japan has also played a very significant role in solving problems with PV waste management. Nowadays, the installed solar capacity of about 67 GW faces the country increasingly with decommissioned photovoltaic panels. PV CYCLE Japan was established in cooperation with the Akita Prefectural Resources Technology Development Organisation in order to play an important part in establishing a sustainable take-back and recycling system. The initiative will undertake discarded PV panels for recycling and reusing valuable materials, ensuring environmentally sound large-scale deployment of solar energy. The initiative also follows in the steps of Japan's increasing focus on principles relating to the circular economy—essential as volumes of PV waste rise.
South Korea	Lee and Jang (2023) [51].	South Korea expanded its solar capacity in less than a decade and is projected to produce over 1 million tonnes of PV waste by 2040. The nation is investing in state-of-the-art recycling technologies that are right for recovering rare and valuable metals such as gallium, silver and silicon. This would add to the contribution of South Korea in handling e-waste while serving the growing renewable energy sector of the country.

Source: own elaboration based on [43–51].

The process of photovoltaic (PV) development must be viewed from multiple perspectives. Proactive policies and management strategies are essential to create new economic opportunities for the development of competitive markets based on recycled materials, which leads to environmental and economic sustainability. Photovoltaic recycling can be acceptable, provided that mass training programs and incentives for recycling are introduced to raise public awareness and facilitate the effective implementation of regulations.

Although the major economies of the world have developed standards for managing photovoltaic waste after decommissioning or are in the process of implementing them, the most vulnerable parts of the world have not even realised the seriousness of this issue, which could continue to contribute to their energy poverty, despite these regions having the highest potential for renewable energy.

Many countries vulnerable to renewable energy have high solar energy potential with a relatively high rate of photovoltaic installations, even though they lack regulations on photovoltaic waste recycling. The absence of regulations on photovoltaic waste in low-income countries can have serious consequences, and it is possible that global photovoltaic waste will end up in these countries. In the long term, these countries may become flooded with photovoltaic waste, potentially leading to social rejection of the photovoltaic industry.

3. Materials and Methods

The objective of this research is to analyse the net impact of photovoltaics on carbon dioxide emissions in European Union countries, taking into account the contribution of generated and disposed energy waste. As indicated in the topic justification in Section 1, the authors wish to investigate the comprehensive impact of photovoltaics on the circular economy in the countries analysed. The link between increasing the generation of energy from PV panels and consequently the consumption of this solar energy in reducing the consumption of fossil fuel energy is well illustrated by an analysis of the relationship between the share of solar energy from PV and the share of fossil fuels in total primary energy consumption. The analysis of energy consumption data by source [52] shows that in all the EU countries analysed, this effect is statistically significant (Table 2).

The analysis shows that in most countries, the fit (R square) between the two variables is at a satisfactory level, confirming that an increase in the share of energy consumption produced by PV influences a reduction in the share of fossil fuels in the energy mix. The correlation is of course negative, but importantly in most EU countries, the relationship between these energy sources is at a high level (coefficient b). Based on this relationship and bearing in mind that solar energy is a low-carbon energy and fossil fuels are sources of CO_2 emissions, it makes sense to study the impact of increasing the consumption of energy generated by photovoltaic panels on reducing emissions and thus decarbonizing the economy.

Solar energy from photovoltaic panels, however, is not only clean, emission-free energy, but also waste, some of which is recovered for reuse and some of which must be disposed of, generating CO_2 emissions. In order to measure the impact of increasing the consumption of renewable energy produced from photovoltaic panels on CO_2 emissions, an environmental efficiency measurement approach was adopted from economic theory, measuring efficiency according to the Kaldor–Hicks criteria. In the literature, the Kaldor–Hicks efficiency criterion is traditionally used to assess the efficiency of social welfare. It is used in the literature to conduct a cost–benefit analysis, or in other words, an efficiency of resource re-allocation. Thus, it can be used in practice to evaluate any resource where there is a distribution of the resource and offsetting of losses by gains. This efficiency criterion is used in the literature, among others, to assess the benefits of policies in the economy [53], the efficiency of the supply chain system [54] or the assessment of the social cost of carbon [55]. In this article, the authors applied the principle of the Kaldor–Hicks criterion to carry out a cost–benefit analysis on the production of PV technologies and the production of energy with them, and more specifically their environmental effect. In our framework, resource allocation, i.e., consumption of energy solar from photovoltaic panels, is effective when it produces more benefits than costs. Net impact on the environment means the potential impact on the amount of CO_2 emissions. The identification of benefits and costs from the consumption of energy that comes from photovoltaic panels is presented in the model below (Figure 1).

Table 2. Analysis of the relationship using regression analysis between the share of fossil fuels in primary energy consumption (dependent variable) and the share of solar energy consumption (with PV) in the energy mix in 1990–2023 (number of periods n = 34).

Country	Statistics					
	R Square	Adj. R-sq.	Coefficient b	Standard Error of b	t-Statistic(32)	*p*-Value
Austria	0.5494	0.5393	−0.7412	0.1187	−6.2461	0.0000
Belgium	0.6593	0.6487	−0.8120	0.1032	−7.8694	0.0000
Bulgaria	0.5169	0.5018	−0.7190	0.1229	−5.8518	0.0000
Czech Rep.	0.7804	0.7735	−0.8834	0.0828	−10.6640	0.0000
Denmark	0.6915	0.6819	−0.8315	0.0982	−8.4696	0.0000
Estonia	0.5732	0.5599	−0.7571	0.7746	−6.5556	0.0000
Finland	0.7101	0.7010	−0.8426	0.0952	−8.8524	0.0000
France	0.5013	0.4857	−0.7080	0.1248	−5.6715	0.0000
Germany	0.8500	0.8454	−0.9220	0.0685	−13.4680	0.0000
Greece	0.9386	0.9367	−0.9688	0.0438	−22.1200	0.0000
Hungary	0.4601	0.4433	−0.6783	0.1299	−5.2226	0.0000
Ireland	0.3685	0.3487	−0.6070	0.1405	−4.3210	0.0001
Italy	0.9350	0.9330	−0.9670	0.0451	−21.4541	0.0000
Luxembourg	0.9019	0.8989	−0.9497	0.0554	−17.1540	0.0000
Netherlands	0.9211	0.9186	−0.9597	0.0447	−19.3291	0.0000
Poland	0.5003	0.4846	−0.7073	0.1250	−5.6598	0.0000
Portugal	0.5016	0.4860	−0.7083	0.1248	−5.6752	0.0000
Romania	0.6840	0.6741	−0.8270	0.0994	−8.3225	0.0000
Slovakia	0.5191	0.5041	−0.7205	0.1226	−5.8770	0.0000
Spain	0.7859	0.7792	−0.8865	0.0818	−10.8383	0.0000
Sweden	0.4807	0.4645	−0.6933	0.1274	−5.4425	0.0000

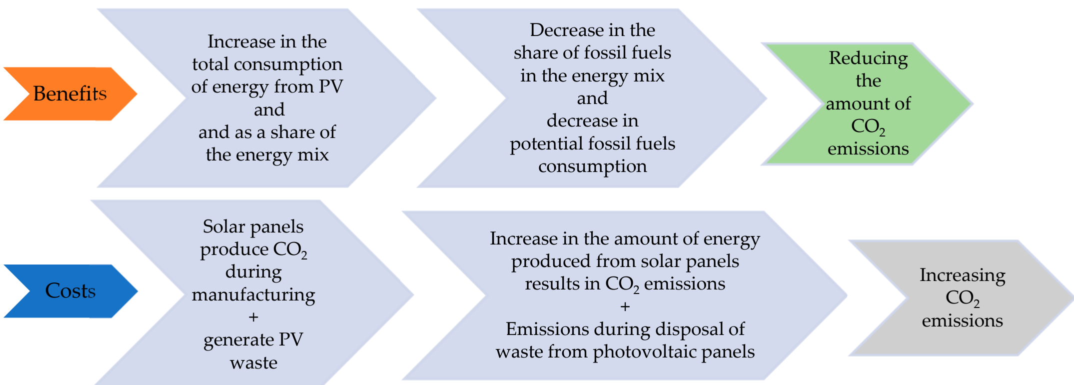

Figure 1. Model the net environmental impact of energy consumption that comes from photovoltaic panels.

