energies

Article

Life Cycle Assessment of Electricity Production from Different Biomass Sources in Italy

Amalia Zucaro [1,*,†], Giuliana Ansanelli [1,*,†], Antonietta Cerbone [1], Antonio Picarelli [2], Caterina Rinaldi [1], Tiziana Beltrani [1], Silvia Sbaffoni [1] and Gabriella Fiorentino [1]

1 ENEA, Department for Sustainability, Division Resource Efficiency, 00196 Rome, Italy; antonietta.cerbone@enea.it (A.C.); caterina.rinaldi@enea.it (C.R.); tiziana.beltrani@enea.it (T.B.); silvia.sbaffoni@enea.it (S.S.); gabriella.fiorentino@enea.it (G.F.)
2 ENEA, Department of Energy Technologies and Renewable Sources, Division Smart Sector Integration and Distributed RES Generation, 00196 Rome, Italy; antonio.picarelli@enea.it
* Correspondence: amalia.zucaro@enea.it (A.Z.); giuliana.ansanelli@enea.it (G.A.)
† These authors contributed equally to this work.

Abstract: The European Union is targeting climate neutrality by 2050, with a focus on enhancing energy efficiency, expanding renewable energy sources, and reducing emissions. Within Italy's electricity mix, bioenergy sources, namely biogas, solid biomass, and bioliquids, play a crucial territorial role. A comparative analysis was conducted through Life Cycle Assessment (LCA), utilizing national data from the ARCADIA project, to assess the environmental sustainability of the investigated bioenergy chains and identify the most convenient ones. The study revealed that, among the bioenergy sources, solid biomass emerges as the most environmentally friendly option since it does not rely on dedicated crops. Conversely, biogas shows the highest environmental impact, demonstrating less favorable performance across nine out of the sixteen evaluated impact categories. The LCA underscores that the cultivation of dedicated energy crops significantly contributes to environmental burdens associated with electricity generation, affecting both biogas and bioliquids performance. The cultivation process needs water and chemical fertilizers, leading to adverse environmental effects. These findings highlight the importance of prioritizing residual biomass for energy generation over dedicated crops. Utilizing forestry and agro-industrial residues, municipal solid waste, and used cooking oils presents numerous advantages, including environmental preservation, resource conservation and recovery, as well as waste reduction.

Keywords: environmental impacts; Italian LCA database; bioenergy; electricity mix; biogas; solid biomass; bioliquids

Citation: Zucaro, A.; Ansanelli, G.; Cerbone, A.; Picarelli, A.; Rinaldi, C.; Beltrani, T.; Sbaffoni, S.; Fiorentino, G. Life Cycle Assessment of Electricity Production from Different Biomass Sources in Italy. *Energies* **2024**, *17*, 2771. https://doi.org/10.3390/en17112771

Academic Editor: Om P. Malik

Received: 7 May 2024
Revised: 30 May 2024
Accepted: 4 June 2024
Published: 5 June 2024

1. Introduction

The European Union (EU) population is projected to decline over the very long term. According to EUROSTAT, on 1 January 2020, the EU population was estimated at 447.7 million with a projection to reach 449.3 million in 2025 and then 449.1 in 2030 [1].

The substantial population residing in EU countries contributes to elevated energy consumption and demand. Following its peak in 2006, energy consumption has progressively decreased, indicating a successful decoupling of energy demand from economic growth. However, this downward trend is expected to pause between 2020 and 2025, primarily due to the resurgence of energy demand following the aftermath of the COVID-19 pandemic. However, it is expected that, in the future, the improvement of energy efficiency and the implementation of renewable energy policies will lead to an increasingly greater decoupling between energy consumption and economic growth [2].

In 2012, with the Energy Roadmap 2050, EU countries aimed to reduce greenhouse gas emissions (GHG) by 95% by 2050 through virtually complete decarbonization. Then, the European Commission issued the 'Clean Energy Package', which set the commitment to reduce CO_2 emissions by at least 40% by 2030 compared to 1990, focusing on three main objectives: (i) prioritizing energy efficiency, (ii) achieving global leadership in renewable energy, and (iii) ensuring a level playing field for consumers. In addition, it was proposed to increase energy efficiency by 32.5% by 2030 and to reach 32% of renewables in overall consumption. Subsequently, in order to reach the targets proposed in the Paris COP21 (i.e., to limit global warming to 2 °C, possibly 1.5 °C), Europe set new, more ambitious targets with the Green Deal (adopted in December 2019) [3], such as the reduction of climate-altering gases by 55% by 2030 and climate neutrality by 2050.

Furthermore, during the recent COP28, held in Dubai in December 2023, several important decisions were made. These include: (i) the establishment of a fund to address losses and damages, specifically for the most vulnerable countries affected by climate change disorders, and (ii) agreements on mitigation measures that involve a more decisive phase-out of fossil fuels (surpassing the previous phase-down efforts) with the aim of achieving net-zero emissions by 2050.

The transition to clean energy aims to establish an energy system primarily fueled by renewable energy sources (RES). Technologies for generating renewable electricity offer a more sustainable solution compared to non-renewable alternatives [4–7]. Furthermore, the integration of RES technology development with carbon capture systems and storage has the potential to create negative emission technologies (NETs) [8,9]. This approach can contribute significantly to reducing carbon emissions and fostering a more environmentally friendly energy landscape.

It is apparent that each EU country must attain the targets set by the European Commission, considering its unique energy production system composed of diverse technologies and energy sources, thereby shaping its national electrical mix. Conducting a life cycle assessment (LCA) becomes crucial for a comprehensive understanding of the environmental impact. LCA serves as a valuable tool to quantify the environmental implications of any product, process, or service, employing various methods that take into account material and energy flows, as well as input resources and output emissions.

In recent years, different studies based on a LCA approach have focused on energy scenarios at a national scale, for example: Portugal [10], Belgium [11], French insular territories [12], Denmark [13], Spain [7], the UK [14], and Germany [15], or at a regional scale (Sicilia Region in Italy) [16].

Some other projects were focused on the comparison of the national energy mix with the European or extra-European context [17,18].

The analysis conducted in Portugal revealed that installing desulphurization and denitrification systems in coal power plants could significantly reduce the impact on certain environmental categories, notably acidification (−62%) and photochemical oxidation (−74%) [10].

In Belgium, the focus shifted to studying the global warming potential (GWP). Understanding the hourly CO_2 content of 1 kWh of electricity is crucial for assessing the potential benefits of upcoming smart grid technologies [11].

A life cycle cradle-to-gate electricity analysis was conducted for French coastal and insular territories. The findings indicated that French Guyana has the lowest greenhouse gas (GHG) emissions per kilowatt hour produced, mainly attributed to its significant reliance on renewable energy sources [12].

In Denmark, the assessment was primarily centered on the distribution of electricity and its associated impacts, with a comparative analysis against the generation and transmission processes. The goal was to evaluate the significance of electricity distribution in the overall impact of the energy system. The argument put forth suggests that impacts from electricity distribution are poised to rise in the future due to the proliferation of renewables and decentralized electricity generation. Furthermore, it is anticipated that impacts from infrastructure, such as distribution networks, could become increasingly significant compared to electricity generation itself [13].

The study on the electrical system in Spain assessed sustainability using eight environmental indicators (climate change, fossil depletion, ozone layer depletion, terrestrial acidification, human toxicity, and photochemical smog), along with economic indicators like the levelized cost of electricity and socio-economic indicators such as direct employment. Various future scenarios were analyzed, revealing that the most ambitious projections regarding renewable energy penetration yield the best outcomes in terms of environmental performance, employment generation, and reduced costs (EUR/MWh) [7].

Interesting research was conducted in the UK, exploring various electricity scenarios spanning up to 2070. These scenarios encompassed key technologies relevant to the UK (nuclear, gas, coal with and without carbon capture and storage—CCS, wind, solar photovoltaics, and biomass), and three levels of decarbonization were examined, evaluating the techno-economic, environmental, and social impacts on a life cycle basis. The findings revealed that a very low-carbon mix featuring nuclear and renewables offers the best overall environmental performance. Indeed, the complexity of energy systems extends beyond environmental considerations to encompass social and health impacts as well. While a low-carbon mix involving nuclear and renewables may offer significant environmental benefits, it is important to acknowledge and address potential social concerns such as health impacts from radiation and the requirements for storage of radioactive waste. Balancing these various factors is crucial to formulating sustainable and socially responsible energy policies. Conversely, in a scenario where an equal weighting is assigned to each sustainability impact, an equal share of nuclear and renewables emerges as the top-ranked option [14].

The life cycle assessment (LCA) of electricity production plays a pivotal role in evaluating the environmental impact. In particular, the LCA serves as an indispensable tool for decision-making in the development of roadmaps for near-future decarbonization efforts. By analyzing different perspectives and considering diverse factors, LCA enables informed decision-making that prioritizes environmental sustainability. On the path towards decarbonization, LCA will continue to be instrumental in guiding the development of more sustainable energy systems.

In this framework, the present study is the first attempt to evaluate the impacts of bioenergy sources in the Italian electricity mix by using site-specific data collected during the ARCADIA project (Life Cycle Approach in Public Tenders and the Italian LCA Database for Resource Efficiency) [19,20]. The main objective was the development of a national LCA database (IT-LCA Database) [19], not yet available in Italy, for 23 different supply chains representative of the Italian production system. The IT-LCA Database is available for free upon registration, and by now, over 180 datasets have been implemented belonging to the agri-food, buildings, energy, and wood furniture sectors. The dataset is developed according to the format of the International Life Cycle Data System [21]. In the framework of an Agreement between ENEA and the Ministry of the Environment (2024–2028), the IT-LCA Database will be further implemented and updated.

