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Article

Life Cycle, PESTLE, and Multi-Criteria Decision Analyses of Novel Process for Nitrogen Recovery from Reject Water: Combining Electroconcentration and Stripping Methods

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Abstract: Reactive nitrogen (N_r) has become an essential nutrient to reclaim and recycle from wastewater. Nitrogen has become a valued resource that is beneficial to recover in the wastewater sector, as nitrogen is a key component in many fertilizers. The main subject of this work is to investigate the environmental consequences of a novel nitrogen recovery process from reject water. In our study, Life Cycle Analysis (LCA), PESTLE, and Multi-Criteria Decision Analysis (MCDA) were used to examine combining electroconcentration and stripping methods, including Monte Carlo simulation. Using SimaPro V9.3 software, the EF 3.0 Method, IPCC 2021 GWP100, ReCiPe 2016, and IMPACT World+ Endpoint were applied with heat and power, electricity high voltage, nuclear energy, and two renewable energies (solar and wind). EF 3.0 was endorsed by the European Commission for environmental footprinting. The operational unit of 1 m^3 of reject water was chosen as the output, and "gate-to-gate" analysis was investigated. Our calculations show that the energies derived from natural sources reduce fossil-based environmental impacts and CO_2 emissions significantly compared with conventional energy sources. A TOPSIS score was applied to appraise the choices in the case of MCDA. For the Australian territory, for the place of implementation of the technology, the most beneficial option was discovered to be wind energy offshore, with a score of 0.95, and the next was solar energy at 0.87.

Keywords: life cycle analysis; PESTLE; Multi-Criteria Decision Analysis; electroconcentration; stripping; nitrogen recovery

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1. Introduction

In agriculture and wastewater treatment, most nitrogen input is wasted and released into the atmosphere environment and water again. Reactive nitrogen (N_r) removal from wastewater can reduce nitrogen pollution. Therefore it would be important to find a sustainable solution for nitrogen re-usage and removal in wastewater treatment [1]. According to circular bioeconomy, the disposal of waste streams should be avoided, and there is a need to recreate their socio-economic value through their recycling [2].

Nitrogen has also begun to be counted as a valued resource that has benefits in recovery in the wastewater division. Nitrogen is a key component in plenty of fertilizers, and it is a vital nutrient for many cultivated crops [3]. Natural gas shortages and rising prices made nitrogen fertilizers production very expensive. Due to the epidemic and the war in Ukraine, the costs of nitrogen fertilizers have increased, and the price of ammonium nitrate rose from EUR 250 per ton (2021) to EUR 1500 per ton in 2022 [4]. From wastewater treatment plants (WWTPs), renewable nitrogen material is highly available. The nitrogen mainly comes from urea from human urine in municipal wastewater [4]. Human urine contains most of the nutrients, and about 80% of the nitrogen [5].

The recovered ammonia can be utilized to harvest ammonium sulfate, which can be used in agronomy. The process will enable the circular to replace nitrogen in the food system. The life cycle environmental performance of the agricultural sector can be improved by the environmental consequences of producing ammonia-based fertilizers [6].

Currently, several technologies exist for suitable nitrogen recovery from wastewater, like ammonia stripping, bioelectrochemical system, ion exchange and absorption, struvite precipitation, microalgae wastewater treatment, and membrane technologies [1,7–14]. According to Kar et al. [15], the air-stripping technique provides an environmentally and cost-effective choice for nitrogen recovery and ammonium sulfate production [15].

In wastewater treatment, energy consumption costs are one of the major costs [16]. For example, the electricity cost related to power resources in the treatment process can be 25–40% of the total operating expenses [17]. Energy usage also involves life-cycle environmental effects [18]. A mathematical model has also been suggested to evaluate the carbon footprint [19].

Currently, the wastewater sector has changed from a standard of contaminant removal to resource reclaim and the aspiration of circular economies. Thus Life Cycle Analysis (LCA) can play an important part by estimating the environmental permanence of new technologies and methods. Since the beginning of 2000, serious interest has been taken in using LCA in the wastewater area [20]. LCA is a methodology used to analyse and compare various products and provisions by considering their environmental effects along the whole life cycle, i.e., from the subtraction of raw materials until the end-of-life of a product [21]. It is a vital method for analysing the environmental effects of agricultural systems. Lam et al. [22] explicated lately how the LCA method had been accommodated and adopted to evaluate chances for wastewater-based nutrient reusing [20]. The major subject of the present paper is to estimate the environmental impact of the nitrogen removal process by electroconcentration and stripping [23] with LCA methods.

The first method is the EF 3.0 method (adapted), also called the Environmental Footprint Method, which comprises 28 impact categories related to climate change, human toxicity, ecological toxicity, and resource use. Characteristic factors are represented on a European scale. The main descriptive units are as follows. CTUh-Comparative Toxic Unit for human (unit of toxicity impact for humans): cases per kilogram of chemical emitted per unit mass as the rise in morbidity in the total global human community; CTUe-Comparative Toxic Unit for ecosystems or PAF.m^3.year/kg: A chemical's Potentially Affected Fraction (PAF) based on the overtime volume per unit mass [24].

The characteristic factors of IMPACT World+ Endpoint are represented on a global scale. In the case of this method, the main descriptive units are the following. DALY-Disability Adjusted Life Year means the number of lost years of a fully healthy life; PDF.m^2.yr means the rate of potentially extinct species due to pressures on the environment in certain regions and periods [24].

ReCiPe 2016 Endpoint (H) includes damage-oriented impact categories for hierarchic (H) perspectives. Characteristic factors are represented on a global scale. Most midpoint categories are multiplied by the damage factors and grouped into three endpoint classifications: damage to human health, resource availability, and ecosystems [24]. The ReCiPe has been applied widely over numerous LCA studies for wastewater treatment [25,26].

IPCC 2021 GWP 100 method was enhanced by the Intergovernmental Panel on Climate Change and is based on the final government distribution version of the IPCC report "AR6 Climate Change 2021: The Physical Science Basis". Its measurement is the quantity of GHGs generated over a time scope of 100 years, in kilograms of CO_2 equivalent [24].

The Multi-Criteria Decision Analysis (MCDA) methodologies aim to provide a multi-criteria evaluation of alternatives through the application of systematic analyses that address the limitations of individual or group decision-making processes [27]. MCDA undertakes a review and an assessment of the value alignment and identifies the "best alternative(s)" among the group of available options.

Numerous MCDA methods and approaches have been proposed to determine the most probable selection of optimal options, such as TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution), MAVT, AHP, MULTIMOORA, ELECTRE, PROMETHEE, MAUT, ProMAA, FLOWSORT, FMAVT, FMAA, etc. [28,29]. TOPSIS is considered a multi-aspect method for decision-making that provides a basic numerical approximation to the alternative optimal. The Positive Ideal Solution (A+) is the summation of the greatest possible values, and the Negative Ideal Solution (A−) is the set of all the worst potential values for all alternatives [30]. The basic features of the TOPSIS method are briefly recorded in Table 1.

Table 1. The brief features of the TOPSIS technique [29,31].

Features	TOPSIS
Goal	Identify the greatest alternate from the available choices
Type of normalization	Vector normalization-square root of sum
Suitability	Selection problems, classifying problems
Inputs	Optimal and non-optimal option weights
Outputs	Entire hierarchy with nearness score to ideal and distance to non-ideal; the chosen is alternative closest to the positive ideal solution and farthest from the negative ideal alternative
Preference function	Distance metric (Manhattan distance, Tchebycheff distance, and Euclidean distance)
Approach	Quantitative and/or qualitative
Ranking scale	0 to 1 (1 is the best)
Best alternative	Max value
Consistency levels	No restrictions
Software	MS Excel, Matlab, Decerns
Weakness	Has no provision for weight elicitation, and verification of the consistency of judgments
Strength	Has minimal input data, provides straightforward results, gives the minimum distance in geometry from the ideal result
Application	Suitable in cases with numerous alternatives and criteria, particularly objective or numerical data

Besides the Environmental Footprint Method, ReCiPe 2016, IMPACT World+, IPCC 2021 and MCDA approaches, Monte Carlo simulation (MCS) was also implemented to examine six energy sources: solar and nuclear energy, wind energies (onshore, offshore), and electricity uncertainty associated with the parameters of combined electroconcentration and the stripping nitrogen recovery method [32]. MCS can help to offer findings to make better conclusions, in contrast with an exact method to identify optimal solutions [33]. MCS has also been adopted in several fields of application, for example large dimension, or probabilistic approaches [6,34], and uncertainty analysis [35].