The net environmental impact of photovoltaic panels for energy generation will be calculated according to the following formula:

$$\text{Net Env} = \text{FFCR}_{\text{i}} \times \text{CIEP}_{\text{i}} - (\text{SEP}_{\text{i}} \times \text{AV.CO2}_{\text{SE}} + \text{NWE}_{\text{i}}) \quad (1)$$

where

$FFCR_i$—fossil fuels consumption reduction in the i-th country, i.e., primary energy consumption that comes from photovoltaic panels, which has reduced fossil fuels consumption in the energy mix (in MWh). This parameter indicates the level of reduction in the consumption of fossil fuels that are the source of emissions in the economy due to the consumption of solar energy from PV;
$CIEP_i$—carbon intensity of energy production, i.e., the amount of carbon dioxide emitted per unit of energy production (of all fossil fuels), measured in tonnes of CO_2 per 1 MWh in the i-th country. The economy of each country is characterised by a different level of energy efficiency, and thus the emission intensity of energy production. Knowing what the carbon intensity of energy production is, and knowing the amount of energy from PV that replaces fossil fuels, thanks to CIEP, we are able to determine potential reductions in carbon emissions;
SEP_i—solar energy production, i.e., energy produced from solar panels in the i-th country (in MWh);
AV.CO2SE—the average amount of CO_2 that is emitted in order to produce 1 MWh. This is the value specified in the literature. The average value determined for the EU will be adopted;
NWE_i—net waste emissions, i.e., the amount of CO_2 that is emitted in order to dispose of waste from photovoltaic panels in the i-th country in a given year.

Fossil fuels consumption reduction (FFCR) is calculated as (Formula (2)):

$$\text{FFCR}_{\text{i}} = \Delta\text{SEC}_{\text{i}} \quad (2)$$

where

ΔSEC_i—change in solar energy consumption from PV to the previous year in the i-th country.

Net waste emissions NEWi is calculated as:

$$\text{NWE}_{\text{i}} = (\text{WC}_{\text{i}} - \text{WR}_{\text{i}}) \times \text{ERPP} \quad (3)$$

where

WC_i—waste collected from photovoltaic panels (in kg);
WR_i—amount of waste recovered for reuse (in kg);
ERPP—emissions from recycled photovoltaic panels, i.e., the average amount of emissions required to recycle waste from photovoltaic panels.

Solar energy from photovoltaic panels is renewable energy, which means that the more renewable energy an economy consumes from this source, the greater the environmental benefits are potentially. The environmental effect in this article is understood as CO_2 emissions. The benefits arise from the fact that by consuming energy manufactured through photovoltaic panels, CO_2 emissions from consuming energy generated from fossil fuels are avoided. These are therefore potential environmental benefits. However, photovoltaic systems generate not only environmental benefits but also environmental costs, namely, CO_2 emissions. These costs come from two sources: photovoltaic panels produce CO_2 during energy manufacturing and waste. In the case of the second cost, photovoltaic panels for energy production generate waste, so they must be disposed of, which generates emissions. Given that part of this waste is subject to recovery, the amount of waste that is subject to disposal is calculated as the waste collected minus the amount of recovery of waste of photovoltaic panels.

The model also makes the following methodological assumptions:

AV.CO2SE—the average amount of CO_2 that is emitted in order to produce and install 1 MWh energy by solar photovoltaic panel in its lifetime is 0.041 tonne [29]; ERPP—recycling 1 tonne of photovoltaic panels spares 1.2 tonnes of CO_2 emissions (Fraunhofer Institute for Solar Energy Systems ISE, in [36]).

Both of the assumptions are based on widely accepted and literature-verified data on technical average CO_2 emissions by PV in the EU. The average values adopted in the model for waste recycling rates and carbon dioxide emissions during the PV production phase are a research limitation. In order to calculate precisely the actual value of CO_2 emissions in each country, it would be necessary to take the values for each country separately, instead of taking the average value in the EU. The authors are aware that waste emission values from photovoltaic panels vary from region to region [30,31]. However, taking into account that within the EU the waste incineration technologies used do not differ drastically, and the fact that, according to studies, the key factor for the net benefit of PV energy production is the amount of this solar energy consumed, the authors have therefore adopted the EU average value identified in the literature [29]. A further justification for this approach by the authors is the framework approach adopted, i.e., the Kaldor–Hicks criterion, where the most relevant issue is the assessment of social welfare (in our case, the amount of CO_2 emissions emitted) and the factors determining this, rather than determining the differences between countries in the technology used in the production of PV and in the disposal of the resulting waste.

The analysis is carried out for all European Union countries for which data are available. Due to the availability of data (for Croatia, Latvia, Lithuania, Malta and Slovenia there are no data on the amount of waste of photovoltaic panels, so these countries were omitted from the analysis), the analysis is carried out for 22 countries. Such a territorial area is due to two reasons. First, the European Union is a leader in the implementation of climate policy in the world and has the most ambitious decarbonization targets in the world, resulting from the Green Deal package. The second reason is that the European Union is an economic community of many countries, which makes it possible to verify the hypothesis of the positive impact of photovoltaics on environmental performance on a large number of countries. In addition, it is worth mentioning that the availability of data for these countries is relatively the largest. The research period is 2019–2021 and is also determined by data availability.

4. Results

In beginning the analysis, the first step was to measure the benefits resulting from the increase in the consumption of renewable energy from solar energy (photovoltaic panels). These benefits stem from the consumption of solar energy generated by PV, which, when consumed, replaces energy produced from fossil fuels, which are carbon-emitting. The value of these benefits is determined not only by the amount of energy consumed but also by the level of carbon intensity of energy production. The total potential environmental benefits resulting from the reduction in CO_2 emissions are presented in Table 3.

Table 3. Analysis of the environmental benefits of reducing potential CO_2 emissions from fossil fuels.

Year	2019	2020	2021	2019	2020	2021	2019	2020	2021
Country	**$FFCR_t$ (TWh)**			**$CIEP_i$ (Tonne/MWh)**			**Total Carbon Benefits (Thous. Tonnes)**		
Austria	4.5	5.4	7.3	158.8	155.2	162.6	712.4	833.0	1183.9
Belgium	11.2	13.4	14.7	134.7	137.2	129.6	1510.0	1842.0	1904.8
Bulgaria	3.7	3.9	3.8	199.6	187.0	190.5	745.8	721.3	731.3
Czech Rep.	6.0	5.9	5.6	211.4	207.2	207.3	1274.9	1217.4	1167.2
Denmark	2.5	3.1	3.4	157.9	160.4	156.3	400.9	497.2	535.3
Estonia	0.2	0.6	0.9	196.4	157.3	169.7	38.0	101.2	157.2
Finland	0.4	0.6	0.8	129.8	120.2	118.3	50.4	69.0	92.1
France	30.7	33.4	38.9	115.6	115.3	118.3	3548.3	3851.6	4605.6
Germany	119.2	130.0	129.1	191.5	187.9	191.5	22,824.8	24,430.8	24,724.4
Greece	11.7	11.7	13.7	207.5	200.8	190.2	2422.4	2345.4	2614.0
Hungary	3.9	6.5	9.9	179.4	175.1	171.0	707.8	1130.8	1698.8
Ireland	0.1	0.1	0.2	199.2	199.5	209.2	17.5	27.9	43.5
Italy	62.4	65.5	65.5	187.1	183.6	190.7	11,681.9	12,025.7	12,492.8
Luxembourg	0.3	0.4	0.5	206.6	199.0	195.1	71.0	84.3	92.0
Netherlands	14.2	22.5	29.6	149.2	138.0	137.9	21,232.0	3105.9	4078.6
Poland	1.9	5.1	10.3	267.6	265.5	270.3	501.2	1365.1	2783.0
Portugal	3.5	4.5	5.9	162.1	157.2	149.9	573.3	708.3	877.3
Romania	4.7	4.6	4.5	200.3	200.3	197.9	938.8	911.9	882.0
Slovakia	1.6	1.7	1.8	182.7	171.7	180.1	283.7	298.9	316.3
Spain	39.8	54.3	70.9	158.3	150.1	150.5	6302.6	8148.6	10,669.8
Sweden	1.7	2.7	3.9	65.5	61.6	60.8	114.5	166.1	239.7

Source: based on [52,56].

The results indicate that in most EU countries, these benefits are increasing over the years. The only notable exceptions are Bulgaria and Romania. These benefits are primarily determined by the growing consumption of generated solar energy. Since the carbon intensity of energy production is relatively constant in all countries, with a slight downward trend, the increasing consumption of energy from PV systems determines the environmental benefits. The analysis (Figure 2) also shows that, depending on the country, annual benefits range from approximately 0.1% in the case of Ireland to 4–5% in the case of Greece and Spain. Other countries that have recorded significant environmental benefits related to the reduction in CO_2 emissions from fossil fuels, due to the development of photovoltaic energy, include Germany, Hungary, Italy, and the Netherlands.