Within the energy sector, in the ARCADIA project, the following processes were investigated: (i) production of the national energy mix (including photovoltaic chain), (ii) electricity production from biogas, (iii) electricity production from solid biomass, and (iv) electricity production from bioliquids [19].

The energy sector and electricity production are important for their potential environmental impacts, as they are responsible for a significant share of national GHG. This gave rise to the need to include the national electricity mix in the Italian LCA database, and, therefore, an in-depth study was carried out on bioenergy chains, due to their strongly territorial nature.

In Italy, electricity is still largely produced from non-renewable sources such as natural gas, coal, and oil, although the development of renewable sources such as hydroelectric, solar, wind, bioenergy, and geothermal energy is steadily increasing. In 2022, 31.1% of energy demand in Italy was covered by renewable sources [22].

According to GSE [23], electricity production from renewable sources has increased in the last decade. After a peak of 120.7 TWh reached in 2014 and a significant reduction in the following years up to 2018 (114.4 TWh), a growing trend has been recorded. In 2019, electricity production from renewables amounted to 115.8 TWh, with an increase of 1.6 TWh compared to 2018, to reach a value of approximately 116.3 TWh in 2021. Among RES, bioenergies include all those organic materials that can be used directly as fuel or transformed into solid, liquid, or gaseous fuels. In 2021, the total power of Italian bioenergy plants was equal to 4106 MW and represented 7.1% of the total electrical power from renewable sources in Italy. There were 2985 bioenergy plants for electricity production installed in Italy in 2021 [23]. In detail, 42.6% of the production in 2021 came from biogas, 35.8% from solid biomass, and 21.5% from bioliquids. Among the various bioenergies, biogas plants are still more numerous than the plants for the other biomass sources. In terms of electrical power, 41.4% of the plants are fueled by solid biomass, 35.4% by biogas, and the remaining 23.2% by bioliquids [23].

Biomass is defined as the decomposable portion of items, discards, and remnants of organic origin derived from agricultural sources (comprising both plant and animal materials), forestry, and associated industries. This encompasses materials from fisheries and aquaculture, as well as clippings and trimmings from public and private green spaces. Additionally, it includes the biodegradable segment of both industrial and municipal waste, as specified in Legislative Decree No. 28 of 3 March 2011 [24].

The primary matrices frequently utilized within the biogas supply chain originate from agriculture, specifically dedicated energy crops and livestock waste. Energy crops, being specifically cultivated for energy production, offer the advantage of yielding high amounts of biogas. However, the contentious aspect surrounding the space requirements for energy crops, along with associated environmental costs, remains one of the most unresolved and debated issues concerning this energy source [25]. Due to sustainability concerns, there has been a recent shift in focus towards plants that utilize waste biomass, which can be integrated into agro-energy supply chains. In Italy, for instance, the CRPA (Animal Production Research Centre) [26] conducted a study in collaboration with the CIB (Italian Biogas Consortium) [27] on various biomass types. This study quantified the residual biomass that could potentially be directed to anaerobic digestion plants, including livestock effluents, residues from herbaceous crops, and agro-industrial by-products, along with their associated methane yields. The findings of this study revealed that livestock effluents could represent a crucial resource in biomethane production scenarios, accounting for over 75% of what can be produced from other residual biomass and more than 25% of the total biomethane production. The projections for 2030 anticipate a significantly wider adoption of livestock effluents compared to energy crops, primarily due to the incentive mechanism outlined in the biomethane decree in Italy [28]. This mechanism offers tariff advantages only if less than 30% of the biomass used for energy production originates from dedicated crops. Consequently, it is expected that the utilization of dedicated crops will comprise less than 30% of the feedstock for anaerobic digestion plants, with a corresponding increase in the contribution of livestock effluents [29].

An interesting Italian study by the Ca' Foscari University of Venice Foundation [30] has identified the socio-economic impact of the solid biomass power generation sector in Italy, examining the economic aspects in terms of employment, income, and tax impacts, considering the biomass production and supply sector, the transport sector, and the power generation sector in the year 2017. The concept of a solid biomass "short supply chain" [31] is very important to reduce the impact of biomass transportation and its impact in terms of GHG emissions. In Italy, according to the Ministerial Decree (DM) of 2 March 2010 [31], biomasses produced within a radius of 70 km from the power plant are considered to have a short supply chain.

On the other hand, bioliquids refer to "liquid fuels intended for energy applications beyond transportation, encompassing uses such as electricity generation, heating, and cooling". Essentially, these are fluid fuels sourced from plant and animal biomass, serving as an alternative to fossil fuels in the generation of electricity. Bioliquids, which are investigated in this study, are only those complying with the sustainability criteria laid down in Legislative Decree No. 55 of 31 March 2011 (containing the same criteria as Directive 2009/28/EC) [32]. In addition, from a socio-economic point of view, the use of different sources of bioenergy can generate impacts [33]. The socio-economic aspects of the bioliquid production chain can be addressed on different scales, starting from the local to the global scale. The raw materials from which bioliquids are produced, namely oilseeds, have a dual market: food and energy production. These markets overlap, making it difficult to delineate on a large scale what share of the world's production goes to the food market and what goes to the energy market. Certainly, the evidence shows an important environmental and social impact of the massive production of oilseeds that has prompted large-scale assessments, especially in the areas of the world where these crops are concentrated.

Finally, biogas is defined as "a gas primarily composed of methane and carbon dioxide, generated through the anaerobic digestion of biomass" according to EU Regulation 147/2013 [34]. An interesting socio-economic analysis of the biogas supply chain was carried out in 2018 by Fiper (the Italian Federation of Renewable Energy Producers) [35], together with CMA (Consorzio Monviso Agroenergia), bringing together more than 120 farms owning biogas and other agro-energy plants. This study showed that the biogas chain represents an important element of strength in the national production fabric. In detail, the agricultural sector in Italy invoiced about EUR 2 billion per year of incentivized electricity from biogas, corresponding to about 4% of the total standard electricity production in 2016 [35,36]. The incentives granted to the biogas sector made the national rural area grow, develop, and innovate, with significant positive economic and social impacts.

Therefore, the key contribution and novelty of this research work is the assessment and comparison of the environmental impacts of three different renewable energy sources in the Italian electrical mix, based on local national data. Similar studies have yet to be found in the literature.

2. Materials and Methods

2.1. LCA Methodology

Life Cycle Assessment (LCA) is a methodology that provides qualitative and quantitative data on the environmental performance of a product, process, or service throughout its entire life cycle, encompassing indirect impacts. LCA was employed in this study to assess the environmental performance of electricity production from biomass, specifically comparing electrical energy derived from biogas, solid biomass, and bioliquids in Italy. This assessment adheres to the protocols recommended by ISO standards 14040 and14044 2006 [37,38]. As per standard procedure, the LCA process comprises four phases: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) impact assessment (LCIA), and (iv) interpretation of results. Each phase is detailed in the following paragraphs.

2.2. Goal and Scope Definition

LCA analyses were carried out according to an attributional approach (ILCD Handbook). The aim of this study was two-fold: (i) collection of data, specific to the national context, for building the datasets for the Italian LCA database; (ii) evaluation and comparison of the impacts associated with the Italian electricity production from biogas, solid biomass, and bioliquids in order to identify the environmental advantages and disadvantages of each energy source as well as the most eco-friendly option. Such an assessment could help to support the elaboration of decarbonization strategies, suggesting which bioenergy chain should be more incentivized through ad hoc politics.

Functional Unit and System Boundary

According to ISO 14040 [39], the functional unit (FU) plays a crucial role in defining the performance characteristics of the product, service, or system under investigation [39]. The primary objective of the FU is to establish a reference point to which inputs and outputs are connected, thereby ensuring the comparability of LCA results [40]. The FU chosen in this study is the Italian production of 1 kWh of electricity from each source, namely biogas, solid biomass, and bioliquids. The biogas energy supply chain [19,20] consists of the following phases: (i) production of biomass, including collection and transport to the treatment site; (ii) biomass treatment (anaerobic digestion) to transform the collected biomass into biogas; and (iii) production of heat and electricity through cogeneration in a combined heat and power (CHP) plant. For biogas production, both dedicated biomass (different types of energy crops, such as corn, ryegrass, and sorghum) and discarded biomass were considered. The discarded biomass includes residual biomass (livestock manure, agricultural, and agro-industrial residues) as well as the organic fraction (OF), consisting of municipal solid waste (MSW) and sewage sludge. For the biogas, energy supply chain, a "Cradle-to-Gate" approach was followed. In particular, for dedicated biomass, all phases from biomass cultivation up to energy generation were considered (Figure 1a). As for biogas from discarded biomass, the "zero burden" approach was applied, i.e., the environmental burden of the process generating the waste was neglected, according to the pertinent literature [41]. The biogas supply chain generates electricity and heat; therefore, an exergetic allocation was applied to determine the environmental impact of each energy co-product.