MCS is also included in determining the best energy resource for the nitrogen removal process [36]. It can model and obtain numerically substantial results of environmental effects obtained by LCA. It will generate random variables with a certain plausibility distribution and forecast the numerical parameters of the model with statistical methods, so it obtains the numerical result for the concrete problems [37,38].

The energy demand for wastewater treatment is high, which is the reason various energy resources were investigated. It has to be examined for specific countries. Polruang et al. [39] in Bangkok examined the environmental effects of seven wastewater treatment plants with LCA, utilizing three power plans, including three effluent management systems. These power plans contained the current generated electricity, as well as the following five-year and twenty-year power generation schemes. The study observations showed that power generation was the prominent collaborator in nearly all environmental effects.

It must be mentioned, at an initial stage of a novel technology process, it is fundamental to introduce the environmental burdens. Calculating the effects when assessing a new technology is demanding, as the number of possible results can be enormous [40]. More than two-thirds of the final expenses and effects on the environment are based on decisions that are made in the initial development phase of the technology [41,42]. That is why it is extremely important to study technologies' environmental effects even before they are put into practice.

Background of the Novel Nitrogen Removal Technology: Combining Electroconcentration and Stripping Methods

Figure 1 represents the simplified sketch of the investigated nitrogen recovery process with electroconcentration and stripping methods.

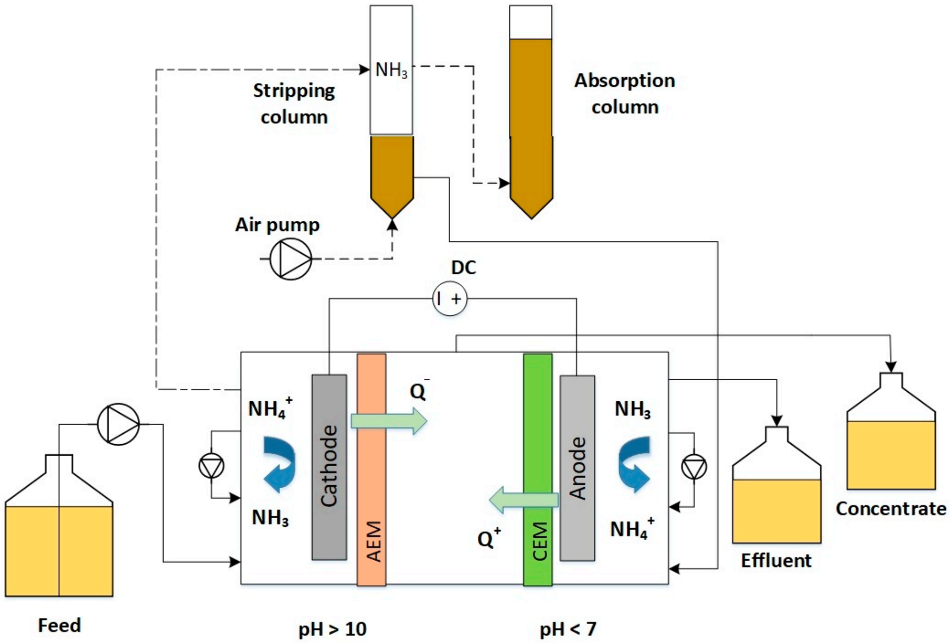

Figure 1. The investigated nitrogen recovery process with electroconcentration and stripping methods (amended from [23]).

The investigated nitrogen removal technology was implemented in a laboratory system, in combined reactors of stripping and electroconcentration, with modernized electrochemical oxidation occurring at the anode. The three-chamber electroconcentration part is made of polycarbonate sheets, with the three chambers (anode, concentrate, and cathode). The anode is a diamond electrode joined to a stainless steel or niobium rod, and a stainless-steel sintered fibre felt with titanium wire is used as the cathode.

A cation exchange membrane (CEM) is situated between the middle chambers and the anode, as well as an anion exchange membrane (AEM) being allocated between the cathode and the middle chambers. The membranes are bathed all night in a 5% (w/w) NaCl solution before application. In order to make the system fluid and airtight, rubber seals are also utilized between the chamber plates and the membranes. For membrane deformation prevention, the middle chamber is filled with glass beads.

The stripping tower is a glass column filled with K1-type filter carriers. Another glass column containing 5 M H_2SO_4 is filled with filter wool used in aquariums. The K1 media carriers and filter wool are used to reduce the gas flow rate, thus achieving maximum interaction time with the liquid in the columns. The solids in the reject water are allowed to remain at the bottom of the containers to avoid clogging in the system.

Anions can pass across the anion-exchange membrane (AEM) into the concentrate chamber because protons are reduced at the cathode to hydrogen gas, which raises the pH of the catholyte and transformed the inflowing NH_4^+ to volatile NH_3.

For liquid–gas separation, the catholyte-hydrogen gas compound is pursued into the stripping tower. The liquid segment is extracted from the lowest part of the stripping tower and fed into the electroconcentration unit's anode. Here, as an outcome of oxidation reactions, protons are generated.

Due to the resulting low pH, the remaining NH_3 is converted back into NH_4^+, which allows it to move to the concentrate chamber above the CEM, together with other cations. An effluent bottle is used to collect the anode's effluent. Osmotic and electro-osmotic forces also cause water to be pumped into the concentration chamber at the same time. The generated liquid concentrate is gathered into a concentration bottle as an overflow. In the respective chambers, the anolyte and the catholyte are also circulated to reduce mass transfer limitations. In the middle chamber, mixing is also employed. To remove the volatile NH_3 from the liquid, air is flowed into the stripping tower from the bottom part. At the top of the stripping tower, the gas mixture is gathered, and the stripped NH_3 is captured by bubbling through H_2SO_4 to re-solubilize it [23].

2. Materials and Methods

As a first step, a novel nitrogen removal technology was looked for, where the input and output data are accurately described, so it is possible to conduct an environmental analysis. The technology, which is demonstrated in the introduction, was developed by Koskue et al. [23] and it is selected for evaluation. The subject of our research is the environmental analysis of this developed technology in an Australian sewage treatment plant, because the reject water samples originate from Australia. It must be mentioned that the LCA analysis of this selected technology was not performed until now. In this present publication, we are following an earlier form of our scientific presentation [43]: the environmental impact assessment of the process is carried out before industrial implementation in accordance with the literature recommendation [41,42].

The reject water stream was used as feed; the parameters of the reject water can be seen in Table 2. The reject water was gained from Brisbane, Australia's Luggage Point municipal WWTP. The capacity of the WWTP is 25.55 m^3/h [23].

Table 2. The characteristics of reject water from Brisbane WWTP [23].

Components	mg/L
Cl	656 ± 25
Na	341 ± 19
K	221 ± 11
NH_4-N	983 ± 50
PO_4-P	7.3 ± 1.9
Ca	36 ± 4
Mg	18 ± 7
organic carbon	853 ± 416
inorganic matter	752 ± 59

The nitrogen removal was $\leq$94% from the investigated reject water; therefore 924 mg/L NH_4-N was the amount recovered.

The energy consumption of the process was 57 kWh/m^3. The functional unit of 1 m^3 of reject water was examined as output and "gate-to-gate" analysis was implemented. In the case of MCDA, the TOPSIS score was used to evaluate the alternatives and the most appropriate wastewater treatment was selected with six different energy alternatives [23] based on the PESTLE factors: environmental factors, social, political, legal, and economic.

Life cycle analysis was performed with SimaPro V9.3 software to investigate the environmental effects of a novel nitrogen removal process based on the combination of electroconcentration and stripping methods.