The costs associated with the carbon footprint result from two factors, namely, the production of solar energy and the waste collected from PV systems, which require disposal. The results of the analysis show the level of these costs in Table 4.

The results indicate that the decisive factor in the environmental costs resulting from solar PV energy is the amount of energy produced. The carbon footprint associated with waste collected from PV systems that is not recyclable is negligible, and in relation to the overall environmental costs resulting from the operation of photovoltaic panels, it is minimal, shaping up to be less than 1%. Although most of the waste will be generated in most countries in 20–30 years, when the lifespan of photovoltaic panels ends, it should be noted that already over 90% of the collected PV waste is suitable for reuse. Therefore, it can be concluded that in the future, the share of environmental costs generated by PV waste will be low and will decrease.

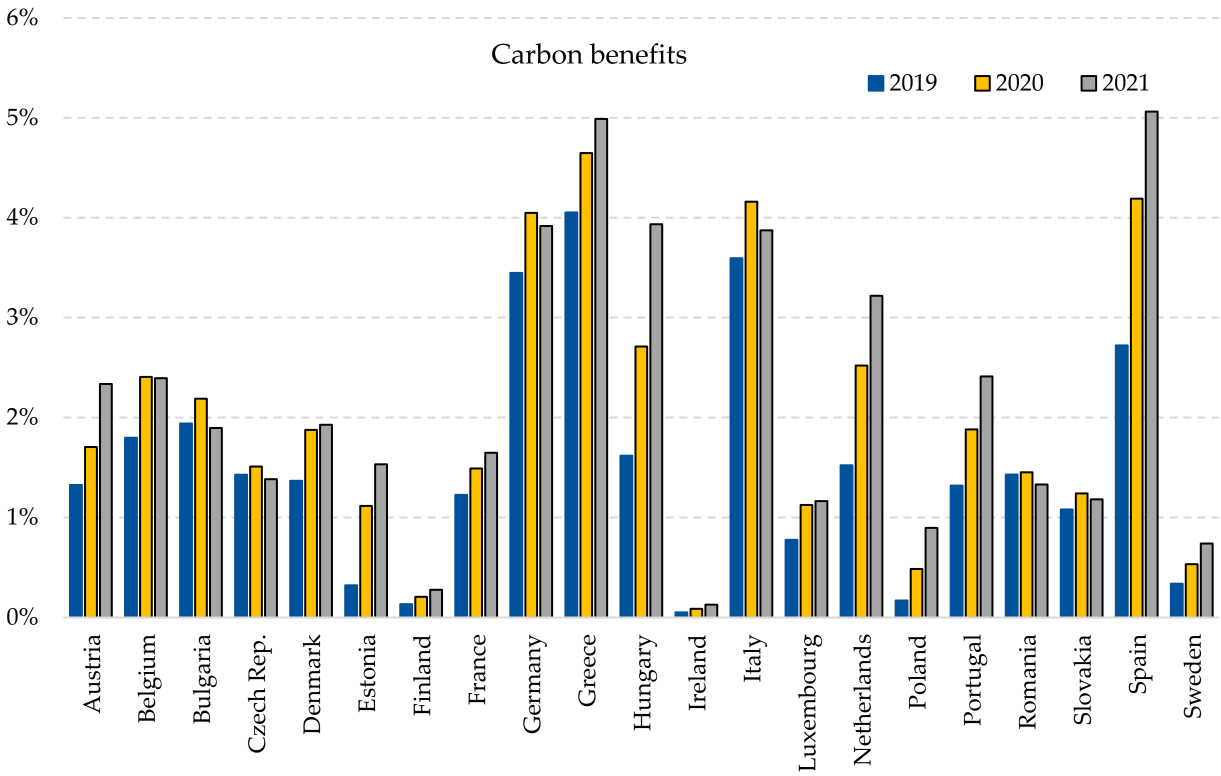

Figure 2. Total carbon benefits resulting from PV energy consumption in relation to total energy sector CO_2 emissions in the EU countries. Source: own elaboration.

Table 4. Analysis of environmental costs resulting from solar PV energy.

Year	2019	2020	2021	2019	2020	2021	2019	2020	2021
Country	**CO_2 Emissions of SEP (Thous. Tonnes)**			**NWE_i (Tonne)**			**Total Costs (Thous. Tonnes)**		
Austria	184.0	220.0	298.5	1.2	1.2	1.2	184.0	220.0	298.5
Belgium	459.6	550.5	602.7	42.0	255.6	360.0	459.6	550.7	603.1
Bulgaria	153.2	158.1	157.3	0.0	0.0	0.0	153.2	158.1	157.3
Czech. Rep.	247.2	240.9	230.9	31.2	15.6	277.2	247.3	240.9	231.2
Denmark	104.1	127.1	140.4	28.8	18.0	19.2	104.1	127.1	140.4
Estonia	7.9	26.4	38.0	0.0	0.0	0.0	7.9	26.4	38.0
Finland	15.9	23.5	31.9	20.4	4.8	1.2	15.9	23.5	31.9
France	1258.8	1369.3	1596.4	394.8	3309.6	−646.8	1259.2	1372.6	1595.8
Germany	4887.3	5329.6	5293.4	249.6	187.2	248.4	4887.5	5329.8	5293.6
Greece	478.6	478.8	563.3	0.0	0.0	66.0	478.6	478.8	563.4
Hungary	161.8	264.8	407.2	0.0	0.0	4.8	161.8	264.8	407.3
Ireland	3.6	5.7	8.5	0.0	0.0	0.0	3.6	5.7	8.5
Italy	2560.2	2685.6	2686.3	957.6	730.8	1766.4	2561.1	2686.4	2688.0
Luxembourg	14.1	17.4	19.3	0.0	0.0	0.0	14.1	17.4	19.3
Netherlands	583.5	922.5	1212.7	56.4	319.2	106.8	583.6	922.8	1212.8
Poland	76.8	210.8	422.1	16.8	12.0	255.6	76.8	210.8	422.4
Portugal	145.0	184.7	240.0	30.0	10.8	−26.4	145.1	184.7	240.0
Romania	192.2	186.6	182.7	110.4	115.2	0.0	192.3	186.7	182.7
Slovakia	63.7	71.4	72.0	3.6	4.8	2.4	63.7	71.4	72.0
Spain	1632.8	2225.6	2907.2	130.8	222.0	−256.8	1671.7	2225.6	2906.9
Sweden	71.7	111.4	161.7	82.8	0.0	1.2	71.7	111.4	161.7

Source: own calculations based on [52,57].

So, what is the net environmental impact of solar energy from PV? The answer to this question is provided by the data in Table 5 and Figure 3.

Table 5. Net Environmental impact of PV in 2019–2021 (thousand tonnes CO_2).

Country	Net Environmental Impact			Net Env. Taking Into Account the Increase in Primary Energy Consumption in the Economy		
	2019	2020	2021	2019	2020	2021
Austria	528.5	613.0	885.3	75.0	100.4	233.0
Belgium	1050.3	1291.3	1301.7	82.6	213.0	112.5
Bulgaria	592.6	563.1	573.9	29.1	17.7	−2.9
Czech. Rep.	1027.6	976.5	936.0	−28.1	−25.7	−40.9
Denmark	296.7	370.0	394.9	2.1	67.0	37.4
Estonia	30.1	74.8	119.2	17.4	52.3	36.4
Finland	34.4	45.4	60.2	13.2	14.7	15.8
France	2289.1	2479.0	3009.8	251.5	196.9	428.9
Germany	17937.3	19101.0	19430.8	292.1	1585.2	−133.3
Greece	1943.8	1866.6	2050.6	273.8	0.8	307.6
Hungary	546.1	866.1	1291.5	315.8	336.9	451.8
Ireland	13.9	22.1	35.0	6.4	8.2	11.4
Italy	9120.8	9339.3	9804.7	365.3	435.6	0.5
Luxembourg	56.9	66.9	72.6	4.9	12.6	7.4
Netherlands	1539.6	2183.1	2865.8	478.4	801.9	685.8
Poland	424.4	1154.2	2360.6	244.6	733.7	1181.5
Portugal	428.2	523.5	637.3	106.3	112.5	146.8
Romania	746.6	725.1	699.3	0.1	−21.6	−14.9
Slovakia	220.1	227.5	244.3	0.7	24.6	2.0
Spain	4669.7	5923.0	7762.9	716.1	1577.0	1820.7
Sweden	42.8	54.7	78.1	17.4	19.5	24.3

Source: own work.