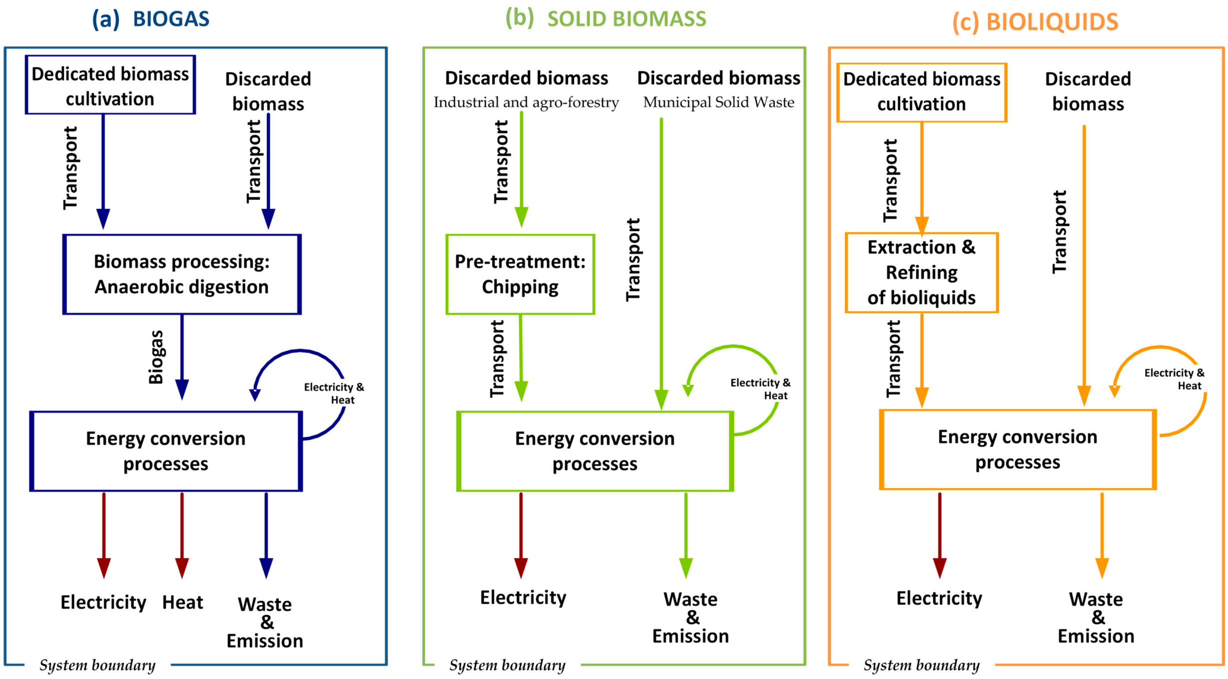

Figure 1. Selected system boundaries of: (**a**) energy production from biogas; (**b**) electricity production from solid biomasses; and (**c**) electricity production from bioliquids. The red arrows indicate the products obtained and sold to the grid.

Also, in the analysis of the solid biomass supply chain, a "zero burden" approach was applied since discarded biomass (solid urban waste, industrial residues, and agro-forestry residues) was employed at 95% [42]. Thereby, the analyzed phases were [19,20]: (i) biomass collection and pre-treatment (chipping); (ii) biomass transportation to an energy conversion plant; and (iii) energy production in a combustion plant. In this case, (solid biomass energy supply chain), the produced heat was considered only used for self-consumption and/or dissipated and, therefore, not accounted for as a co-product (Figure 1b).

Regarding the bioliquids supply chain, all the phases, from crop cultivation up to energy production, were included in the system boundary, according to a "Cradle-to-Gate" approach (Figure 1c). Indeed, in Italy, 77.4% of bioliquids for energy purposes are obtained from dedicated biomass, such as palm, soybean, sunflower, corn, and rapeseed crops [19,20]. The remaining percentage is represented by exhausted oils, like edible oils as well as vegetable and animal fat oils [43]. For this energy chain, the investigated phases were: (i) biomass production from dedicated crops; (ii) transport of dedicated and discarded biomass; (iii) oil extraction and refining (only in the case of dedicated biomass); (iv) transport of bioliquids from the place where dedicated biomass is cultivated to the energy conversion plant; and (v) energy production in a combustion plant. However, it is worth noting that for exhausted oils, the "zero burden" approach was applied. Moreover, it should be pointed out that the produced heat was not included in the system boundary since it was assumed that the part exceeding self-consumption was dissipated [43].

2.3. Inventory Data Analysis and Assumptions

The life cycle inventory includes recognizing and measuring the utilization of materials and energy (input flows), along with the generation of products, by-products, waste, and emissions (output flows), across the complete life cycle of the investigated systems [44]. For all the investigated bioenergy supply chains, data representative of the Italian context, derived from GSE technical reports, company reports, interviews, bibliographic sources, and environmental declarations, were used. In Table 1, the inventory of each bioenergy supply chain, referred to as the selected FU (1 kWh of electricity), is reported.

2.3.1. Biogas Inventory

For the production chain of electricity from biogas, national data were used for processes relating to cultivation, biomass transport, anaerobic digestion (biogas production), biogas conversion into electrical and thermal energy (CHP plant), as well as waste and emissions generation. According to the GSE report [45], the main biomass sources for electricity from biogas in Italy were of agro-forestry origin, including animal manure (82%). Instead, the residual biomass was made up of MSW and sewage sludge (about 18%). Specifically, the amount of dedicated and residual biomass (i.e., livestock manure and agricultural and agro-industrial residues) was retrieved from the National Agency for Agricultural Mechanization (ENAMA) project and referred to different regions of Italy. Moreover, for the OF (MSW and sewage sludge), data from two Italian plants, representative of the national context, were used. In detail, the selected Italian plants were the Province of Bolzano's Plant [46] and the Herambiente Spa composting plant in Voltana [47].

The anaerobic digestion and cogeneration processes were modeled according to the processes in the EcoInvent database v.3.7.1, using data from: (i) GSE [45] for biogas amounts; (ii) the Higher Institute for Environmental Protection and Research [48] for the emissions from the cogeneration plant fed with agro-forestry biomass; (iii) Reichhalter et al. [46] and Herambiente [47] for emissions from conversion plants fed with OF; and (iv) ENAMA for the emissions from the anaerobic digester (methane, CH_4). The consumption of water and chemicals was considered negligible due to their recycling in the system. Moreover, for each MJ of biogas combusted in the cogenerator, a lubricant consumption of 0.03 g, according to [49], was considered. Regarding the biomass transport, an average distance of 70 km between the collection point and the conversion plant was assumed, in accordance with the Ministerial Decree [31].

2.3.2. Solid Biomass: System Description and Inventory

According to the GSE report [43], in Italy, 65% of the solid biomass used in energy conversion processes was of agro-forestry and industrial origin, while 35% came from MSW. In this study, for the production of 1 kWh of electricity from solid biomass in Italy, both primary and secondary data were used. Primary data were provided by the Energy from Solid Biomass (EBS—Energia da Biomasse Solide) association, made up of 15 operators and counting 18 facilities distributed across the national territory [42]. In detail, primary data were related to residual biomass amount, water consumption, waste amount (wastewater, hazardous waste, and non-hazardous waste), and the cogeneration plant (quantity of electricity produced). Specifically, the plants of EBS members fell within the 1–75 MWe power range, which is representative of approximately 98% of the Italian electricity production from agro-forestry and industrial residues [50]. For all other flows and processes, secondary data were used. In particular, for the pre-treatment (chipping) phase of agricultural and forestry biomass, data were retrieved from Scrucca et al. [19,51], while data for the energy conversion process were taken from the EcoInvent (v.3.7.1) process "Electricity, high voltage {IT} | cogeneration of heat—electricity, wood chips, 6667 kW, state of the art 2014 | Cut-off, U". Moreover, data about emissions generated by the energy conversion plant were provided by ISPRA [48].

Data related to electricity production from MSW biomass were obtained as an average from environmental declarations of 7 waste-to-energy plants (located in Friuli Venezia Giulia, Lombardia, Piemonte, Veneto, Emilia Romagna, Lazio, and Molise regions), representative of the Italian context. They were based on primary data concerning biomass quantities, water consumption, characteristics of cogeneration plants (e.g., nominal electric power and self-consumption of electricity by the plant), and quantity of electricity produced [50]. Since all urban waste (not just biomass-related waste) is processed into waste-to-energy plants, biomass energy has been considered to account for only 51% of the total energy produced by waste-to-energy plants, in accordance with D.M. 06/07/2012 [52].

For all solid biomass from Italy, the average distance between the biomass collection point and the energy conversion plant was assumed to be 70 km, in accordance with [31]. For the solid biomass of foreign origin, representing 10% of agro-forestry biomass [53] used for electricity production in Italy, transport was estimated as follows: (i) for the biomass from Europe (8%), road transport was considered, assuming an average European distance of 543 km [54]; (ii) for the biomass extra-Europe (2%), mainly from the USA and Canada [55], transport by sea for an average distance of 7458.5 km [56], followed by road transport for the national average distance of 125 km [57] were accounted for.

2.3.3. Bioliquids: System Description and Inventory

In Table 1, the input and output data referring to 1 kWh of electricity from bioliquids in Italy are shown. Only secondary data [43] about the typologies of used bioliquids and their percentage weight in the mix of bioliquids used for Italian electricity production (in 2020) were employed. The electricity production plant, considered in the LCA analysis, was a plant powered by fossil fuels with a nominal power of 500 kW and an average lifetime of 30 years, considering a production efficiency of 38% and a yearly operating time of 65%, according to the EcoInvent (v.3.7.1) process "Oil power plant, 500 MW {GLO} | market for | Cut-off, U". The bioliquids production was included in the system boundary (Figure 1c), considering the cultivation, extraction, and refining phases. Transport distances (by sea, train, and road) between the place of oil plant cultivation (if applicable), the location for bioliquid extraction and refining, and the energy conversion plant were taken into consideration [57]. In detail, the investigated bioliquids were produced in Italy, Indonesia, Malaysia, other EU countries, and other non-EU countries [43]. Instead, for the calculation of transport by sea, the following reference sites (relevant commercial ports) were considered for calculating average distances from Italy [56]: Trieste (Italy), Port Kelang (Malaysia), Tanjung Priok (Indonesia), Jebel Ali, Dubai (United Arab Emirates—Non-EU), and Denmark (EU). The total emissions produced by the cogeneration plant, also in this case, were retrieved from ISPRA [48].

Table 1. Life cycle inventory (LCI) of the three bioenergy chains.