LCA helps to determine which product has the most negligible environmental impact over others by assessing the effects of products and processes throughout their lifecycle. The ISO 14040 (2006) [44] and ISO 14044 (2006) [45] standards define the four steps of the life cycle analysis model structure [23]: defining goals and scope; [24] analyzing life cycle inventories; [25] evaluating life cycle impacts; and [26] interpreting life cycle impacts [23]. Ecoinvent V3.8 databases have been expanded to include the municipal waste scenarios in SimaPro V9.3, in which recycle rates are compared with ignition and landfill rates in various countries. In our study, a model framework was built using SimaPro V9.3 based on the methodologies in the following paragraphs.

The methodological steps of the impact assessment are described in the ISO 14040:2006 standard [44]. In the impact assessment according to the standard, the inventory results were first assigned to the impact categories corresponding to the goals and framework of the LCA study. Impact categories are nothing more than classes representing environmental problems to which the results of the inventory can be assigned. An inventory item can even be linked to several impact categories. For each impact category, the authors of the method defined a reference unit. For example, the effect of 1 kg of CO_2 on global warming is 1, but the contribution of methane emissions to global warming (GWP) is given by a value expressed in [kg CO_2 equivalent], depending on the method used [46].

The LCA begins with the definition of the goal and scope, where we define exactly to what the LCA refers. After that, the material and energy consumption of the life cycle, or an inventory of the emissions, is prepared for the analysis. Based on the inventory, environmental impacts are calculated using LCA methods, which result in quantitative indicators. The last step of the LCA is the life cycle interpretation; when we evaluate the results, we can examine the quality and reliability of the results or formulate the conclusions that can be drawn taking into account the goals.

1. Goal definition

The purpose of the LCA is often to compare individual design alternatives during the product design process and to determine the more environmentally beneficial design directions.

2. Definition of subject

Knowing the purpose of the LCA, we define the subject of the analysis, which includes several decisions that determine the further steps of the procedure. Then, we define exactly the examined life cycle, i.e., which parts of the life cycle are taken into account during the survey and which are not. In our case, “gate-to-gate” analysis was applied.

3. Life cycle inventory analysis

The life cycle inventory analysis follows after we have determined exactly to what the LCA refers, and the definition of the goal and scope has been completed. Inventory analysis means the collection, systematization, processing, and documentation of quantitative data on material and energy consumption and emissions (input and output currents) occurring during the life cycle. We usually use literary sources and databases for those process units of the life cycle for which we are not able to collect on-site data directly. During the inventory analysis, we built a model of the entire life cycle based on the data collected from each process unit. In practice, we do this with the help of a suitable software. In our case, SimaPro V9.3 was used.

4. Life cycle impact assessment

The life cycle impact assessment is a procedure for quantifying the possible environmental effects associated with the extraction of raw materials (e.g., minerals, energy sources) from nature and the release of various substances into nature (e.g., air, water, soil pollutants) during the entire life cycle. Its steps: classification and characterization, normalization, and weighting.

5. Life cycle interpretation: The life cycle interpretation includes determining the most critical points of the life cycle from an environmental point of view and investigations related to the quality and reliability of the LCA (e.g., sensitivity investigation). During the

life cycle interpretation, we look to answer what conclusions can be drawn based on the life cycle survey and what possible recommendations can be formulated.

6. Critical review: The review of any scientific activity and publication involves checking and criticizing the work undertaken and the results, which is usually performed by independent experts. The critical review used in the LCA is compliant with the requirements of international standards (ISO 14040 and ISO 14044) [44,45,47]. Figure 2 shows the main framework of LCA.

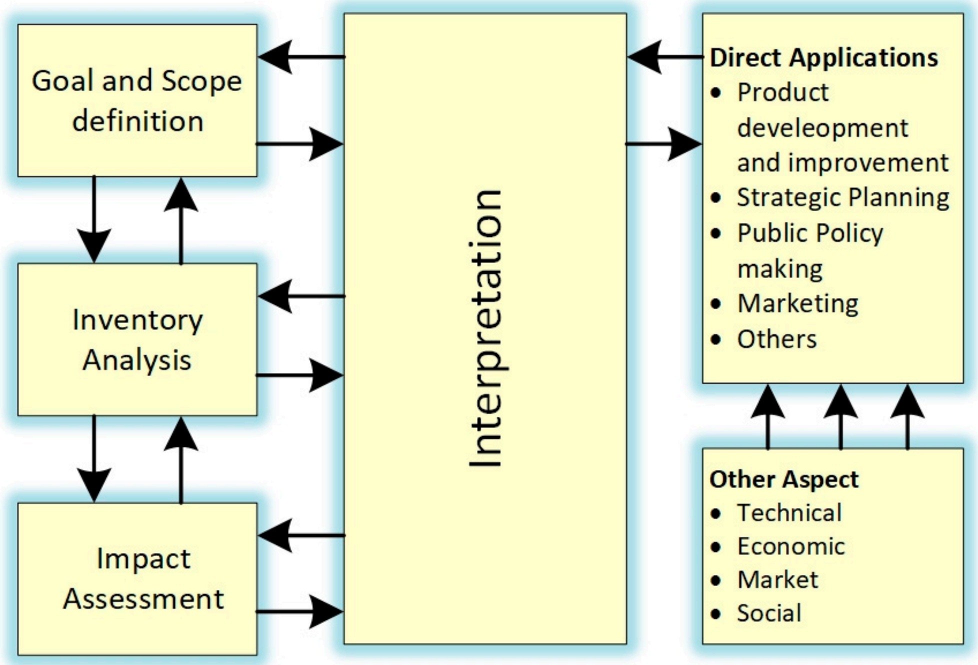

Figure 2. LCA framework (ISO 14040:2006) [48].

Describing the classical TOPSIS process with negative and positive ideal solutions for a single decision maker includes a continuous series of tracing equations, in which we sort the priority by selecting the closest option to 1 [49]:

$$A^{+} = \left(v_1^{+},\, v_2^{+}, \ldots, v_n^{+}\right) = \left\{\max_i\left(w_j n_{ij}\right)\right\} \tag{1}$$

$$A^{-} = \left(v_1^{-},\, v_2^{-}, \ldots, v_n^{-}\right) = \left\{\min_i\left(w_j n_{ij}\right)\right\} \tag{2}$$

$$v_{ij} = w_j n_{ij} \tag{3}$$

$$n_{\mathrm{ij}} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{4}$$

$$R_{\mathrm{i}} = \frac{\sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^{-}\right)^2}}{\sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^{-}\right)^2} + \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^{+}\right)^2}} \tag{5}$$

where

x_{ij} is the value of i-alternative with respect to j-criterion, $i = 1, 2, \ldots m$;
n_{ij} is a normalized value, $j = 1, 2, \ldots n$
v_{ij} is a weighted normalized value
w_j is the weight of the jth criterion, $\sum_{j=1}^{n} w_j = 1$

(v_1^+, v_2^+, v_n^+) *or* (v_1^-, v_2^-, v_n^-) are the minimum or maximum value of the benefit criteria R_i is the relative closeness to the Ideal Solution of the *i*th alternative, $0 \leq R_i \leq 1$.

TOPSIS, a fuzzy-based multi-criteria decision-making practice developed by Hwang and Yoon [50], is a notable MCDA method. The elementary idea of the TOPSIS technique is that the selected alternative should have the farthest distance from the negative ideal result and the shortest distance from the positive ideal result. During the TOPSIS method, different score functions and different circumstances of criterion importance were investigated including political and legal, social, technological, economic, and environmental. To reach a sustainable and cleaner operation, we should concentrate on social and environmental conditions since these conditions may have a significant and positive effect on the technology [51–53].

In this study, Decerns (Decision Evaluation in Complex Risk Network system) MCDA V1.5 software has been applied for the MCDA of the membrane contactor-based nitrogen recovery process. DECERNS provides methods and tools to support decision-making in alternative options, providing a multi-aspect policy analysis of different alternatives, involving planning of land use, protection of the environment, and management of risks [28].

3. Results and Discussion

The results are demonstrated by using Environmental Footprint Method, IMPACT World+, ReCiPe 2016, and IPCC 2021 approaches. These methodologies were used in this research study with six different energy sources. Figures 3–14 represent the calculated findings for climate change, global warming, human toxicity, acidification, and the eutrophication of freshwater. The environmental impact data represent the industrial data in two categories: Rest of the World (RoW) and Global (GLO).