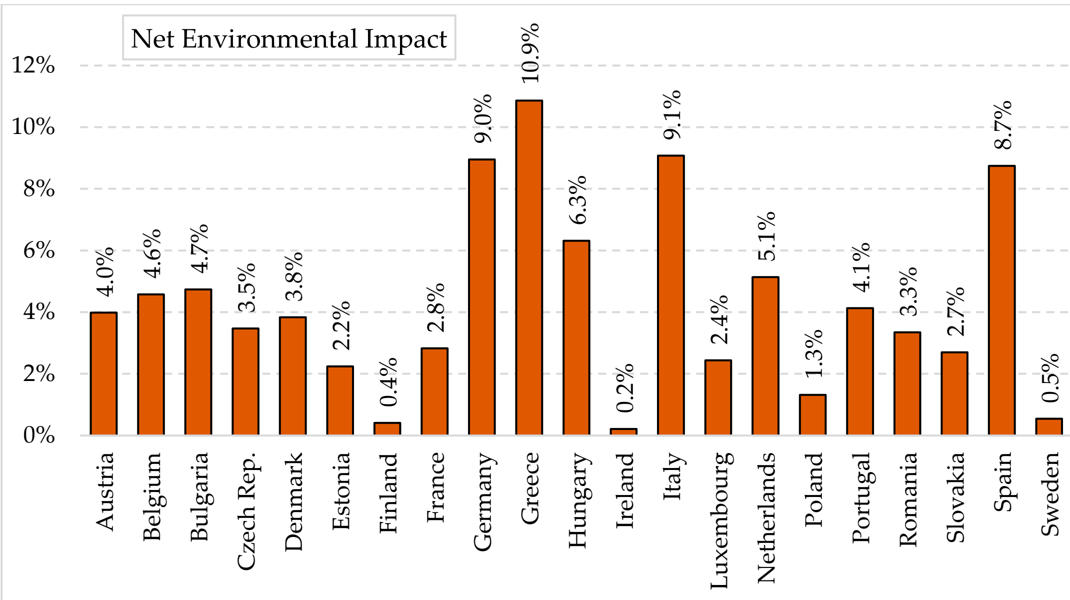

Figure 3. Net Environmental impact of PV as % of CO_2 emissions in the total energy sector in 2019–2021. Source: own elaboration.

The results indicate that in all countries, solar energy produced by PV systems had a positive environmental impact during the study period, meaning it contributed to reducing CO_2 emissions that, in the absence of this type of energy source, would have been emitted by fossil fuels. The results also showed that, with the exception of Bulgaria, the Czech Republic and Romania, in all other EU countries, this positive environmental impact increased during the study period. In terms of absolute values, meaning the amount of

CO_2 emissions, the greatest benefits were observed in Germany, Italy and Spain. On the other hand, the smallest carbon benefits were observed in Ireland and Luxembourg.

By analysing the benefits, costs and overall net environmental impact of the development of photovoltaic solar energy, it was concluded that the decisive factor was the benefits side, which, in fact, results from the scale of consumption of this type of energy. Therefore, it should be stated that the primary pro-environmental factor is the scale of solar energy development. It is important to emphasise that this conclusion is applicable regardless of the country. It was also found that, in each country, the costs associated with the need for waste disposal have a negligible impact on shaping the net environmental efficiency of photovoltaic panels.

When analysing the net environmental impact of PV in percentage terms, as a share of total CO_2 emissions in the economy (Figure 3), it was found that the greatest potential benefits in terms of CO_2 emission reduction were recorded in Greece, Italy, Germany and Spain, at around 9–10% collectively over the studied 3 years. Comparing these data with the increase in the share of solar energy in the energy mix, it was concluded that the greatest net environmental benefits were achieved in the countries where the highest increase in solar energy consumption occurred. Thus, these data confirm the previous conclusion that the main decarbonization determinant for solar energy is the scale of solar energy development.

In conclusion, it is worth analysing the data presented in Table 5, taking into account the increase in primary energy consumption in the economy. These data show what benefits in CO_2 emission reduction would be achieved if only the increase in the share of solar energy in the energy mix were considered, rather than the change in consumption in absolute terms. These results indicate that the environmental benefits are significantly lower if the goal is additionally to decrease the share of fossil fuels in the energy mix and to calculate the growth in the share of solar energy in percentage points. The results showed that the development of photovoltaics did not exceed the overall rate of primary energy consumption growth in all countries to the extent that it would yield relative environmental benefits. Such exceptions were the Czech Republic and Romania.

To better illustrate and explain the differences between countries, Figures 4 and 5 summarise the factors influencing the net environmental efficiency of photovoltaic panels in EU countries.

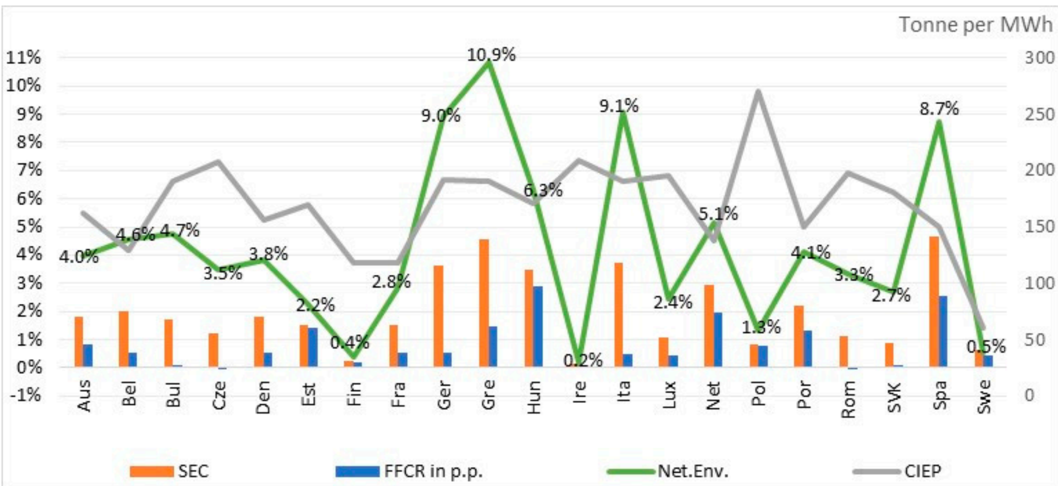

Figure 4. Beneficial factors influencing the net environmental impact of PV. Source: own elaboration.

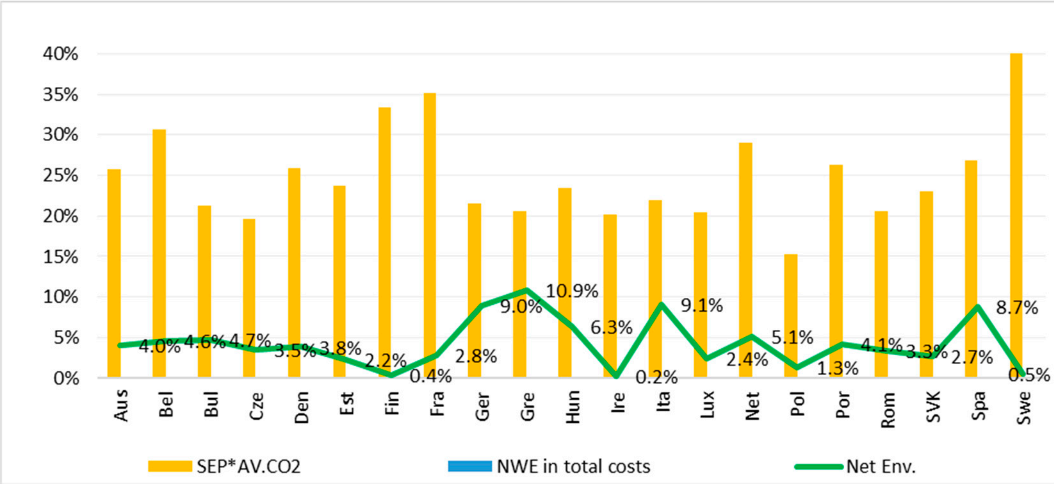

Figure 5. Contribution of cost drivers in determining the net environmental impact of PV. Source: own elaboration.