Input/Output Flows	Unit	Biogas	Solid Biomass	Bioliquids
Inputs				
Biomass				
Dedicated biomass	ton	2.41×10^{-03}	-	1.68×10^{-04}
Residual biomass	ton	4.53×10^{-03}	1.43×10^{-03}	4.88×10^{-05}
Transformation proceses				
Pre-treatment (chipping)	ton	-	9.69×10^{-04}	-
Anaerobic digestion plant	p	3.64×10^{-08}	-	-

Table 1. *Cont.*

Input/Output Flows	Unit	Biogas	Solid Biomass	Bioliquids
Oil power plant	p	-	-	9.24×10^{-10}
Cogeneration Plant				
Electricity	kWh	$1.15 \times 10^{+00}$	6.50×10^{-01}	-
Heat	MJ	$4.07 \times 10^{+00}$	-	-
Amount of lubricant	kg	7.99×10^{-04}	-	-
Water consumption				
Water (vegetable, industrial, washing)	ton	2.95×10^{-04}	1.71×10^{-03}	-
Transport				
Transport, freight, lorry	tkm	1.33×10^{-01}	1.38×10^{-01}	1.09×10^{-02}
Transport, freight, sea	tkm		1.44×10^{-01}	$1.83 \times 10^{+00}$
Transport, freight, train	tkm			3.65×10^{-02}
Outputs				
Electricity	kWh	1.00	1.00	1.00
Heat	MJ	3.52	-	-
Waste				
Wastewater	m^3	-	5.36×10^{-04}	-
Hazardous waste	ton	-	5.67×10^{-08}	-
Inert waste	ton	-	4.36×10^{-07}	-
Emissions to the air				
* *Methane, biogenic*	g	$4.10 \times 10^{+00}$	-	-
Carbon dioxide, biogenic	g	$4.35 \times 10^{+02}$	$3.26 \times 10^{+02}$	$3.43 \times 10^{+02}$
Methane, biogenic	g	$1.46 \times 10^{+00}$	7.54×10^{-01}	1.08×10^{-02}
Dinitrogen monoxide	g	2.46×10^{-02}	4.36×10^{-02}	7.20×10^{-03}
Nitrogen oxides, IT	g	$8.21 \times 10^{+00}$	1.56×10^{-01}	$1.09 \times 10^{+00}$
Carbon monoxide, biogenic	g	$2.46 \times 10^{+00}$	$1.09 \times 10^{+01}$	$5.40 \times 10–^{02}$
NMVOC, non-methane volatile organic compounds, unspecified origin	g	7.30×10^{-01}	$1.25 \times 10^{+00}$	1.08×10^{-02}
Particulates, < 10 um	g	8.21×10^{-02}	7.74×10^{-01}	3.60×10^{-03}
Particulate, <2.5 um	g	8.21×10^{-02}	7.74×10^{-01}	2.76×10^{-03}
Carbon black	g	3.29×10^{-03}	7.35×10^{-02}	1.54×10^{-04}
Sulfur dioxide, IT	g	-	3.27×10^{-02}	4.74×10^{-02}
Ammonia, IT	g	-	1.13×10^{-02}	-
PAH, polycyclic aromatic hydrocarbons	g	-	4.55×10^{-04}	3.20×10^{-06}
Benzo[a]pyrene	g	-	1.37×10^{-04}	-
Benzo[ß]fluoranthene	g	-	1.55×10^{-04}	-
Benzo[κ]fluoranthene	g	-	6.96×10^{-05}	-
Indeno[1,2,3-cd]pyrene	g	-	8.91×10^{-05}	-
Dioxin,2,3,7,8 Tetrachlorodibenzo-p-	g	-	8.65×10^{-10}	8.77×10^{-11}
Polychlorinated biphenyls	g	-	1.38×10^{-07}	-
Benzene, hexachloro	g	-	1.38×10^{-08}	-
Cadmium	g	-	1.27×10^{-05}	5.16×10^{-07}
Copper	g	-	1.74×10^{-05}	1.72×10^{-05}
Mercury	g	-	1.17×10^{-05}	2.79×10^{-06}
Lead	g	-	4.53×10^{-05}	9.08×10^{-06}
Zinc	g	-	3.30×10^{-04}	1.25×10^{-05}
Arsenic	g	-	5.77×10^{-07}	2.79×10^{-06}
Chromium	g	-	3.95×10^{-06}	1.71×10^{-05}
Nickel	g		2.31×10^{-06}	1.03×10^{-04}
Selenium	g		5.77×10^{-07}	3.71×10^{-06}

* data referring to methane emissions from the anaerobic digester (primary data from [46,47,58]).

2.4. Impact Assessment

The collected data were analyzed using SimaPro software v.9.3.0.3 [59]. Furthermore, the EcoInvent database (v.3.7.1) and cut-off datasets for data on agricultural processes and conversion plants were selected. The EF 3.0 method [60], indicated by the European Commission for calculating the environmental footprint, was adopted. In this study, sixteen impact categories, considered relevant for our purposes, were examined to evaluate the environmental impacts coming from the three biomass energy sources (biogas, solid biomass, and bioliquids). Table 2 lists the impact categories, with the related acronyms and units of measurement.

Table 2. Selected impact categories from the EF 3.0 method.

Impact Category	Unit	Abbreviation
Climate change	kg CO_2 eq	CC
Ozone depletion	kg CFC11 eq	OD
Ionising radiation	kBq U-235 eq	IR
Photochemical ozone formation	kg NMVOC eq	POD
Particulate matter	disease inc.	PM
Human toxicity, non-cancer	CTUh	HTnon-c
Human toxicity, cancer	CTUh	HTc
Acidification	mol H^+ eq	AC
Eutrophication, freshwater	kg P eq	EUf
Eutrophication, marine	kg N eq	EUm
Eutrophication, terrestrial	mol N eq	EUt
Ecotoxicity, freshwater	CTUe	ECT
Land use	Pt	LU
Water use	m^3 depriv.	WU
Resource use, fossils	MJ	RDf
Resource use, minerals and metals	kg Sb eq	RDm

3. Results

A comparison of the environmental impacts associated with the production of 1 kWh of electricity from different bioenergy sources, namely biogas, solid biomass, and bioliquids, is illustrated in Figure 2 and Table 3.

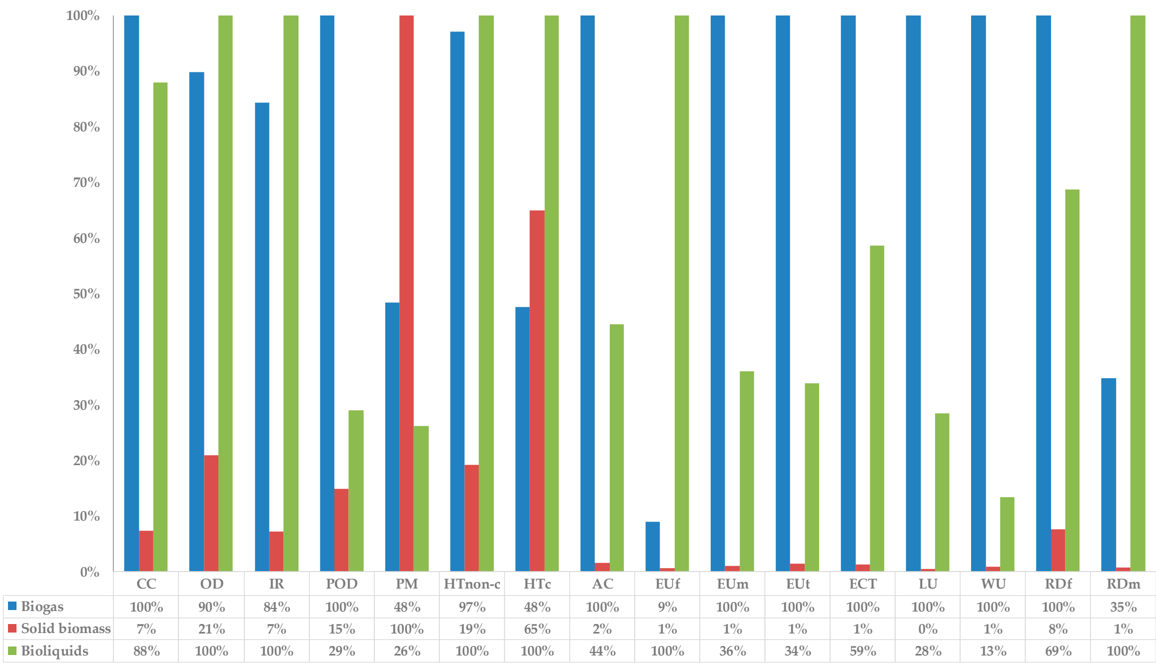

Figure 2. Characterization graph of 1 kWh of electricity produced by three different RES (biomass, bioliquids, and biogas).

Table 3. Characterized values of 1 kWh of electricity produced by three different RES (biomass, bioliquids, and biogas).