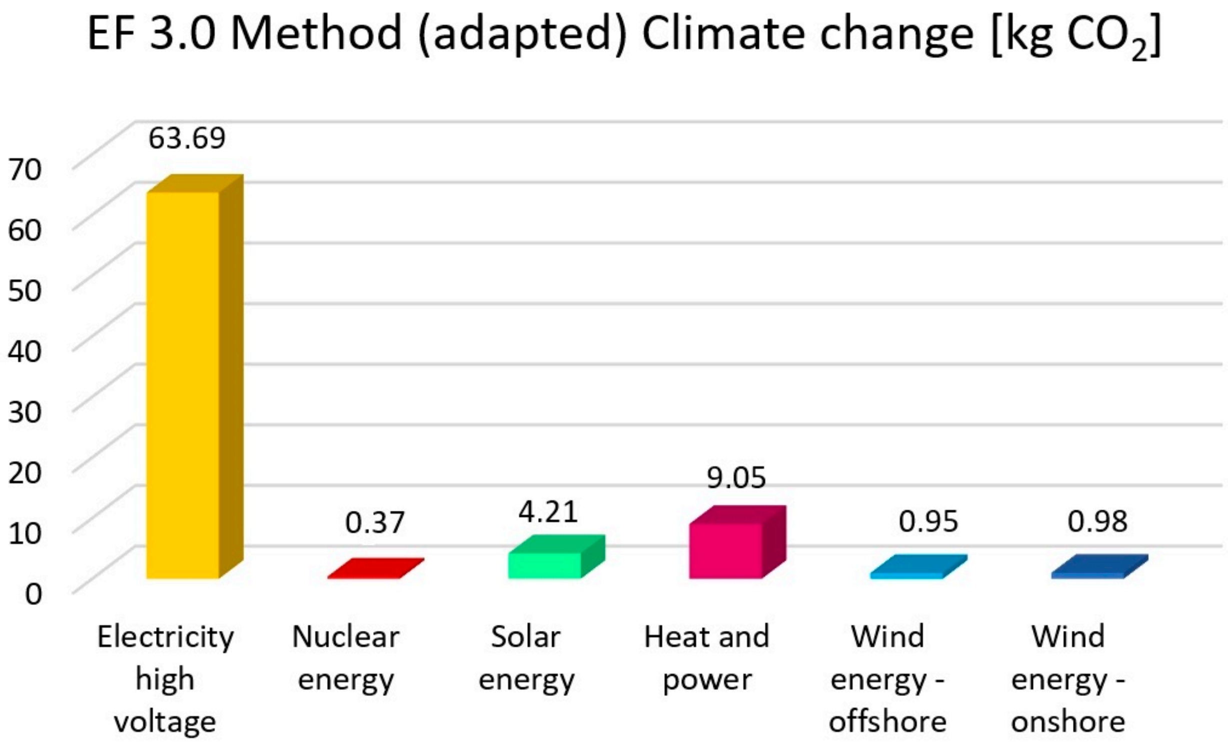

Figure 3. Examination of climate change with Environmental Footrprint approach with various forms of energies.

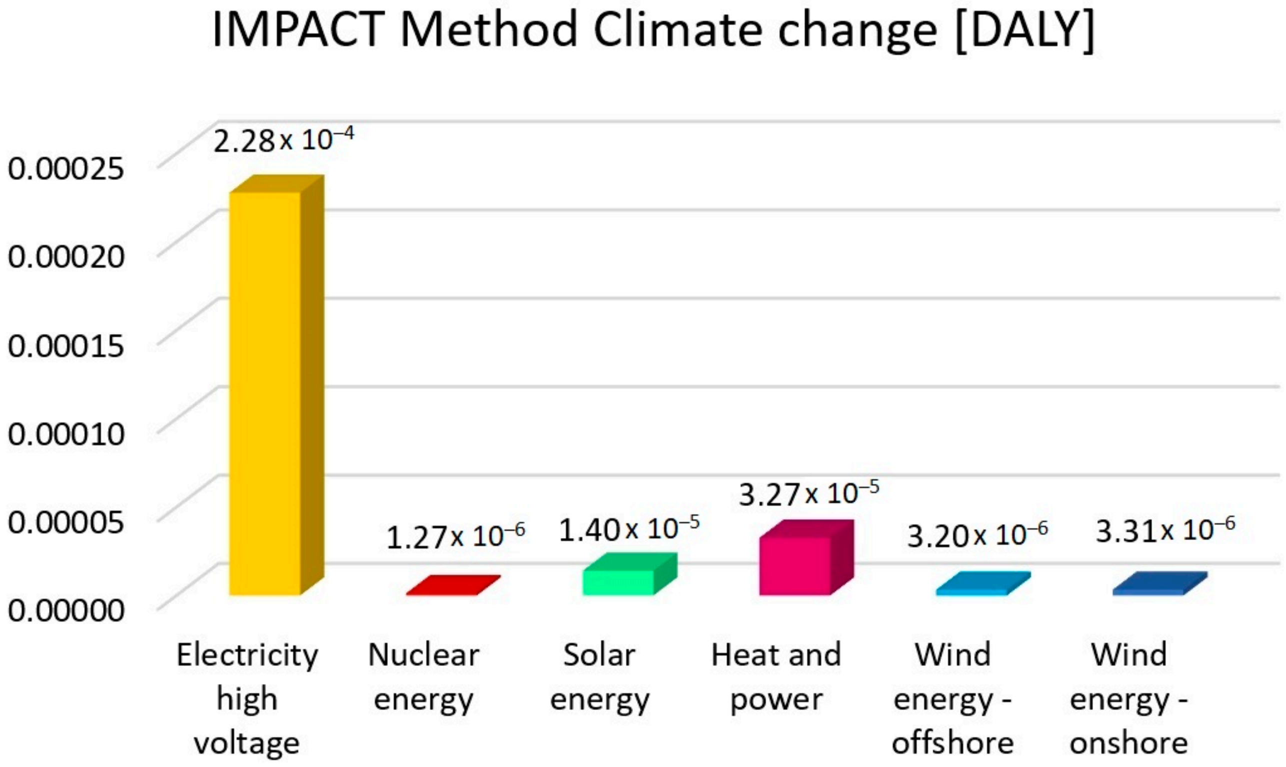

Figure 4. Examination of climate change with IMPACT World+ approach with various forms of energies.