The results of the cross-country comparative analysis indicated (Figure 5) that cost drivers are not decisive in determining the net environmental impact of PV. Among the cost drivers, CO_2 emissions occurring during the production of panels (SEP*AV.CO2) are decisive. In most EU countries, they account for just over 20% in relation to the environmental benefits achieved through PV panels. In the case of Sweden, Finland, France and Belgium, this share is higher (above 30%), but this is due to the fact that these countries rely heavily on hydropower and nuclear energy, making the carbon intensity of energy production (Figure 4) in these countries low. As a result, the environmental benefits of producing solar PV and substituting emission-intensive fossil fuels are relatively lower than in other countries. The comparative analysis also indicated that the second cost driver, net waste emissions, represents a negligible share of total environmental costs for all EU countries (in the region of 0.1%). This means that NWE is not a factor in determining the net environmental benefits of energy consumption that comes from PV. Thus, this factor does not significantly differentiate countries from each other in terms of environmental impact. In contrast, what explains the differences between countries in net environmental effectiveness from PV in the study results are the environmental benefits (Figure 4). A comparative analysis of countries has shown that the greatest benefits are achieved by countries that have significantly increased the share of primary energy consumption that comes from PV over the study period and where this renewable energy represents the largest share of the energy mix. Examples are countries such as Germany and southern European countries (Greece, Italy and Spain). At the opposite extreme are the Scandinavian countries (Finland, Sweden) and Ireland. The carbon intensity of energy production (CIEP) also plays a role in achieving benefits, as in the case of the CEE countries; however, the most important factor is still the high consumption of this energy in the energy mix and increasing this share in the country's net positive environmental effect from energy consumption that comes from PV.

5. Discussion

Discussion of results regarding the analysis of photovoltaic energy development in selected EU countries indicates the duality in PV systems, which, on one side, represent a green source of energy, yet, on the other side, contributes to problems. Data show that PV technology is of paramount importance for an EU decarbonization strategy; however, it generates not only a reduction in dependence on fossil fuels but also environmental costs in terms of waste and CO_2 emissions at all stages of the value chain related to panel production, installation and decommissioning. The key findings of the study bring out the fact that large-scale diffusion of PV technology would be in line with the Green Deal goals of the EU, as this would result in a substantial reduction in carbon emissions in the energy sector—a fact that is substantiated by the negative correlation between the consumption of PV energy and fossil fuel in most of the EU nations. The latter relationship underlines the potential that PV energy has to support the development of a cleaner mix of energy, therefore meaningfully contributing to national and regional GHG reduction targets. A more nuanced perspective in terms of the environmental implications of PV emerges when waste from the end-of-life of photovoltaic panels is studied.

While solar energy is intrinsically clean, it produces CO_2 emissions and waste that offset some of the environmental benefits accrued during the operational life of the panels through production and transportation, and eventual disposal. Although small in volume compared with emissions from fossil fuels, such emissions do represent an important cost—mostly because the appropriate infrastructure for the management of waste does not exist in most parts of the world. These findings reflect that in life cycle terms, PV panels are beneficial, but their contribution to CO_2 emissions in both the beginning and the end brings about a reduction in the net environmental benefit of solar energy differently between some countries and others. Countries such as Germany and Italy have more advanced waste management practices where, at a lower net environmental cost, the recycling facilities are able to recover valuable materials from the PV panel, including silicon and silver. This infrastructure does not exist in most EU countries; hence, this leads to inconsistencies regarding the net positive effect that PV technology presents in the region. The different policies and practices governing the recycling of PV wastes throughout the EU would further compound the related environmental costs.

This means in real life that it would be obviously different between those countries with stringent recycling systems and those countries without. Indeed, this inconsistency in the handling of waste reduces the overall efficiency and sustainability of the PV systems themselves, as materials that could otherwise have been in their sustainable loop may end up being discarded with extra CO_2 emissions and a loss of resources. This discrepancy underlines that harmonised standards and recycling policies about waste management must be established among EU countries if the maximum net benefits of PV energy are to be reaped. Common guidelines on PV waste management can further create a more circular economy and, therefore, enable PV technology to contribute positively towards the sustainability goals of the European Union by reducing resource dependence and lowering environmental costs. Aside from environmental issues, the study also unravels the potential economic gain in photovoltaic waste recycling.

If properly managed, the recycling of PV wastes can even open a new market for recovered materials such as rare metals that are in high demand by the production process of new photovoltaic panels. Lower demand for virgin raw materials would thus decrease the environmental impact of producing PVs. The recycling process for PV would also ensure the added economic feasibility related to the creation of new job opportunities and encouraging innovation in the renewable energy sector since such technological advancements in recycling would reduce costs and increase efficiencies related to the recovery of resources. It would require investment in recycling infrastructure, developing some innovative technologies relating to waste recycling and policy coordination that could standardise the recycling practices, if the benefits were to be exploited. This would start contributing to the EU's long-term sustainability agenda by creating a self-sustaining circular economy in the PV sector. Results regarding the development of photovoltaic energy in selected countries of the EU allow one to draw certain insights from a net environmental impact theory perspective.

The theoretical framework underlines that the overall environmental benefit of any given technology or intervention needs to be measured by weighing its positive against its negative environmental impacts. Under PV energy, net environmental impact theory would therefore present not only the fact that PV technology contributes to a significant reduction in GHG emissions but also accounts for environmental costs associated with wastes and CO_2 emissions through all production and operation phases and post-operational disposal [58–60]. The results of this study indicate the very strong positive net environmental impact of PV energy in EU countries, given that the GHG reductions accomplished through the replacement of fossil fuels by solar energy are quite significant.

Such an outcome, however, is a consequence, from the perspective of net environmental impact theory, of a reduced carbon footprint in the energy sector in the EU since increasing the use of PV energy translates to a decrease in reliance upon carbon-intensive fossil fuels [61,62]. The switch also rhymes with the objectives of the European Union's Green Deal, since GHG emissions reduction linked to transitioning to PV energy plays a very important role in the decarbonization efforts charted by the European Union policy. Thus, the contribution of PV technology to decarbonization underlines the explicitness of its net positive impact; therefore, solar energy is a low-carbon alternative that could go a long way in reducing harm to the environment caused by conventional methods of energy production. It also underlines the fact that PV systems bear environmental costs mainly produced by wastes generated at the end of the life cycle in the PV panel.

The theory of the net environmental impact provides a balanced theoretical framework for how these costs related to waste dent the overall benefit from PV energy [63,64]. While there is a low carbon footprint in the operating process of solar energy, in the case of photovoltaic panels, it leads to associated wastes and emissions from manufacturing, maintenance and final processes of wastes. This inevitably involves management through recycling and waste processing, which themselves all contribute to CO_2 emissions. If there is no infrastructure for this—as is most often the case—then wastes are disposed of in an unsustainable manner and the net environmental benefit is reduced. This has resulted in most European Union countries recovering the vast majority of collected PV waste and increasing their capability to recycle [57], which implies a net positive effect from the PV energy due to the fact that it assists in decreasing some of these environmental costs associated with the proper management of PV wastes [65]. While in countries with less developed infrastructure for recycling, the environmental cost exacerbates the net from the PV technology. The theory of net environmental impact also explains how the policies on waste management can determine the overall environmental outcome from PV technology [66,67].

Countries that have strict policies and a framework in place regarding waste management are well placed in ensuring that the environmental cost of waste emanating from photovoltaic technology is reduced. In this respect, the overall net environmental effect is still highly positive since the environmental benefit obtained by the reduction in emissions surpasses the waste-generated emissions [68]. This theory predicts a very limited positive outcome in countries that have poor waste management infrastructures due to unresolved environmental costs of waste disposal. The variability underlines the need for uniform recycling policies and infrastructure across the EU that can guarantee a positive environmental impact consistently from PV energy. Discussion of net environmental impact theory will help to understand the potential of the approach of the circular economy in enhancing the positive net benefit of PV energy by minimizing the generation of waste [69–71].

While the EU might reduce the possible environmental cost of PV waste by considering a more circular economy approach—a method whereby PV panels and their components would be recycled and repurposed—she would, in fact, turn what could be a negative impact into one that is a resource contributing to further PV development. In relation, such thinking corresponds with the theory of net environmental impact; thus, the circle should lean more towards maximizing the positive outcome by reducing extracted resources and waste [72–74]. Therefore, a well-structured framework in relation to circular economies and photovoltaic technology can reduce part of the lifecycle cost or environmental cost and increase the overall net photovoltaic benefits. Such a transition would create some economic value from waste materials and reduce the demand for new raw materials. In this way, it will decrease the environmental burden of producing photovoltaic panels and contribute towards long-term sustainability. Moreover, the improvement in maintenance [75] must be realised, according not only to TMP (Technical Maintenance Protocol) but for the panels.