Impact Category	Unit	Biogas	Biomass	Bioliquids
CC	kg CO_2 eq	9.62×10^{-01}	7.10×10^{-02}	8.46×10^{-01}
OD	kg CFC11 eq	4.96×10^{-08}	1.16×10^{-08}	5.52×10^{-08}
IR	kBq U-235 eq	2.54×10^{-02}	2.17×10^{-03}	3.02×10^{-02}
POD	kg NMVOC eq	1.03×10^{-02}	1.53×10^{-03}	2.99×10^{-03}
PM	disease inc.	1.19×10^{-07}	2.47×10^{-07}	6.45×10^{-08}
HTnon-c	CTUh	1.88×10^{-08}	3.72×10^{-09}	1.94×10^{-08}
HTc	CTUh	6.50×10^{-10}	8.88×10^{-10}	1.37×10^{-09}
AC	mol H^+ eq	1.09×10^{-02}	1.68×10^{-04}	4.84×10^{-03}
EUf	kg P eq	3.23×10^{-04}	2.46×10^{-05}	3.62×10^{-03}
EUm	kg N eq	1.10×10^{-02}	1.13×10^{-04}	3.96×10^{-03}
EUt	mol N eq	4.96×10^{-02}	7.16×10^{-04}	1.68×10^{-02}
ECT	CTUe	$8.05 \times 10^{+01}$	$1.07 \times 10^{+00}$	$4.72 \times 10^{+01}$
LU	Pt	$7.86 \times 10^{+01}$	3.43×10^{-01}	$2.23 \times 10^{+01}$
WU	m^3 depriv.	$9.72 \times 10^{+00}$	8.56×10^{-02}	$1.30 \times 10^{+00}$
RDf	MJ	$6.27 \times 10^{+00}$	4.77×10^{-01}	$4.30 \times 10^{+00}$
RDm	kg Sb eq	5.33×10^{-06}	1.13×10^{-07}	1.53×10^{-05}

The results revealed that, among the three bioenergy sources, solid biomass (red bars, in Figure 2) showed the lowest environmental burden in all the investigated impact categories, except in particulate matter (PM) and human toxicity, cancer (HTc). In detail, in the PM category, the impact generated by using solid biomass (2.47×10^{-07} disease incidence) for electricity production was approximately double that associated with the use of biogas and quadruple compared to the use of bioliquids. Such an impact was mainly due to local emissions from the energy conversion plant. Furthermore, in HTc, the environmental burden from solid biomass was 25% greater than that from biogas and was mainly due to the combustion plant.

On the other hand, biogas (blue bars in Figure 2) resulted to be the most impactful source of electricity in 9 out of 16 categories: climate change (CC), land use (LU), water use (WU), acidification (AC), photochemical ozone formation (POD), eutrophication, marine (EUm), eutrophication, terrestrial (EUt), resource use, fossils (RDf), and ecotoxicity, freshwater (ECT). In particular, in these categories, the environmental impact associated with the use of biogas for electricity production was up to 7.5 times higher than the impact deriving from the use of bioliquids in the WU category and up to 100 times higher (in 7 categories) than the impact due to the use of solid biomass as an energy source. Specifically, in comparison with the environmental load associated with biogas use, impacts from solid biomass were 0% in LU, only 1% in WU, ECT, EUt, and Eum, and 2% in AC, while they reached up to 15% in POD. On the other hand, electricity production from bioliquids and biogas generated comparable impacts in CC (0.85 kg CO_2 eq. and 0.96 kg CO_2 eq., respectively). Moreover, loads from bioliquids resulted in impacts comparable to those from biogas, also in RDf and ECT, being 31% and 41% lower, respectively. Instead, in the remaining 6 categories, electricity production from bioliquids exhibited lower environmental loads, ranging from 13% in WU to 44% in AC of the impact from biogas.

Finally, electrical production using bioliquids showed the poorest environmental performance in 6 out of 16 of the assessed categories (green bars in Figure 2): ozone depletion (OD), ionizing radiation (IR), human toxicity, non-cancer (HTnon-c), human toxicity, cancer (HTc), eutrophication, freshwater (EUf), and resource use, minerals and metals (RDm). In detail, in the OD, IR, and HTnon-c categories, the impact from bioliquids utilization was only slightly higher (3–19%) than that linked to biogas exploitation. However, in the other three categories (HTc, EUf, and RDm), the environmental load from bioliquids use turned out to be from 2-fold (in HTc) to 10-fold (in EUf) higher than that deriving from biogas employment for electricity generation. The difference in the environmental performance of electricity production grew even more in the comparison with solid biomass use. In fact, in this case, only in HTc, the impact from solid biomass was 35% lower, while in the remaining 5 categories, such impact became even lower (approximately 80% or more) compared to that due to electricity production from bioliquids.

In Figure 3 and Table 4, the normalized impacts for the production of 1 kWh of electricity in Italy through the three investigated energy sources are illustrated. The highest impact (2.26×10^{-03}) was in the EUf category. It was associated with bioliquids utilization as an energy source. As for biogas and solid biomass sources, their impacts on EUf were only 9% and 1%, respectively, of the impact from bioliquids. The analysis of the most impactful processes within the bioliquid energy supply chain highlights the significant role played by the palm oil production phase (cultivation and processing), which accounts for 70% of the whole impact; behind that is the production of rapeseed oil (15.4%). In particular, the treatment of wastewater from the oil refining process is responsible for the contamination of water resources by phosphate, which constitutes the elementary flow with the highest impact (99.4%).

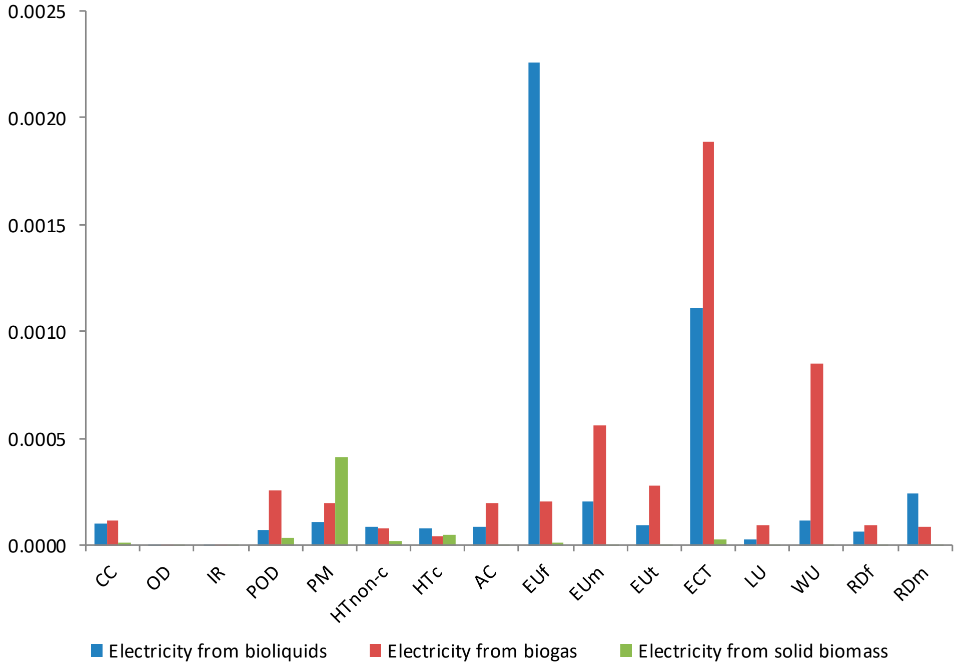

Figure 3. Normalized impacts for the production of 1 kWh of electricity from bioliquids, biogas, and solid biomass in Italy.

Relevant normalized impacts (1.89×10^{-03}) were also observed in the ECT category, attributable to electricity production from both biogas and bioliquids. In detail, the impact from biogas was the highest, being approximately 2 and 75 times greater than those from bioliquids and solid biomass, respectively. The environmental burden associated with biogas usage mainly stemmed from the cultivation of dedicated biomass, with the greatest contributions from the production of maize grain (63.7%) and rye grain (14.5%). Additionally, among the key elementary flows contributing to the ECT impact from biogas, phosphorus (54.2%) and phosphates (45.7%), utilized as fertilizers, were identified. Regarding the burden from bioliquids (1.11×10^{-03}) on ECT, this was primarily attributed (69.3%), once again, to palm oil production, encompassing both the plant cultivation and the extraction and refining of the oil. Soybean oil (9.2%) and rapeseed oil (8.0%) contributed to a lesser extent. It should be considered that the high contribution to the impact from palm oil production, highlighted by LCA analysis, depends on its high percentage weight in the mix of bioliquids for electricity production.

Table 4. Normalized impacts for the production of 1 kWh of electricity from bioliquids, biogas, and solid biomass in Italy.

Impact Category	Electricity from Bioliquids	Electricity from Biogas	Electricity from Solid Biomass
CC	1.04×10^{-04}	1.19×10^{-04}	8.76×10^{-06}
OD	1.03×10^{-06}	9.25×10^{-07}	2.16×10^{-07}
IR	7.15×10^{-06}	6.02×10^{-06}	5.15×10^{-07}
POD	$7.36 \text{x} 10^{-05}$	2.53×10^{-04}	3.78×10^{-05}
PM	1.08×10^{-04}	2.00×10^{-04}	4.14×10^{-04}
HTnon-c	8.43×10^{-05}	8.18×10^{-05}	1.62×10^{-05}
HTc	8.09×10^{-05}	3.85×10^{-05}	5.26×10^{-05}
AC	8.72×10^{-05}	1.96×10^{-04}	3.03×10^{-06}
EUf	2.26×10^{-03}	2.01×10^{-04}	1.53×10^{-05}
EUm	2.03×10^{-04}	5.64×10^{-04}	5.76×10^{-06}
EUt	9.49×10^{-05}	2.81×10^{-04}	4.05×10^{-06}
ECT	1.11×10^{-03}	1.89×10^{-03}	2.50×10^{-05}
LU	2.73×10^{-05}	9.59×10^{-05}	4.18×10^{-07}
WU	1.14×10^{-04}	8.48×10^{-04}	7.46×10^{-06}
RDf	6.62×10^{-05}	9.64×10^{-05}	7.34×10^{-06}
RDm	2.40×10^{-04}	8.37×10^{-05}	1.78×10^{-06}

Within the ECT category, the most significant elementary flows were chlorides (30.6%) and sulfides (23.9%) released into water during the production processes of palm, rapeseed, and soybean oils. In particular, the main sources of chlorides and sulfides were wastewater treatment (sludge incineration) resulting from bioliquid refining (31.5%, responsible only for chloride release) and the production of potassium chloride (22.6%, responsible for chloride and sulfide release), used as fertilizer. Lastly, relevant flows included aluminum released into the atmosphere (15.9%) and deposited on soil (9.7%), associated with both bioliquid production and the energy conversion plant.