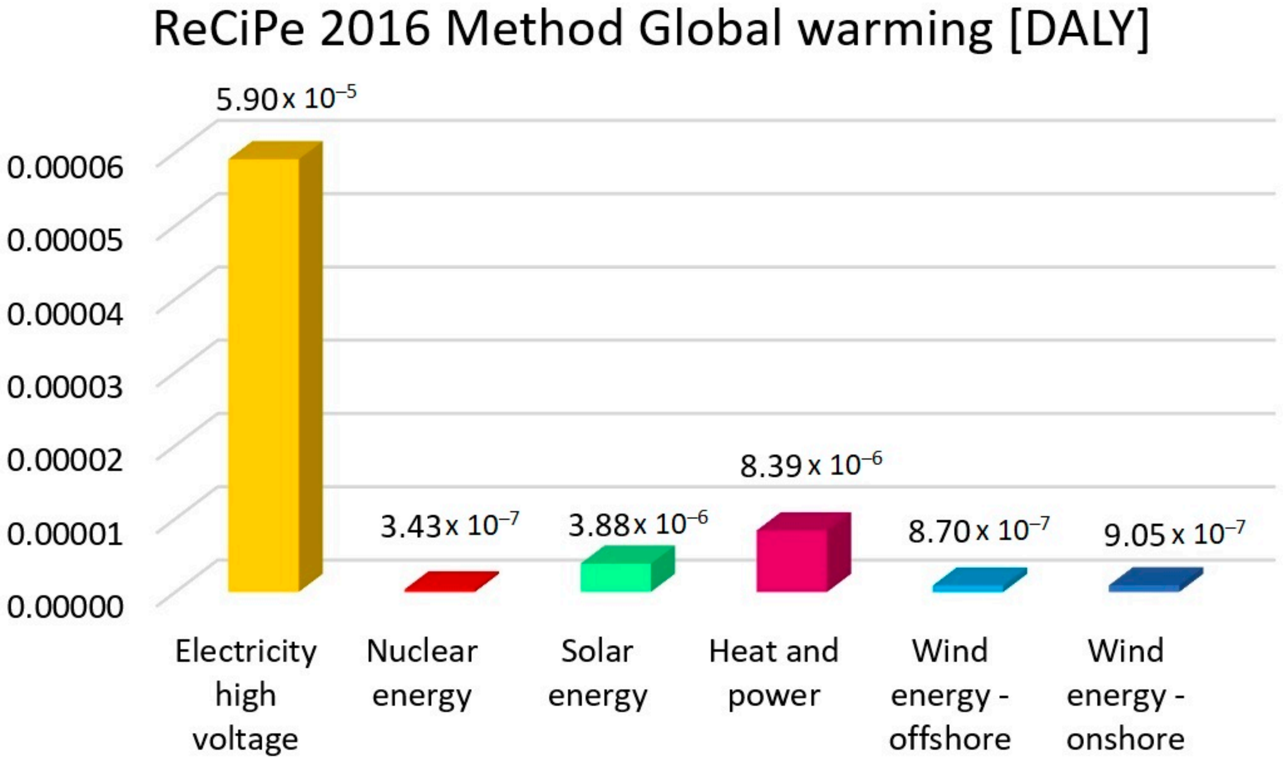

Figure 5. Examination of global warming with ReCiPe 2016 approach with various forms of energies.

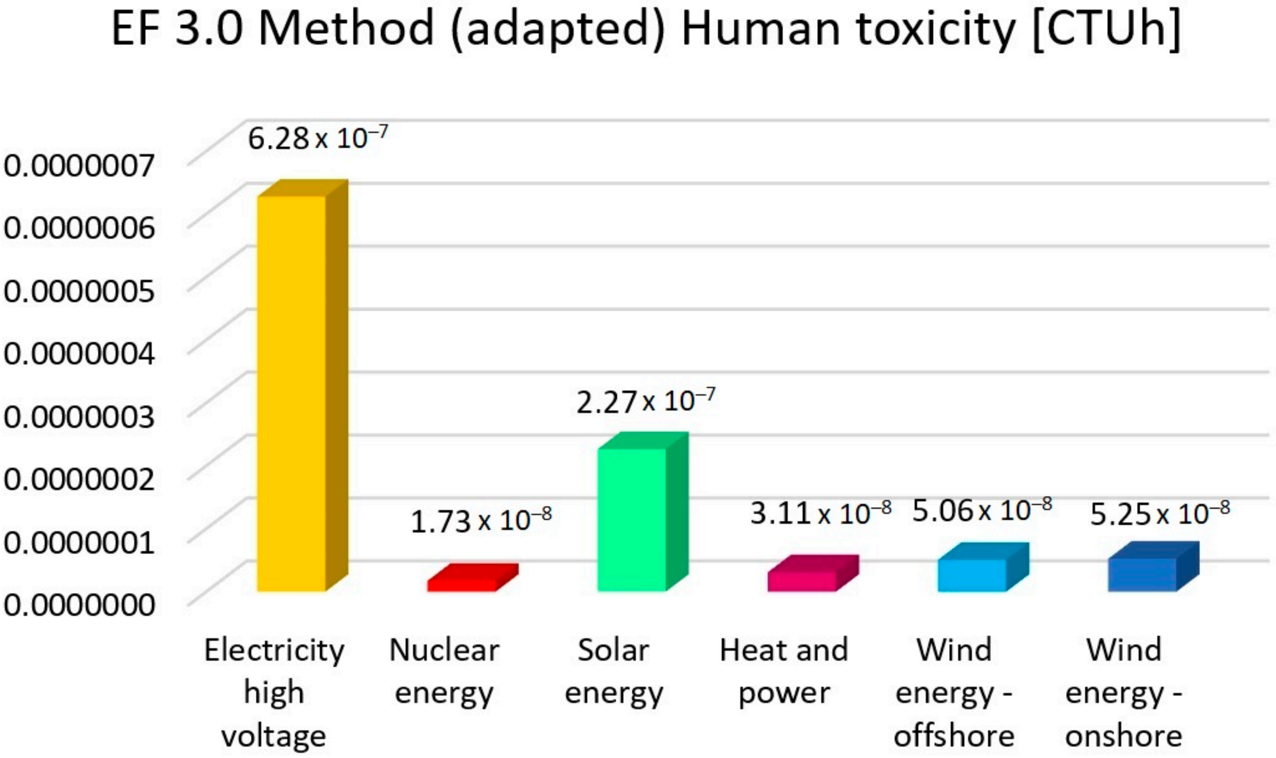

Figure 6. Examination of human toxicity with Environmental Footprint approach with various forms of energies.

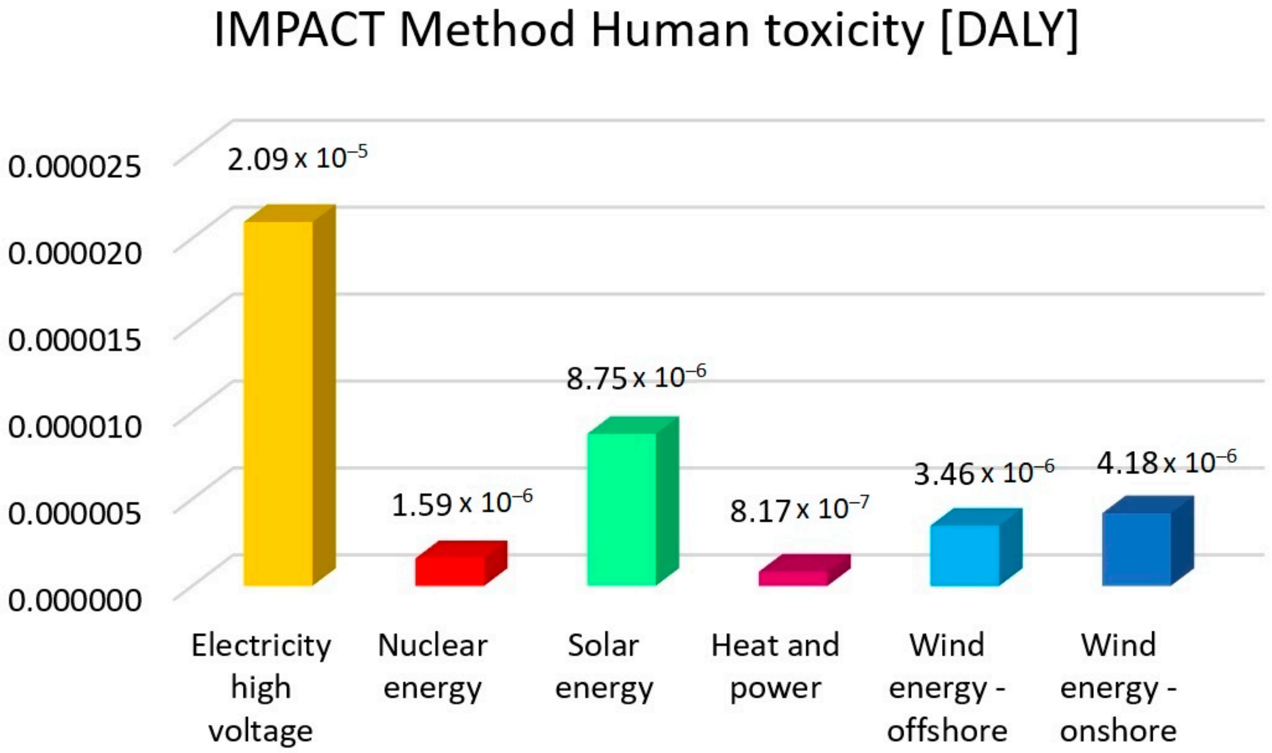

Figure 7. Examination of human toxicity with IMPACT World+ approach with various forms of energies.