The results clearly show how PV technology greatly reduces GHG emissions within the EU and, therefore, might make a potential contribution to the ambitious set of decarbonization policies in this region due to reduced reliance on fossil fuel sources. Interaction of this positive environmental impact brings huge welfare benefits to the public in the form of reduced emissions, which are associated with improved air quality, reduced health risks, and a more sustainable environment. Thus, given that the climate and public health benefits of this action are suspected to be larger than the emissions generated from waste, these huge net benefits outweigh the environmental cost of PV panel production and disposal by the criteria of Kaldor–Hicks efficiency [76–79]. The EU's commitment to an increase in PV energy is, therefore, suitable in line with such a view since the—notionally speaking—social and environmental gains that stem from decreased fossil fuel use pay off for the lifecycle costs of PV systems. This relationship underlines efficiency concerning the PV technology being used as a renewable energy source delivering a net welfare improvement due to reduced emission in EU societies and a cleaner energy mix.

The full Kaldor–Hicks efficiency is, however, being challenged because those countries that do not have appropriate waste management and recycling systems bear some environmental costs arising from PV waste [80,81]. In light of this, this study seeks to strike a balance by noting that even while PV energy throughout its operational life phase generates huge benefits, the end-of-life disposal and recycling processes of the panels are contributors to CO_2 emissions and resultant environmental costs. The environmental cost, therefore, must be at a minimum or nullified through some efficient policy of waste management and recycling infrastructures for the full realisation of Kaldor–Hicks efficiency [82]. In countries that have developed recycling systems, like Germany, the environmental cost will remain low since recovered PV materials like silicon and silver are treated for repurposing to raise the net welfare gain from PV energy. They do this by decreasing the chance of environmental costs being attributed to wastes generated in those countries. Given, additionally, that the production of solar PV energy contributes to a net positive environmental benefit to the economy, such systems would undoubtedly further enhance the positive environmental effects from the consumption of PV energy.

The Kaldor–Hicks framework further bolsters the case that there is a strong case for having a coordinated EU approach to PV waste management, which would be helpful in maximizing the overall welfare benefit of PV energy across members [83]. This implies that investment in standardised recycling infrastructure would establish uniform policies in managing wastes from the EU, enabling it to better minimise the environmental costs of PV wastes and increase the distribution balance between benefits and costs within its member states. Thereby, those countries that currently bear high environmental costs from PV wastes could better catch up with the efficiency principles of Kaldor–Hicks [83,84]. It would spread the cost of waste management over the EU, and such coordination may potentially allow all countries of the EU, whatever their current conditions are with respect to their capability of managing waste, to achieve net welfare gain with the PV technology.

The other important contribution of the Kaldor–Hicks efficiency framework is the emphasis on economic efficiency that is likely to emanate from a circular approach within the PV sector [85,86]. In addition to the material recovery of resources such as silicon, silver and rare metals, there is a possibility that the recycling and reuse of PV wastes may unlock a secondary market for the materials concerned, thereby adding value that will square off the economic cost of production and management of wastes. Responsible research and innovation approach in policy, and cooperation between government, companies (especially industry) and society [87] should support waste management and reduce the waste burden. Recycling in the PV sector would circularly reduce demand for raw materials, hence reducing the environmental burden for new production of PV panels. It is most important as it contributes to economic growth in the renewable energy sector because recycling and waste management create jobs. These economic gains, in terms of Kaldor–Hicks, further enhance the net welfare benefit of the PV technology because the financial and resource advantages gained from recycling could compensate for the environmental costs of the waste management of PVs [88]. This will be in line with the EU objectives related to resource efficiency and sustainable growth and will contribute to a more integrated and efficient renewable energy economy. The protracted energy crisis may affect the PV market, both on the side of producers and consumers; however, regardless of the difficult situations, it is already necessary to take action on PV waste disposal [89]. Unfortunately, a short timeframe, namely, focusing the analysis on 2019–2021, makes it difficult to capture trends on the long-term environmental impacts of PV waste. Although there are studies on the projected future level of solar PV energy consumption, the current global political turmoil means that such projections are subject to a high degree of uncertainty. On the basis of the data obtained in this paper, however, it can be assumed that the net environmental effectiveness of solar PV energy production will increase in the future for all EU countries. The results showed that the countries with the highest increase in PV energy consumption achieved the highest positive net environmental effectiveness. This means that social welfare due to net environmental effects in EU countries will increase. Based on the differences between Sweden, Germany and Bulgaria, it can also be assumed that countries with a high share of RES in the energy mix (and thus a low carbon intensity of energy production) will see a lower and lower change in net environmental effectiveness due to an increase in PV energy production.

The German photovoltaic recycling system is exemplary and can offer a wide range of lessons to learn for improving environmental benefits as well as developing a harmonised policy concerning the management of PV wastes within the European Union [90,91]. With an appropriate mix of strict regulations, advanced technological infrastructure, and public–private collaboration, Germany has emerged as one of the leading countries in renewable energy and waste management for photovoltaic materials. Indeed, the German system shows that combined efforts can address the concerns about the environment while at the same time creating economic opportunities [92].

The German system is based on adherence to the WEEE Directive on collection, recycling, and recovery of PV waste. German policymakers went one step further from what was laid out in the WEEE Directive by setting up extensive collecting networks and ambitious targets for recycling [93]. German law obliges the manufacturers and importers to finance collection and recycling for all end-of-life PV panels, under the principle of a closed-loop system, which gives the guarantee of responsibility throughout the life cycle of the product. This extended producer responsibility system reduces environmental impacts but at the same time creates an incentive for manufacturers to design more recyclable panels [91,92,94].

Germany has also invested in advanced recycling technologies to make its system even more efficient. In turn, facilities in this country can recover approximately 95% of the valuable material in the panels, including silicon, glass and other rare metals like silver and indium. These are those facilities that employ innovatory methods such as thermal, chemical and mechanical separation methods that allow minimum wastage but maximum re-utilisation of critical components. It is through collaboration between research institutions, industry participants, and government agencies that Germany continues to enhance its recycling capabilities and raises the bar higher for other countries [90–92].

Drawing from the German experience, further harmonisation of PV waste management policies at the EU-wide level could increase the overall environmental benefits of PV technologies. First, harmonisation in the processes of recycling would mean the elaboration of unified standards for assurance that methods applied by all the member states are of high quality. A difference in infrastructure and policies of recycling currently leads to uneven environmental and economic performance across countries, whereby some lack proper treatment capacity for PV waste. Harmonised standards would bridge these gaps in such a way that material recovery and environmental protection become comparable by all member states.

A good example of PV development is Germany, due to its achievements in the production of solar energy. It is the biggest PV energy producer in the EU, and due to this effort, it has substituted large percentages of electricity produced from fossil fuels with solar energy, thus making CO_2 emissions lower to a remarkable level. For instance, it is estimated that from 2019 to 2021, the environmental dividends for PV energy in Germany averted approximately 20 million tonnes of CO_2 annually. This example shows how the policy related to renewable energy is translated into practical applications and shows how well Germany has been able to adjust to solar energy in the national grid without losing its focus on sustainability [95,96]. On the opposite side of this argument is the case of Bulgaria [97]. Despite the enhanced dependence of the country on solar energy, the environmental benefits have remained at a relatively low level. Such obtained situation might be explained by several reasons, namely, the slow development of advanced photovoltaic technologies and scarce financing of extensive solar networks. Therefore, the environmental benefits of Bulgaria regarding solar energy do not exceed one million tonnes of CO_2 annually, whereas the respective indicators of such countries as Germany are considerably higher [98]. Another indicative example of the environmental impacts of the PV technology is Italy.

Up until 2021, Italy was the leader among EU countries in terms of installed PV capacity, after Germany. The majority of such installations are rooftop PV systems that have spread throughout the country, especially in regions with high solar irradiance, and have contributed much to reducing greenhouse gas emissions. It has also used financial incentives and supportive regulatory frameworks in order to develop individual and community-level solar investments, thereby reducing over 10 million tonnes of CO_2 every year. Similarly, Spain is one such country whose climate closely coincides with the potential for energy generation via solar energy [99,100].