Moreover, the normalization phase highlighted relevant impacts for the WU and EUm categories, both associated with electricity production from biogas. Specifically, in WU, the impact from biogas (8.48×10^{-04}) was over 7 times greater than that associated with bioliquid usage and over 100 times higher than the impact from solid biomass electricity production. This impact primarily stems from water consumption for irrigation during the cultivation of dedicated biomass.

In EUm, the impact from bioliquids is only one-third of that from biogas, while the solid biomass energy supply chain generates a negligible impact compared to the other two energy sources investigated. The impact of biogas on EUm was attributed to the production of rye grain (28.8%), maize grain (28.1%), and the anaerobic digestion process (24.7%), releasing nitrates into water (65.9%, associated with biomass cultivation processes) and nitrogen oxides into the air (24.7%, derived from both cultivation and anaerobic digestion). Conversely, the impact from bioliquids is attributed to palm (42.7%) and rapeseed (21.9%) cultivation, as well as to the treatment of wastewater from oil processing (8%). Once again, the most significant flows were represented by nitrates released into water (77.5%) and nitrogen oxides released into the atmosphere (19.8%).

Therefore, the characterization and normalization phases pointed out that the highest impacts were from biogas use as an energy carrier in most of the investigated categories, followed by bioliquids employment as an electricity source.

4. Discussion

The LCA analyses revealed that among the investigated energy sources, the most impactful was represented by biogas, primarily, followed by bioliquids. In particular, the major damages affected freshwater and marine water, which undergo depletion (WU category), toxicity (ECT category), and eutrophication (EUf and EUm categories). These damages, in the case of biogas, were mainly attributable to biomass cultivation, which releases phosphorus and nitrogen into water (due to the use of mineral fertilizers), and, to a lesser extent, to nitrogen oxide emissions from the anaerobic digestion process. Therefore, in order to minimize the impacts generated by electricity from biogas, the use of dedicated crops should be replaced with residual biomass. In addition, utilizing residual biomass brings several benefits: environmental advantages (e.g., reduced waste generation) and economic opportunities for waste producers (e.g., saving money on disposal expenses and new incomes from selling biogas or energy from biogas).

In Table 5, the comparison between the current scenario (Business and Usual—BaU), employing both residual and dedicated biomasses for electricity production, and an alternative scenario, exploiting only residual biomass, is reported. The average reduction in all investigated impact categories is 87%, highlighting the high impacts associated with dedicated crops for energy purposes [61].

Table 5. Comparison between the current scenario (business and usual—BaU), employing both residual and dedicated crops for biogas electricity production, and an alternative scenario exploiting only residual biomass.

Impact Category	Unit	Electricity from Biogas		
		BaU Scenario	Alterative Scenario	% of Variation
CC	kg CO_2 eq	9.62×10^{-01}	1.87×10^{-01}	81%
OD	kg CFC11 eq	4.96×10^{-08}	3.31×10^{-09}	93%
IR	kBq U-235 eq	2.54×10^{-02}	1.69×10^{-03}	93%
POD	kg NMVOC eq	1.03×10^{-02}	7.75×10^{-03}	25%
PM	disease inc.	1.19×10^{-07}	3.32×10^{-08}	72%
HTnon-c	CTUh	1.88×10^{-08}	5.95×10^{-10}	97%
HTc	CTUh	6.50×10^{-10}	2.75×10^{-11}	96%
AC	mol H^+ eq	1.09×10^{-02}	5.86×10^{-04}	95%
EUf	kg P eq	3.23×10^{-04}	5.10×10^{-06}	98%
EUm	kg N eq	1.10×10^{-02}	2.74×10^{-03}	75%
EUt	mol N eq	4.96×10^{-02}	1.06×10^{-02}	79%
ECT	CTUe	$8.05 \times 10^{+01}$	$1.07 \times 10^{+00}$	99%
LU	Pt	$7.86 \times 10^{+01}$	2.93×10^{-01}	99%
WU	m^3 depriv.	$9.72 \times 10^{+00}$	2.39×10^{-03}	99%
RDf	MJ	$6.27 \times 10^{+00}$	2.82×10^{-01}	95%
RDm	kg Sb eq	5.33×10^{-06}	3.60×10^{-07}	93%

However, it should be noted that, compared to fossil fuels such as natural gas and oil, dedicated biomass has the advantage of being a renewable resource. Also, the use of soil for the cultivation of crops for energy purposes could represent a social advantage by counteracting rural depopulation and boosting the local economy. Furthermore, cultivating biomass on less productive lands (e.g., marginal lands) for bioenergy or biomaterial production can sometimes present a feasible solution to mitigate conflicts between food, energy, and environmental concerns [62].

Finally, another important aspect to take into account is the possible upgrading of biogas to produce biomethane. This allows for the diversification of energy sources and the reduction of dependence on imported natural gas [63].

As for bioliquids, the major impact derives from the production phase (cultivation and processing). An increase in the use of exhausted oils, also known as used cooking oils (UCO), following the principles of circular economy could contribute to minimizing environmental impacts [64]. Currently, the quantity of exhausted oils generated in Italy annually is about 20–30% of the bioliquids employed for Italian electricity production [45,65,66], and only less than half is properly recovered and recycled (EconomiaCircolare.com). Indeed, UCO, although not classified as hazardous waste (CER code 200125), causes significant damage when improperly dispersed in the environment [65]. Specifically, UCOs improperly released on the soil adhere to soil particles, making them impermeable to nutrient absorption and coating plant roots, thereby preventing water and nutrient uptake. In water, UCOs form a surface layer that hinders the passage of oxygen and sunlight, resulting in hypoxia, reduced photosynthesis, and, consequently, harming aquatic life in the underlying water column. It is worth noting, as highlighted by CONOE (2018), that 1 kg of exhausted oil can cover up to 1000 m^2 of water surface. Furthermore, the presence of oil in pipes leads to blockages and, in treatment plants, increases energy consumption (up to 3 kWh/kg oil), requiring more frequent cleaning of pipes and pumps [66]. In turn, these problems lead to higher energy and maintenance costs. On the other hand, UCO could be used to produce energy. It is estimated that 1 L of UCO can yield 3.6 kWh of electricity and 3.5 kWh of heat [66]. Hence, through the complete recovery and recycling of UCO, not only natural resource consumption and expenditure on fossil fuel purchases would be reduced, but also lower pollution would be generated compared to the use of fossil fuels (such as oil). Therefore, it is critical to take action against the dispersion of UCOs through massive public awareness campaigns educating citizens on UCOs' dangers and proper disposal methods.

Moreover, pertinent literature reports that intensive palm oil cultivation drives widespread deforestation. This not only results in soil erosion, increased greenhouse gas emissions (GHGs), and water pollution but also destroys natural habitats, leading to a dangerous loss of biodiversity [67–69].

Finally, this work reveals that solid biomass is the least impactful energy source of the three investigated. However, it is the most responsible source for PM < 2.5 and PM < 10 emissions (PM impact category), mainly attributable to the energy conversion process of solid biomass of agro-forestry and industrial origin. Moreover, the contribution of solid biomass energy sources to the HTC category is comparable to that of biogas and bioliquid fuels. Therefore, to improve the environmental impact of this source, modern and efficient combustion technologies (i.e., the best available technologies) should be used to minimize pollutant emissions. Furthermore, it should be noted that the low impact recorded for this electricity source is also due to the avoided use of dedicated biomass. Indeed, in Italy, forest resources are abundant, covering approximately 36% of the territory, although they are not fully exploited. For instance, despite the extensive national forest heritage, less than half of the potentially available woody biomass is currently recovered. However, the full utilization of this resource, through proper forest management, could significantly reduce the risks of wildfires and hydrogeological instability [70]. As for residual biomass, its energetic valorization could contribute to safeguarding peripheral areas, preventing their degradation and abandonment.

5. Conclusions

This study, carried out in the framework of the ARCADIA project, compares the environmental impacts of three bioenergy sources for electricity production in Italy: biogas, solid biomass, and bioliquids. Our findings highlight that solid biomass emerges as the most environmentally friendly bioenergy source due to the avoidance of dedicated crops, unlike biogas and bioliquids supply chains.

Conversely, biogas exhibits the highest environmental impact, demonstrating the least favorable environmental performance in 9 out of the 16 investigated impact categories. Life cycle analysis (LCA) highlights that dedicated energy crops contribute significantly to the environmental impacts associated with electricity production, not only for biogas but also for bioliquids. Indeed, the cultivation of these crops needs water and chemical fertilizers, leading to adverse environmental consequences. Therefore, these results point out the importance of prioritizing residual biomass for energy production over dedicated crops. This includes utilizing forestry and agro-industrial residues, municipal solid waste, and used cooking oils. Leveraging these discarded materials offers numerous benefits, including environmental preservation, resource conservation and recovery, and waste reduction.

Overall, while this research promotes the utilization of solid biomass, it also highlights that bioliquids and biogas continue to present viable alternatives for energy production. This underscores the importance of diversifying energy sources and reducing dependence on non-renewable resources, especially given the finite nature of fossil fuels. However, it is imperative to prioritize sustainable practices and the utilization of non-dedicated biomass sources to minimize environmental impacts and maximize the benefits of bioenergy production.