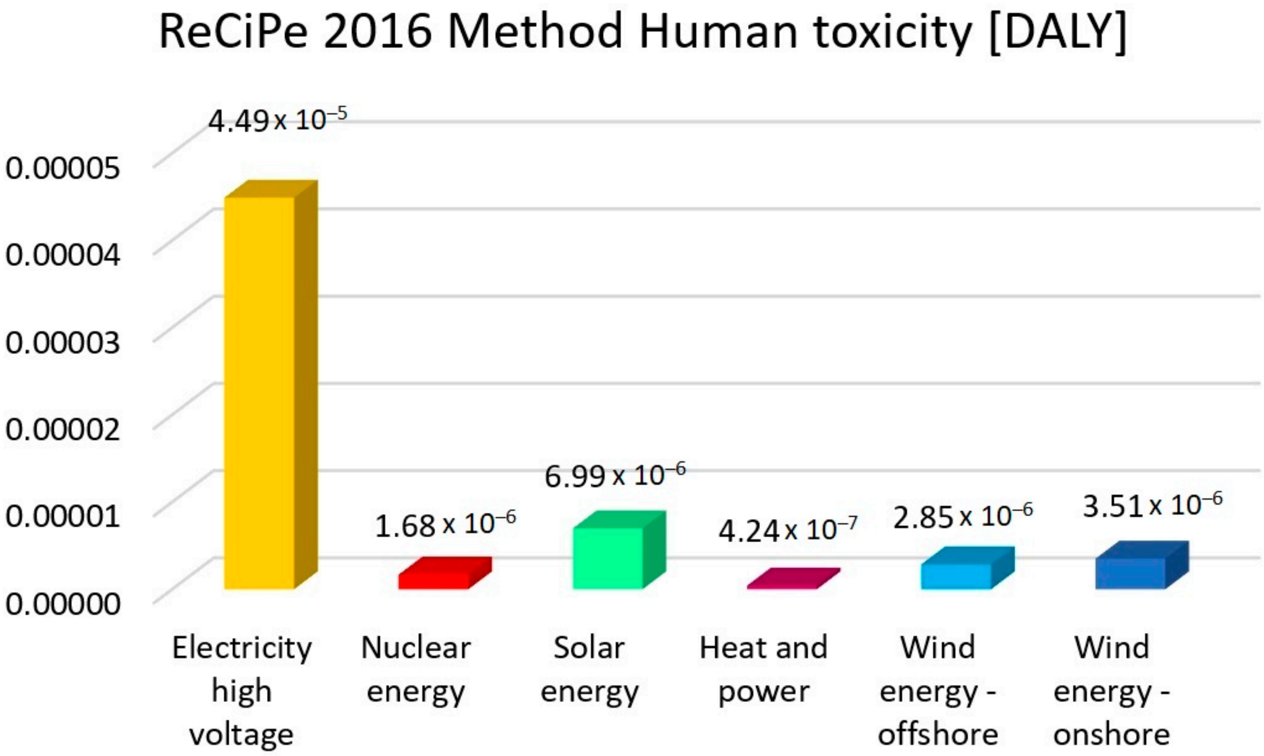

Figure 8. Examination of human toxicity with ReCiPe 2016 Endpoint approach with various forms of energies.

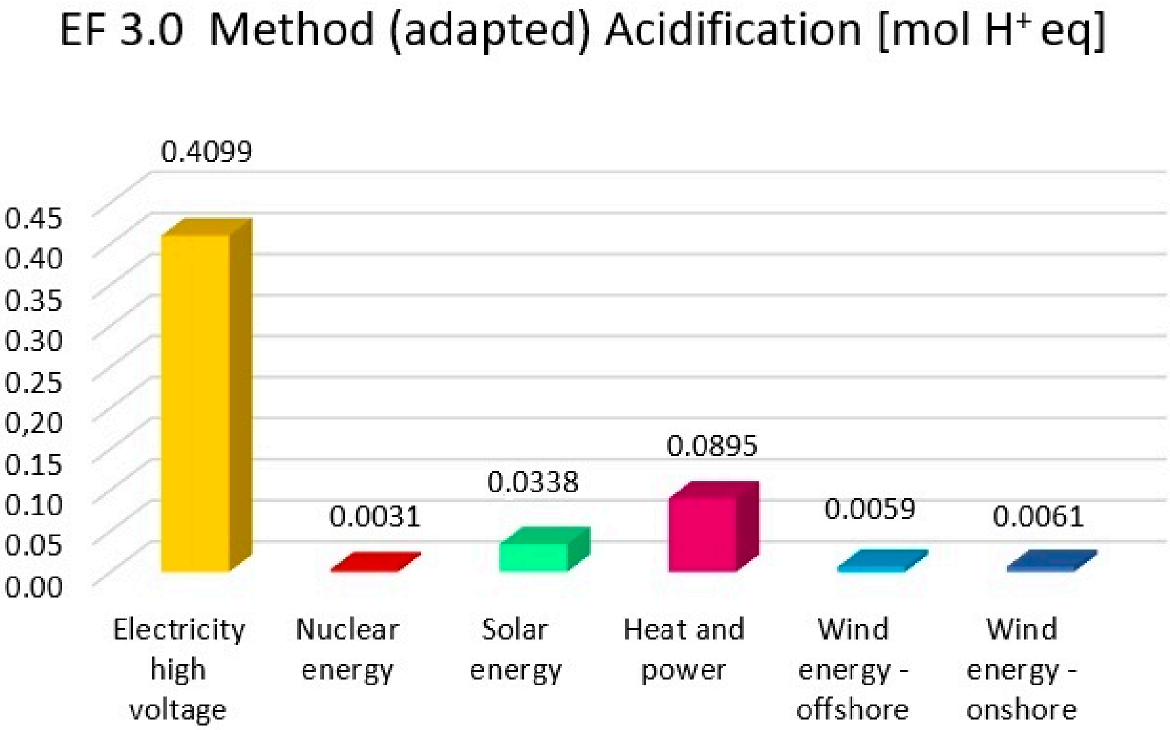

Figure 9. Examination of acidification with Environmental Footprint approach with various forms of energies.

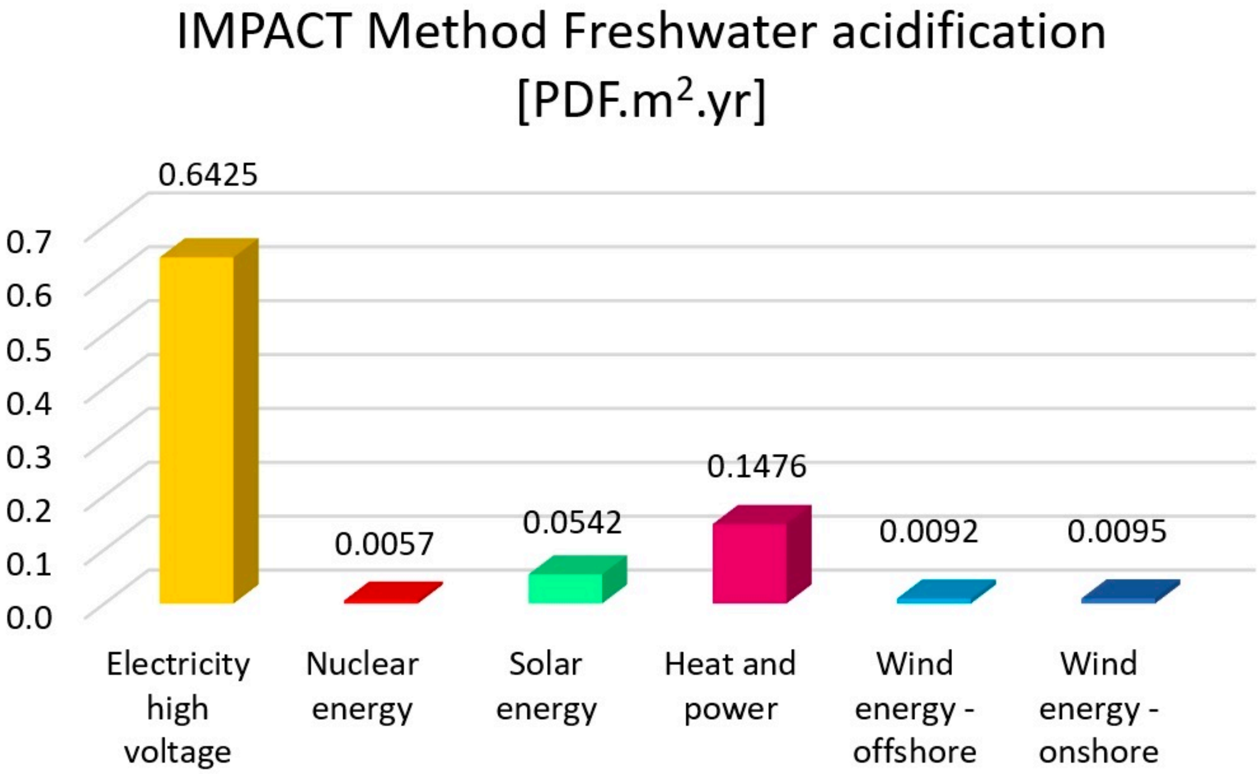

Figure 10. Examination of freshwater acidification with IMPACT World+ approach with various forms of energies.