Advances in Photovoltaic technologies and large-scale solar farms mean that Spain has the potential to achieve about 9% CO_2 reduction within its total energy sector. Solar farms, such as the largest operating photovoltaic installation in Europe, Núñez de Balboa, demonstrate Spain's approach to its transition towards renewables. The case study of how solar investments might return significant environmental dividends with energy independence [101]. The picture is further muddled by France. Much was invested in solar energies, but the great dependence of the country on nuclear power—a low-carbon source, though renewable energy—pulls down the comparative advantage of its photovoltaic systems in the case of mitigated CO_2 emissions. This was visible, for example, in the case of France in 2021, whose solar energy-related CO_2 abatement was only a fraction of that for countries like Germany or Spain, simply because of the much lower substitution effect [102,103].

Last but not least, improper waste management of photovoltaics is another crucial environmental expense in the operation of solar systems. For example, Germany has been driving a path towards efficient processes in the recycling of retired panels from which valuable materials like silicon, silver and copper could be recovered. On the other side, serious infrastructural obstacles prevent the process of waste recycling in Romania, and such rates are foreseen to further increase environmental costs over the upcoming years once the installation reaches the end of its life. The various PV development examples represent manifold consequences of this development throughout the European Union [104,105]. This study also brings to light issues regarding the ways in which the capacity for economic, technological innovation, and the policy framework shape the net environmental benefits from solar, and thus, critical choices to be taken in future decarbonization strategies.

This could also include pan-European regional recycling hub development inspired by such centralised facilities in Germany. It would establish hubs in strategic locations serving various countries, thus minimizing emission and transportation costs while providing the best usage of advanced recycling technologies. For example, Germany can work with its neighbours to increase the capacity of its facility by making it a common facility for the wider region. This harmonisation needs to be extended to the application of EPR schemes. Whereas EPR is a cornerstone of the German system, it is applied inconsistently across the EU as a whole. A common framework on EPR would ensure that all manufacturers, irrespective of their location, financially contribute to managing the costs of PV wastes. This will create a level playing field for companies and help in accountability along the value chain. Second, the EU could introduce a central registry that could track the PV panels through their entire life cycle. This would also allow for better data gathering and more transparent methods of waste management.

Another thing that constitutes a part of German success and should be emulated at the EU-wide scale is public awareness and education. Consumers, in fact, have to understand their role in the proper disposal of the PV panels and the environmental benefits related to recycling. Coordinated campaigns across the member states can raise awareness and participation in recycling programs, thus increasing collection rates and reducing illegal dumping.

Other financial mechanisms to be harmonised are subsidies and tax incentives, which support the development of recycling infrastructure and the adoption of eco-friendly designs throughout the EU. A good example could be how Germany incentivises innovation in recycling technologies and how such concentrated investments pay off eventually for the whole region. This harmonisation also extends to making the penalties for non-compliance with the mandates for recycling at the same level where enforcement and deterrence for environmentally hazardous practices remain comparable.

Implementing lessons learnt from the German PV recycling system, the pursuit of policy harmonisation can significantly contribute to ensuring increased environmental benefits for the EU derived from PV technologies. By not only enhancing resource recovery and a reduction in waste, this is also supposed to make the EU the leading region in sustainable management of waste coming from PV technologies and set yardsticks for other regions as well.

Policy Recommendation

Photovoltaic waste management is a very intricate problem with multi-faceted influences. To set up an action framework, coherence, technological development, policy coordination and the principles of the circular economy should all head towards achieving sustainable development and environmental protection.

From this perspective, research and technological development regarding the comprehensive framework should, in particular, underline innovations in recycling technologies addressing the volume of waste from these end-of-life panels that are now continuously coming up. This covers the extraction of valuable materials such as silicon, silver and rare earth metals through methods at a low cost. Advanced research needs to be directed towards design improvements in the photovoltaic panel to enhance its recyclability, reduction in toxic substances used, and employ sustainable materials. Partnerships between research institutions and industry should look at energy-efficient recycling processes that will also reduce carbon emissions associated with waste management.

Development and deployment of such technologies require considerable investment in R&D. This must be undertaken, among other ways, through public–private partnerships, correct linking of funding, and environmental sustainability goals. A database on photovoltaic materials' life cycle and their streams of waste will provide fundamental data for recycling technology optimisation. The policy coordination cannot be dispensed with for the harmonisation to take place across regions and sectors. It is felt that policies need to clearly state the guidelines for the management of PV waste, including binding quotas for recycling and full application of EPR schemes, so that manufacturers may be made responsible for the whole life cycle of their products, with incentives given for eco-designs and efficient waste management systems.

Equally significant is cross-border cooperation. Given that in the EU, the member states all have different capacities for recycling and waste infrastructures, harmonised standards for the recycling and transportation of PV waste will avert ineffectiveness and make sure responsibilities are fairly distributed. Secondly, policies should have monitoring and compliance mechanisms with associated penalties for noncompliance to ensure that targets on waste management are met efficiently. Given the circular economy, the action framework should have among its guiding principles the reuse, refurbishment and recycling of photovoltaic panels. The circular approach, therefore, looks towards minimizing waste while keeping materials in use as long as possible; hence, the creation of secondary markets for recovered materials and panels, design for longer lives of the panels, and the adoption of modular systems permitting easy repair or replacement.

In fact, the stakeholders—manufacturers, policymakers and consumers—need to be involved in creating a culture of sustainability. Public awareness campaigns can be organised for the stakeholders on the issue of recycling and proper waste disposal of photovoltaics. Economic incentives in the form of tax benefits or subsidies for companies that undertake circular practices may potentially accelerate the shift to more sustainable waste management.

Based on this, some additional policy recommendations could be made to enrich the PV waste management framework. The following suggestions aim at improving environmental sustainability and resource recovery with equity across regions:

- Implementation of a Harmonised Recycling Directive: The EU and other regions should enact a common directive that imposes uniform standards for the management of PV waste. This directive should cover specifications regarding the dismantling, transportation and recycling of the panels. Uniformity across countries can minimise regulatory discrepancies and create economies of scale for recycling operations.

- Encourage closed-loop manufacturing: for example, the proper and facilitating policy could encourage manufacturing designs such that they fit circular economic goals; the government might try a few tactics to induce production like offering tax breaks and giving subsidies on these items for whom its products will have the capacity to recover themselves, hence also enhancing its recyclability at later stages or for achieving "green product" certification.
- PV Recycling Hubs: Building central recycling hubs, especially in areas with the highest PV installations, could efficiently streamline waste collection and processing. This is where governments can support investment in such infrastructure through public–private partnerships. Such a hub will also double as a research centre for enhancing recycling technologies and processes.
- Demanded Recycling Quotas: Regulations must bind the industries for certain percentages of the PV waste to be recovered and used anew. In this way, gradual development for the industry must provide sufficient time for readaptation for the manufacturer and the recycler too. The illustration would be having a target first with a rate like 70% within the coming five years and then raising that up to 90% gradually.
- Digital Traceability of Photovoltaic Panels: The development of policies that will ensure the implementation of digital tagging of photovoltaic panels by manufacturing companies is important. This helps in tracing materials in real time throughout their life cycle. Materials origin, composition, and movement of the PV waste are documented using blockchain or secure digital technologies that enable tracing and efficient recycling.
- Subsidies for New Recycling Technologies: Government funding for programs developing new recycling technologies—such as hydrometallurgical and pyrometallurgical processes—for the extraction of key raw materials like silicon, indium and silver. These will be further accelerated with start-up and pilot demonstration stages at an industrial scale.
- International Cooperation on Waste Trading: The PV waste management policies need to address the issue of international agreement impeding the exports of toxic wastes to countries that have very limited infrastructures for recycling. Rather, bilateral or multilateral agreements could be arrived at to provide common facilities in places having state-of-the-art facilities for recycling so as to undertake effective and environmentally safe processing.
- Integration with Renewable Energy Goals: Waste management policies need to be integrated with the general renewable energy policies. For instance, a policy may tie incentives for installing new PV systems to commitments for managing end-of-life panels. Governments may also wish to give priority funding to regions showing leadership both in renewable energy expansion and in best waste management practices.
- Public Awareness and Consumer Participation: The roles that consumers can play in managing PV waste through education campaigns. Policies can be put in place that force manufacturers and installers to clearly spell out how recycling or disposal will be carried out at the time of purchase. Rewards or rebates given for compliance with proper waste disposal also increase individual participation.
- Financial Penalties for Non-Compliance: Policies can contain penalties for non-compliance with the set standards of waste management; for example, fines levied on manufacturers for failing to achieve the required quota for recycling, or levies against entities for inappropriate disposal of PV waste. The revenue collected through such fines may be used in waste management programs or research.
- Low-Income Region Support: As not-so-well-off regions are having a hard time managing wastes from PV, financial and technical support programs need to be

included in the policies. Capacity-building programs would include training for recyclers at the local level along with low-cost recycling technologies.