Author Contributions: A.Z. and G.A. contributed equally to this work. Formal analysis, writing—original draft preparation, A.Z., G.A. and G.F.; formal analysis, writing—review and editing; A.C., A.P., A.Z., G.A. and G.F.; investigation, data curation, validation T.B. and S.S.; conceptualization, project administration, C.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was done in the frame of the ARCADIA Project, (September 2019–October 2023), which was financed by the "National Operational Programme on Governance and Institutional Capacity 2014–2020", Axis 3—Specific Objective 3.1—Action 3.1.1. This Program is a 2014–2020 cohesion policy tool funded by the European Union under the European Structural and Investment Funds—ESI Funds.

Data Availability Statement: Data are contained within the article and for each data the correct reference is reported.

Acknowledgments: The authors would like to acknowledge all the researcher, associations, public authorities and academics engaged in ARCADIA project for the precious discussions and feedback.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results. All the Authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Eurostat. «Eurostat Population Projections, 2019». Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Population_projections_at_regional_level (accessed on 20 February 2024).
2. European Commission. «EU Reference Scenario 2020—Energy, Transport and GHG Emissions—Trends to 2050». Available online: https://energy.ec.europa.eu/system/files/2021-07/eu_reference_scenario_2020_final_report_0.pdf (accessed on 20 February 2024).
3. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions—The European Green Deal. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52019DC0640 (accessed on 3 June 2024).
4. Evans, A.; Strezov, V.; Evans, T.J. Assessment of sustainability indicators for renewable energy technologies. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1082–1088. [CrossRef]
5. Martín-Gamboa, M.; Iribarren, D.; García-Gusano, D.; Dufour, J. A review of life-cycle approaches coupled with data envelopment analysis within multi-criteria decision analysis for sustainability assessment of energy systems. *J. Clean. Prod.* **2017**, *150*, 164–174. [CrossRef]
6. Madurai Elavarasan, R. The Motivation for Renewable Energy and its Comparison with Other Energy Sources: A Review. *Eur. J. Sustain. Dev. Res.* **2019**, *3*, em0076. [CrossRef] [PubMed]
7. San Miguel, G.; Cerrato, M. Life Cycle Sustainability Assessment of the Spanish Electricity: Past, Present and Future Projections. *Energies* **2020**, *13*, 1896. [CrossRef]
8. Mastisya Saharudin, D.; Kumar Jeswani, H.; Azapagic, A. Bioenergy with carbon capture and storage (BECSS): Life cycle environmental and economic assessment of electricity generated from palm oil wastes. *Appl. Energy* **2023**, *349*, 121506. [CrossRef]
9. Duval-Dachary, S.; Beauchet, S.; Lorne, D.; Salou, T.; Helias, A.; Pastor, A. Life cycle assessment of bioenergy with carbon capture and storage systems: Critical review of life cycle inventories. *Renew. Sust. Energy Rev.* **2023**, *183*, 113415. [CrossRef]
10. Garcia, R.; Marques, P.; Freire, F. Life-cycle assessment of electricity in Portugal. *Appl. Energy* **2014**, *134*, 563–572. [CrossRef]
11. Messagie, M.; Mertens, J.; Oliveira, L.; Rangaraju, S.; Sanfelix, J.; Coosemans, T.; Van Mierlo, J.; Macharis, C. The hourly life cycle carbon footprint of electricity generation in Belgium, bringing a temporal resolution in life cycle assessment. *Appl. Energy* **2014**, *134*, 469–476. [CrossRef]
12. Rakotoson, V.; Praene, J. A life cycle assessment approach to the electricity generation of French overseas territories. *J. Clean. Prod.* **2017**, *168*, 755–763. [CrossRef]
13. Turconi, R.; Simonsen, C.G.; Byriel, I.P.; Astrup, T. Life cycle assessment of the Danish electricity distribution network. *Int. J. Life Cycle Assess.* **2014**, *19*, 100–108. [CrossRef]
14. Stamford, L.; Azapagic, A. Life cycle sustainability assessment of UK electricity scenarios to 2070. *Energy Sustain. Dev.* **2014**, *23*, 194–211. [CrossRef]
15. Thonemann, N.; Maga, D. Life Cycle Assessment of German Energy Scenarios. In *Book Progress in Life Cycle Assessment*; Springer: Cham, Switzerland, 2019; pp. 165–175. [CrossRef]

16. Cellura, M.; Cusenza, M.; Guarino, F.; Longo, S.; Mistretta, M. Life cycle assessment of electricity generation scenarios in Italy. In *Book Life Cycle Assessment of Energy Systems and Sustainable Energy Technologies*; Springer: Cham, Switzerland, 2019; pp. 3–15. [CrossRef]
17. Carvalho, M.L.; Marmiroli, B.; Girardi, P. Life cycle assessment of Italian electricity production and comparison with the European context. *Energy Rep.* **2022**, *8*, 561–568. [CrossRef]
18. Parvez Mahmud, M.A.; Huda, N.; Hisan Farjana, H.; Lang, C. Life-cycle impact assessment of renewable electricity generation systems in the United States. *Renew. Energy* **2020**, *151*, 1028–1045. [CrossRef]
19. Arcadia. Available online: www.arcadia.enea.it (accessed on 5 May 2024).
20. Zucaro, A.; Ansanelli, G.; Fiorentino, G.; Cerbone, A.; Picarelli, A.; Beltrani, T.; Sbaffoni, S.; Scalbi, S.; Giammartini, M.; Giocoli, A.; et al. Studi di Life Cycle Assessment di filiera e sviluppo di dataset per la Banca Dati Italiana LCA del progetto Arcadia. Arcadia_Monografia_Energia. ISBN 978-88-8286-463-7. 2024. Available online: https://www.arcadia.enea.it/component/jdownloads/?task=download.send&id=57&Itemid=101 (accessed on 3 June 2024).
21. ILCD International Life Cycle Data System. Available online: https://eplca.jrc.ec.europa.eu/ilcd.html (accessed on 3 June 2024).
22. TERNA. Available online: https://www.terna.it/en/media/press-releases/detail/electrical-consumption-2022 (accessed on 20 February 2024).
23. del Verme, M.; Lipari, D.; Lucido, G.; Maio, V.; Surace, V.; Liberatore, P. *Rapporto Statistico 2021 Energia da Fonti Rinnovabili in Italia*; Gestore dei Servizi Energetici S.p.A.: Rome, Italy, 2023.
24. Decreto Legislativo 3 Marzo 2011, n. 28. Available online: https://www.gazzettaufficiale.it/eli/id/2011/03/28/011G0067/sg (accessed on 3 June 2024).
25. Bordoni, A.; Romagnoli, E.; Foppa Pedretti, E.; Toscano, G.; Rossini, G.; Cozzolino, E.; Riva, G.L. *La Filiera del Biogas. Aspetti Salienti Dello Stato Dell'arte e Prospettive*; Ed. ASSAM—Agenzia Servizi Settore Agroalimentare delle Marche: Ancona, Italy, 2009; pp. 1–48; ISBN 9788882490904.
26. Centro Ricerche Produzioni Animali. Available online: https://www.crpa.it/nqcontent.cfm?a_id=1109&lang=en (accessed on 20 February 2024).
27. Consorzio Biogas. Available online: https://www.consorziobiogas.it/en/home-2/ (accessed on 20 February 2024).
28. Ministerial Decree 15 September 2022. Available online: https://www.gse.it/documenti_site/Documenti%20GSE/Servizi%20per%20te/Attuazione%20misure%20PNRR/PRODUZIONE%20DI%20BIOMETANO/Normativa%20Servizi/Decreto%20Ministeriale_Biometano_15-9-2022.pdf (accessed on 3 June 2024).
29. Centro Ricerche Produzioni Animali—C.R.P.A. S.p.A. *Studio per la Valutazione degli Effetti sulle Emissioni delle Trasformazioni in Corso nel Settore degli Allevamenti*; Prot.4/6/7.96 DOC-2018-2844, LaV, Studio_ISPRA_emissioni.docx, 15/10/18; C.R.P.A. S.p.A.: Reggio Emilia, Italy, 2018.
30. Marchiori, C. Ricadute Socio-Economiche della Produzione di Energia da Biomasse Solide. 2019. Available online: https://www.centralemercure.com/wp-content/uploads/2020/06/RICADUTE-SOCIO-ECONOMICHE-DELLA-PRODUZIONE-DI-ENERGIA-DA-BIOMASSE-SOLIDE.pdf (accessed on 3 June 2024).
31. Ministerial Decree 2 March 2010—Attuazione della Legge 27 Dicembre 2006, n. 296, sulla Tracciabilità delle Biomasse per la Produzione di Energia Elettrica. Available online: https://www.gazzettaufficiale.it/eli/id/2010/05/05/10A05115/sg (accessed on 3 June 2024).
32. Legislative Decree 31 March 2011, n. 55. Available online: https://www.gazzettaufficiale.it/eli/id/2011/04/28/011G0098/sg (accessed on 3 June 2024).
33. Zucaro, A.; Fiorentino, G.; Ulgiati, S. Constraints, impacts and benefits of lignocellulose conversion pathways to liquid biofuels and biochemicals. In *Lignocellulosic Biomass to Liquid Biofuels*, 2nd ed.; Elsevier Academic Press: Cambridge, MA, USA, 2020; pp. 249–282. [CrossRef]
34. UE Commission Regulation 147/2013. Available online: https://eur-lex.europa.eu/eli/reg/2013/147/oj (accessed on 3 June 2024).
35. FIPER (Federazione di Produttori di Energia da Fonti Rinnovabili). *Quaderno CMA—Strategia 2024—BIOGAS: Driver per la Filiera Agroalimentare*; FIPER: Milan, Italy, 2018; ISBN 9788894343717. Available online: https://www.monvisoenergia.it/wp-content/uploads/2019/01/QUADERNO-CMA-STRATEGIA-2024.pdf (accessed on 3 June 2024).
36. Carrosio, G. La diffusione degli impianti per la produzione di energia da biogas agricolo in Italia: Una storia di isomorfismo istituzionale. *Studi Organ.* **2012**, 9–26. [CrossRef]
37. *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO (International Organization for Standardization): Geneva, Switzerland, 2006. Available online: https://www.iso.org/standard/37456.html (accessed on 3 June 2024).
38. *ISO 14044*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO (International Organization for Standardization): Geneva, Switzerland, 2006. Available online: https://www.iso.org/standard/38498.html (accessed on 3 June 2024).
39. Singh, A.D.; Upadhyay, A.; Shrivastava, S.; Vivekanand, V. Life-cycle assessment of sewage sludge-based large-scale biogas plant. *Bioresour. Technol.* **2020**, *309*, 123373. [CrossRef] [PubMed]
40. Pennington, D.W.; Potting, J.; Finnveden, G.; Lindeijer, E.; Jolliet, O.; Rydberg, T.; Rebitzer, T. Life cycle assessment Part 2: Current impact assessment practice. *Environ. Int.* **2004**, *30*, 721–739. [CrossRef] [PubMed]