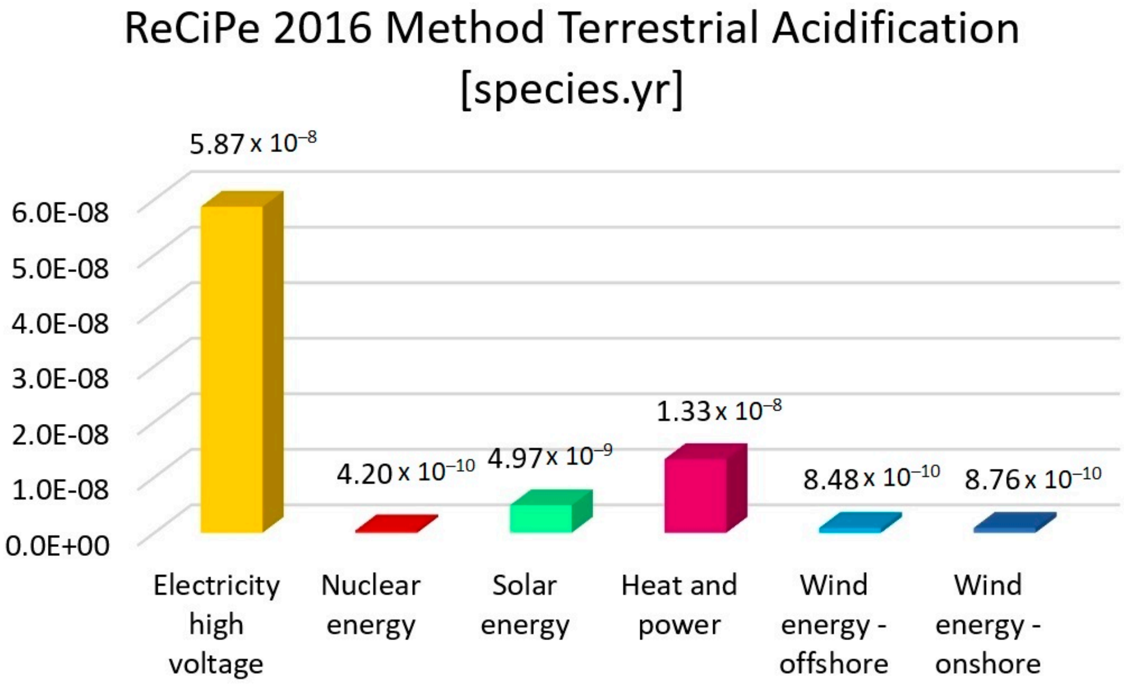

Figure 11. Examination of acidification (terrestrial) ReCiPe 2016 approach with various forms of energies.

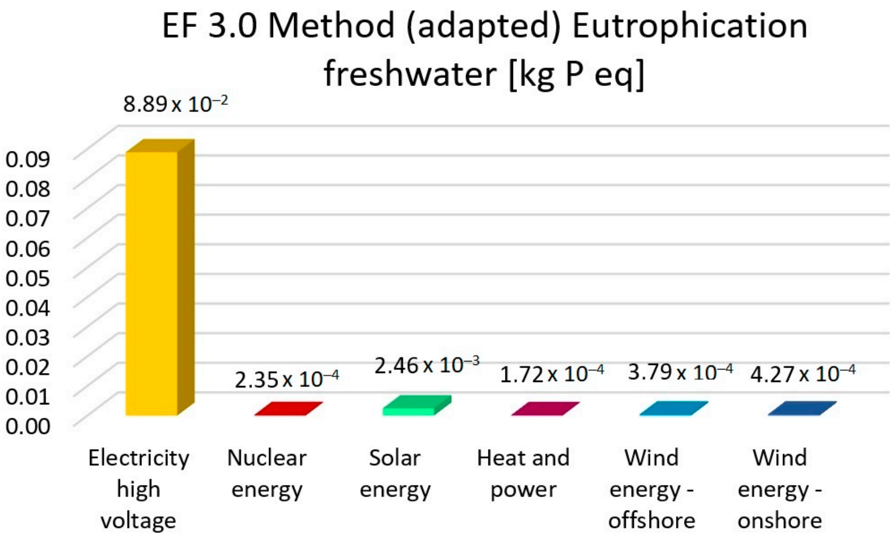

Figure 12. Examination of eutrophication freshwater with Environmental Footprint approach with various forms of energies.

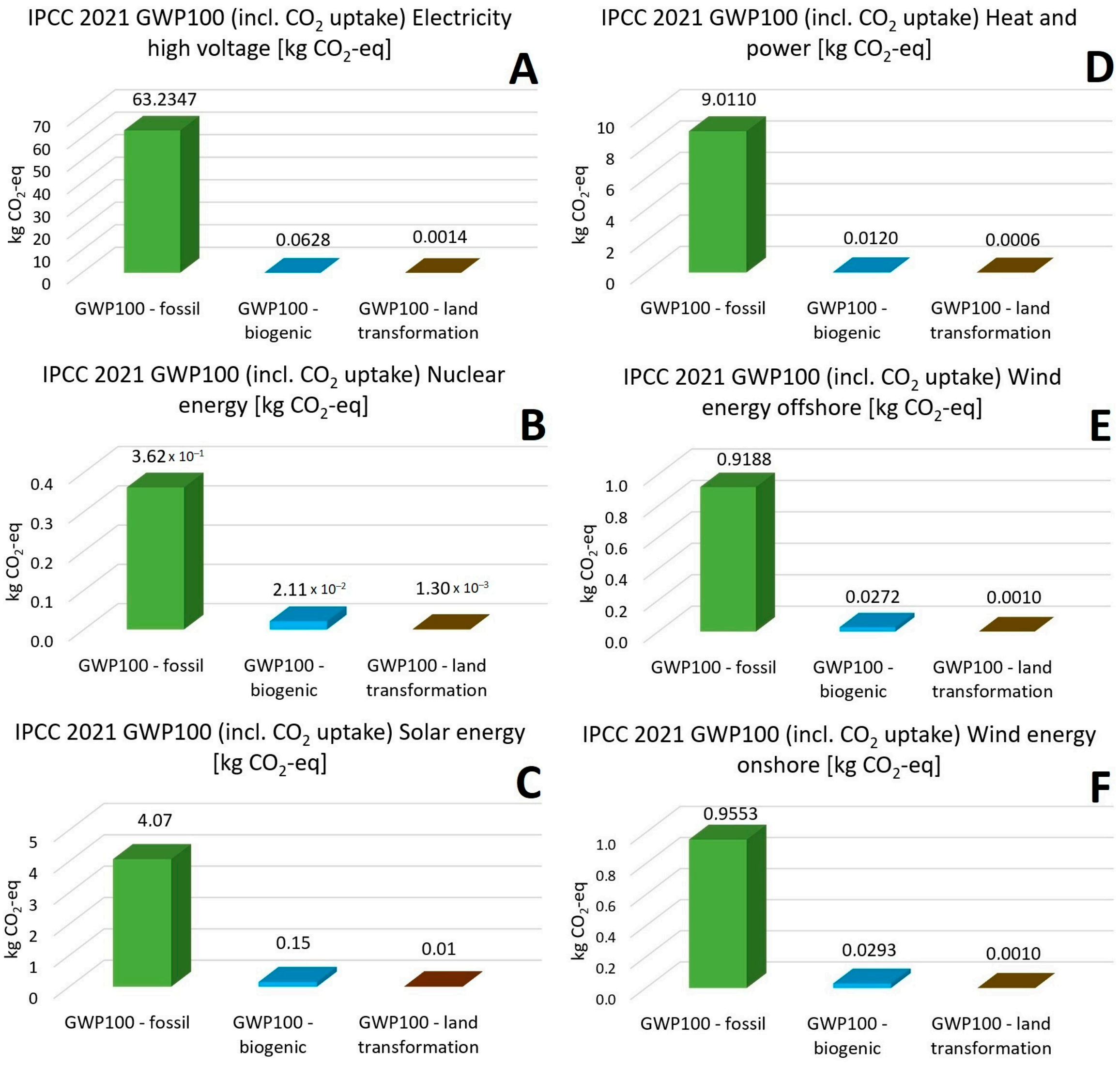

Figure 13. Findings of IPCC 2021 GWP100 (including CO_2 uptake) approach using Electricity high voltage (**A**), Nuclear energy (**B**), Solar energy (**C**), Heat and power (**D**) and Wind energies (**E**,**F**).