- Accountability for Lifecycle Emission: The policy and regulatory framework should incorporate lifecycle emissions assessment. Manufacturers and recyclers must report all the emissions related to production, recycling and waste management practices to capture all environmental costs and reduce them.

6. Conclusions

The aim of the paper was to analyse the net impact of photovoltaics on CO_2 emissions in European Union countries, taking into account the analysis of the impact of generated and disposed of energy waste. To this end, an analysis model was proposed that would consider not only the potential benefits related to CO_2 emissions but also the side effects associated with collected waste and the manufacturing of energy from solar power. Verification of RQ1 and RQ3 allowed for the finding that the consumption of solar energy generated by solar panels provides a net positive environmental impact in all EU countries. Moreover, except for two countries (Bulgaria, Romania), the net environmental benefits in the form of a reduction in potential CO_2 emissions have increased over the years. Verifying RQ2 also revealed that the environmental benefits of solar energy are largely determined by the increasing consumption of generated solar energy. The analysis also indicated that PV waste has a negligible (below 1%) impact on the side effects of photovoltaic panels, such as CO_2 emissions. This confirms the findings from the literature [30,31] that waste should be disposed of, where it does not pose a threat to the positive environmental impact of PV development. Furthermore, this negative impact related to the recycling of PV waste should become even smaller in the future. It was also stated that the consumption of solar energy from PV is not entirely climate-neutral. The costs associated with the carbon footprint primarily arise globally during the manufacturing of solar energy. However, despite this, the overall carbon impact remains highly positive, contributing to a reduction in fossil fuel consumption and, consequently, CO_2 emissions.

By verifying the research questions posed in the study, the authors have contributed new knowledge to the literature. The main contribution is the creation of an analysis model and the proof that CO_2 emissions related to waste constitute a small portion of the total environmental costs incurred during the production and consumption of solar energy using photovoltaic fuel technologies. It was also indicated that in the European Union, the positive impact of solar energy development exists in all countries. However, it was also pointed out that in countries where solar energy consumption is not growing or is growing more slowly than total primary energy consumption, relative benefits from CO_2 emissions in the economy diminish. Therefore, the development of solar energy must continue in order to maintain the decarbonization processes in the EU economies.

The most significant scientific contribution of the paper is that it provides the first in-depth assessment of the net environmental impact of the European Union's Photovoltaic Energy Systems with due concern for waste and disposal costs of PV. While much of the existing literature focuses on quantifying the emissions reduction and decarbonization potential of PV energy, this paper builds by framing the generally hidden problem of energy waste produced throughout the life cycle of photovoltaic panels, from production to disposal. The present research dwells on a novel model that merges the advantages of GHG emissions reduction with environmental costs related to the management of PV waste, providing a balanced framework of the real environmental footprint of photovoltaic technology. This enables a more correct dual focus both on the positive and negative impacts of solar energy within the EU context.

By considering one of the unique values, this paper could be said to apply the Kaldor–Hicks efficiency framework to analyse whether the benefits that PV energy provides outweigh the costs from waste sufficiently. This analysis provides, from an economic perspective, a theoretical justification for discussing environmental policy in terms of net welfare gain through the use of PV energy in emission reduction against the cost of waste management. It also highlights the importance of a circular economy approach towards the wastes generated by PVs, thereby further improving the net environmental benefit of PV energy through effective recycling and resource recovery.

This value is added by the empirical analysis across several EU countries, offering insights at the country level into the efficiency and environmental impact of PV systems under varied waste management practices. These findings are particularly useful for policymakers and environmental agencies because they seek the development of standardised recycling policies and investment in waste management facilities to improve the sustainability of renewable energy systems. This thus advances scientific knowledge on the environmental impacts of photovoltaic technology and also provides practical guidance that assures that the potential of solar energy is maximised in a manner that adheres to EU decarbonization and sustainability goals.

The study also has its research limitations. The primary limitation is that the analysis was conducted over only a 3-year period. This is due to the lack of a larger dataset regarding the quantity of waste. Therefore, this constitutes a direction for future research and a premise for its continuation.

As countries face future increases in energy production from renewable energy sources, including PV panels, PV waste management needs to start being prioritised. As 93.6% of recovered PV waste is recycled and 61.1% of waste collected from PV is recovered [51], the amount of CO_2 emissions generated from the disposal of PV waste in EU countries is small (compared to the net environmental effects). However, given the Green Deal targets and the continually increasing production and consumption of energy from PV, it is suspected that the amount of waste from PV will increase rapidly in the future. Therefore, in the context of future research, it is suggested to analyse the recycling potential of new PV materials (such attempts at analysis are already being carried out in the literature [30]) and to analyse the data over a long period of time, once more data have become available. Another research limitation is the way net waste emissions are calculated, namely, that the authors may have underestimated the volume of recyclable waste and the estimated amount of emissions from recycling. There is a possibility that CO_2 emissions may increase when recovering materials from waste (if higher-emission technologies were used). This is therefore an element that could be improved in future research. Future studies might be conducted on the development of technologies and new methods for PV recycling that will most certainly emerge as demands for waste management continue to become even more sustainable. It is also recommended that the recycling potential of new PV materials or data analysis over longer time spans is explored. The examination of such developments for their environmental and economic implications would provide a detailing of how more efficient means of recycling may go towards reducing carbon emissions due to PV waste disposal. It will also detail the best practices that support an efficient circular economy within the PV sector by comparative studies on different recycling technologies and practices within EU countries, especially on those with mature waste management infrastructures with those still developing such systems.

The research on recycling potential should be developed concerning emerging PV materials to help capture the dynamic nature of innovation in solar technologies. New PV technologies, such as perovskite and thin-film solar cells, are rising to prominence, and their lifecycle impacts need to be understood, including aspects relating to recyclability and material recovery. The research may be in relation to the special challenges these materials create, be it in chemical stability, toxicity or the possibility of large-scale recycling processes. Another hopeful direction in research is the investigation into alternative, environmentally friendly materials that balance performance with environmental sustainability.

Other relevant aspects are the longitudinal studies of environmental and economic impacts related to PV waste management over long periods. This would be further extended to several decades to provide clear trends on the material recovery rate, waste generated and related emissions. This will help the development of long-term sustainability from present policies and practices in recycling, and deficiencies that might occur with the increased volume of decommissioned panels. A retrospective study into the past data, supported by predictive modelling, enables the anticipation of challenges in the future and to orient and focus proactive policy and technological intervention.

Other ways of doing this are by investigating how AI and machine learning can be integrated into PV waste management. An AI-driven system could further optimise the sorting processes, improving material recovery rates while smoothing out logistical operations. Linking these technologies with advanced life cycle assessment tools would lead to more accurate evaluations of the environmental benefits and costs associated with different recycling methods. In this line, socio-economic PV waste management research that pertains to job creation and the market development of secondary raw materials can further strengthen the business case for investment in sustainable waste solutions. Such studies would be most relevant for those regions where the adoption of renewable energy is rapidly expanding but the recycling infrastructure is underdeveloped. Emerging areas, when addressed, can further contribute to a holistic approach wherein the environmental and economic benefits of PV technologies are maximised.

Author Contributions: Conceptualization, B.G., R.W., and R.N.; methodology, R.N.; software, B.G., R.W. and R.N.; validation, B.G., R.W., R.N., and B.Ž.-N., formal analysis, R.N., B.G., and R.W.; investigation, B.G., R.W., R.N., and B.Ž.-N.; resources, R.N., B.G.; R.W., and B.Ž.-N.; data curation, B.G., R.W., R.N., and B.Ž.-N.; writing—original draft preparation, B.G., R.W., R.N., and B.Ž.-N.; writing—review and editing, R.W., B.G., R.N., B.Ž.-N., and W.G.; visualisation, B.G., R.W., R.N., B.Ž.-N., and W.G.; supervision, B.G., R.W., R.N., B.Ž.-N., and W.G.; project administration, R.N., B.G., and R.W.; funding acquisition, B.G. and R.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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