41. Ekvall, T.; Assefa, G.; Björklund, A.; Eriksson, O.; Finnveden, G. What life-cycle assessment does and does not do in assessments of waste management. *Waste Manag.* **2007**, *27*, 989–996. [CrossRef] [PubMed]
42. Energia da Biomasse Solide (EBS). Available online: https://biomasseenergia.eu/en/home-en/ (accessed on 3 June 2024).
43. Agrillo, A.; dal Verme, M.; Liberatore, P.; Lipari, D.; Lucido, G.; Surace, V.M.e.V. *Rapporto Statistico 2020 Energia da Fonti Rinnovabili in Italia*; Gestore dei Servizi Energetici S.p.A.: Rome, Italy, 2022. Available online: https://www.gse.it/documenti_site/Documenti%20GSE/Rapporti%20statistici/Rapporto%20Statistico%20GSE%20-%20FER%202020.pdf (accessed on 20 March 2022).
44. Bosco, S.; Nassi o Di Nasso, N.; Roncuccia, N.; Mazzoncini, M.; Bonari, E. Environmental performances of giant reed (*Arundo donax* L.) cultivated in fertile and marginal lands: A case study in the Mediterranean. *Eur. J. Agron.* **2016**, *78*, 20–31. [CrossRef]
45. Agrillo, A.; dal Verme, M.; Liberatore, P.; Lipari, D.; Lucido, G.; Maio, V.; Surace, V. *Rapporto Statistico 2019 Fonti Rinnovabili*; Gestore dei Servizi Energetici S.p.A.: Rome, Italy, 2021. Available online: https://www.gse.it/documenti_site/Documenti%20GSE/Rapporti%20statistici/Rapporto%20Statistico%20GSE%20-%20FER%202019.pdf (accessed on 20 March 2023).
46. Reichhalter, H.; Bozzo, A.; Dal Savio, S.; Guerra, T. Analisi Energetica, Ambientale ed Economica di Impianti a Biogas in Provincia di Bolzano—Relazione Conclusiva. 2011. Available online: http://www.provincia.bz.it/agricoltura/download/Bilancio_ecologico_di_impianti_a_biogas.pdf (accessed on 3 June 2024).
47. Herambiente, T. Dichiarazione Ambientale 2020 Relativa al Complesso Impiantistico Via Traversagno 30, Località Voltana, Lugo (RA). 2020. Available online: https://ha.gruppohera.it/binary/hera_herambiente_r15/dichiarazioni_ambientali/Dichiarazione_Ambientale_Via_Traversagno_Voltana.1597749927.pdf (accessed on 20 December 2021).
48. ISPRA. (Istituto Superiore per la Protezione e la Ricerca Ambientale, Rome, Italy). Personal communication, 2019.
49. Jungbluth, N.; Chudacoff, M.; Dauriat, A.; Dinkel, F.; Doka, G.; Faist Emmenegger, M.; Gnansounou, E.; Kljun, N.; Schleiss, K.; Spielmann, M.; et al. Life Cycle Inventories of Bioenergy. Ecoinvent Report No.17, Dübendorf, CH. Available online: https://db.ecoinvent.org/reports/17_bioenergy.pdf (accessed on 3 June 2024).
50. GSE—Gestore Servizi Energetici—Atlaimpianti 2020. Available online: https://www.gse.it/dati-e-scenari/atlaimpianti (accessed on 20 November 2022).
51. Scrucca, F.; Rinaldi, C.; Morara, E.; Argnani, A. Studio LCA di filiera del cippato forestale. In *Studi di Life Cycle Assessment di Filiera e Sviluppo di Dataset per la Banca Dati Italiana LCA del Progetto Arcadia*; ENEA: Rome, Italy, 2022; pp. 5–15; ISBN 978-88-8286-465-1. Available online: https://www.arcadia.enea.it/component/jdownloads/?task=download.send&id=55&Itemid=101 (accessed on 3 June 2024).
52. Ministerial Decree 6 July 2012—Incentivi per Energia da Fonti Rinnovabili Elettriche Non Fotovoltaiche. Available online: https://www.mise.gov.it/images/stories/normativa/DM_6_luglio_2012_sf.pdf (accessed on 3 June 2024).
53. Entilocali Online. 2022. Available online: https://www.entilocali-online.it/ebs-energia-da-biomasse-virtuosa-per-ambiente-ed-economia (accessed on 3 June 2024).
54. ISTAT 2020. Available online: http://dati.istat.it/Index.aspx?DataSetCode=DCSC_TRAMERCIS1# (accessed on 20 November 2022).
55. FIPER (Federazione di Produttori di Energia da Fonti Rinnovabili). *Biomasse Legnose—Petrolio verde per il Teleriscaldamento Italiano*; FIPER: Milan, Italy, 2015. Available online: https://www.fiper.it/wp-content/uploads/libroFIPER-biomasse-legnose-petrolio-verde-per-il-teleriscaldamento-italiano.pdf (accessed on 3 June 2024).
56. SeaRates. Available online: https://www.searates.com/it (accessed on 20 February 2023).
57. ISTAT 2022. Available online: http://dati.istat.it/Index.aspx?DataSetCode=DCSC_TRAFERR (accessed on 20 July 2022).
58. Progetto Biomasse. ENAMA (Ente Nazionale per la Meccanizzazione Agricola). Available online: https://www.progettobiomasse.it/it/documenti.php (accessed on 3 June 2024).
59. Simapro. Available online: https://simapro.com (accessed on 3 June 2024).
60. Zampori, L.; Pant, R. *Suggestions for Updating the Product Environmental Footprint (PEF) Method, EUR 29682 EN*; Publications Office of the European Union: Luxembourg, 2019; ISBN 978-92-76-00654-1. [CrossRef]
61. Zucaro, A.; Forte, A.; Fagnano, M.; Bastianoni, S.; Basosi, R.; Fierro, A. Comparative attributional life cycle assessment of annual and perennial lignocellulosic feedstocks production under Mediterranean climate for biorefinery framework. *Integr. Environ. Assess. Manag.* **2015**, *11*, 397–403. [CrossRef]
62. Forte, A.; Zucaro, A.; Faugno, S.; Basosi, R.; Fierro, A. Carbon footprint and fossil energy consumption of bio-ethanol fuel production from *Arundo donax* L. crops on marginal lands of Southern Italy. *Energy* **2018**, *150*, 222–235. [CrossRef]
63. UE 58. SWD/2022/230 Final—Commission Staff Working Document: Implementing the Repower EU Action Plan: Investment, Hydrogen Accelerator and Achieving the Biomethane Targets. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230 (accessed on 3 June 2024).
64. Ghisellini, P.; Santagata, R.; Zucaro, A.; Ulgiati, S. Circular patterns of waste prevention and recovery. In *E3S Web of Conferences*; EDP Sciences: Les Ulis, France, 2019; Volume 119, p. 00003. [CrossRef]
65. CONOE. *Report Annuale 2018—Consuntivo Dell'attività di Raccolta e Trattamento degli Oli e dei Grassi Vegetali ed Animali Esausti da Parte del CONOE*; CONOE: Rome, Italy, 2018. Available online: https://www.conoe.it/wp-content/uploads/2018/11/ANNUAL-REPORT-2018.pdf (accessed on 3 June 2024).
66. EconomiaCircolare.com—Scusa, mi Ricicli L'olio? I Quaderni di EconomiaCircolare.com June 2022. Available online: https://economiacircolare.com/dossier-oli-esausti/ (accessed on 3 June 2024).
67. Reijnders, L.; Huijbregts, M. Palm oil and the emission of carbon-based greenhouse gases. *J. Clean. Prod.* **2008**, *16*, 477–482. [CrossRef]

68. Bissonnette, J.F. Is oil palm agribusiness a sustainable development option for Indonesia? A review of issues and options. *Can. J. Dev. Stud.* **2016**, *37*, 446–465. [CrossRef]
69. Meijaard, E.; Garcia-Ulloa, J.; Sheil, D.; Wich, S.A.; Carlson, K.M.; Juffe-Bignoli, D.; Brooks, T.M. *Oil Palm and Biodiversity: A Situation Analysis by the IUCN Oil Palm Task Force*; IUCN; Oil Palm Task Force: Gland, Switzerland, 2018; p. xiii+116. Available online: https://portals.iucn.org/library/sites/library/files/documents/2018-027-En.pdf (accessed on 3 June 2024). [CrossRef]
70. *Memoria ENEA: Considerazioni sullo Stato Dell'arte e le Prospettive di Sviluppo delle Bioenergie in Italia*; ENEA: Rome, Italy, 2020. Available online: https://www.camera.it/application/xmanager/projects/leg18/attachments/upload_file_doc_acquisiti/pdfs/000/004/007/Memoria_ENEA.pdf (accessed on 3 June 2024).