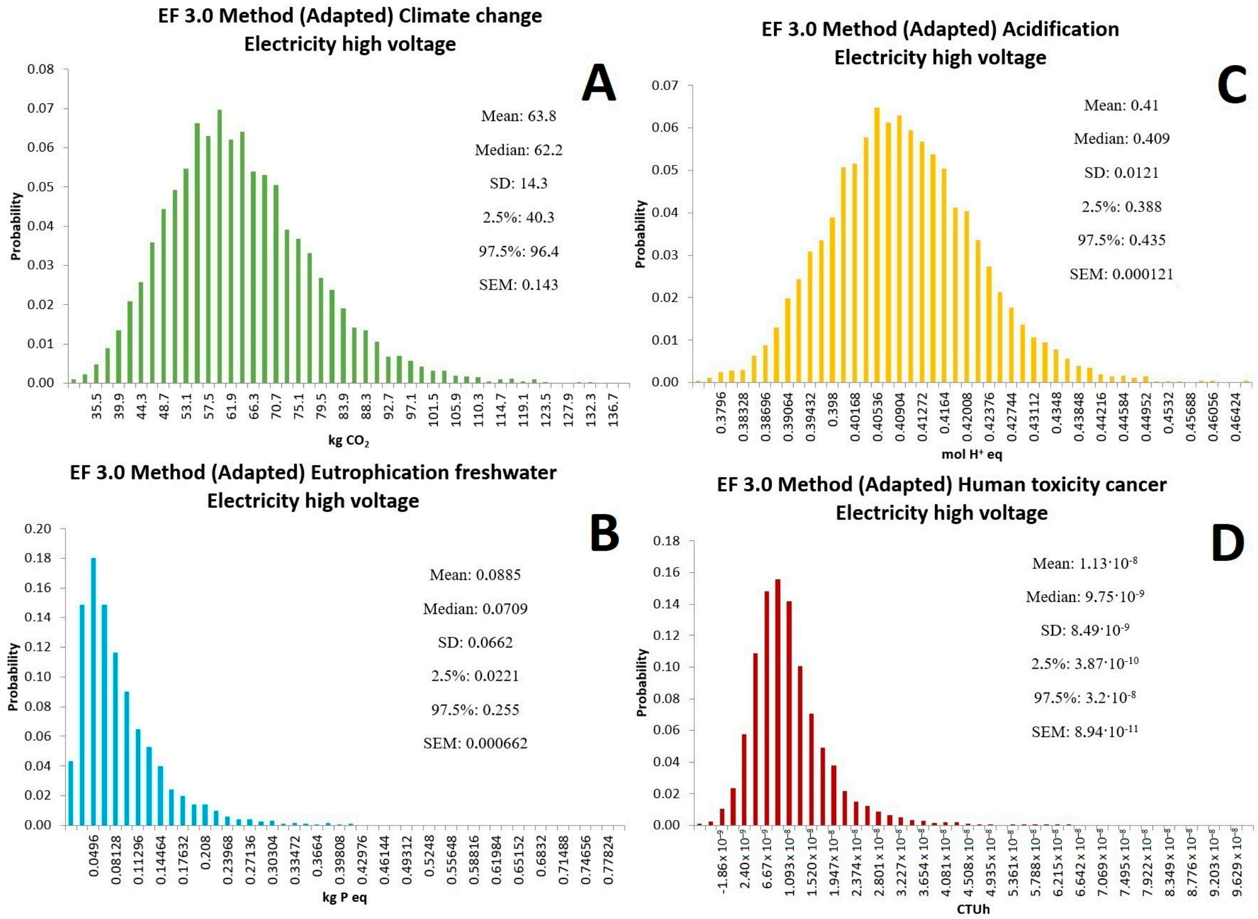

Figure 14. Monte Carlo analysis of EF 3.0 Method (Adapted) using Electricity high voltage in the case of different environmental effects: Climate change (**A**), Eutrophication (**B**), Acidification (**C**) and Toxicity (**D**).

Figures 3–5 represent the outcomes for climate change and global warming with electricity high voltage, heat and power, nuclear energy, and two renewable energies, solar and wind energy onshore and offshore, investigated with IMPACT World+ Endpoint (H), Environmental Footprint Method), and ReCiPe 2016 methods.

In climate change, as seen in Figures 3–5, the electricity high voltage has a much higher value than other resources. Examining climate change data with the Environmental Footprint Method, electricity high voltage is 67 times higher than in wind energy offshore, 65 times higher than in wind energy onshore, and 15 times higher than in solar energy. Also, it is 171 times higher than nuclear energy and 7 times higher than heat and power. Electricity high voltage also has a much higher value in case of global warming. The results will be similar with the IMPACT World+ methodology: electricity high voltage is 71 times higher than wind energy offshore, 69 times higher than wind energy onshore, and 16 times higher than solar energy. Finally, it is 179 times higher than nuclear energy and 7 times higher than heat and power. With ReCiPe 2016 methodology, the outcomes were the following: electricity high voltage is 68 times higher than wind energy offshore, 65 times higher than wind energy onshore, 15 times higher than solar energy, 172 times higher than nuclear energy, and 7 times higher than heat and power. Human toxicity was also examined with Environmental Footprint, ReCiPe 2016, and IMPACT World+ methodologies. Figures 6–8 show the results with the previously used energy resources.

Figures 6–8 indicate that electricity high voltage has the highest value among all the applied resources. Electricity high voltage values are 12 times higher than wind energy offshore, 12 times higher than wind energy onshore, 3 times higher than solar energy, 36 times higher than nuclear energy, and 20 times higher than heat and power with

Environmental Footprint Method. Using IMPACT World+ methodology, the electricity high voltage is 3 times higher than wind energy offshore, 4 times higher than wind energy onshore, 9 times higher than solar, and 2 times higher than nuclear energy. Finally, it is 8 times higher than heat and power. ReCiPe 2016 values show that electricity high voltage is 16 times higher than wind energy offshore, 13 times higher than wind energy onshore, 6 times higher than solar energy, 27 times higher than nuclear energy, and 106 times higher than heat and power.

Figures 9–11 depict the outcomes of the investigation of acidification with the previously mentioned renewable and non-renewable energy sources. The same approaches—Environmental Footprint Method, IMPACT World+ and ReCiPe 2016—were applied.

The results of the acidification are shown in Figures 9–11 with the electricity high voltage as the most dominant value. As for the values with the different energy sources, electricity high voltage is 70 times higher than wind energy offshore and 68 times higher than wind energy onshore, using the Environmental Footprint Method. The rest of the results highlight that electricity high voltage is 5 times higher than heat and power, 132 times higher than nuclear energy, and 12 times higher than solar energy. The IMPACT World+ approach concludes the electricity high voltage values 70 times higher than wind energy offshore, 67 times higher than wind energy onshore, 4.4 times higher than heat and power, 113 times higher than nuclear energy, and 12 times higher than solar energy. The last one, the ReCiPe 2016 approach, shows that electricity high voltage is 0.9 times higher than wind energy onshore and offshore, 0.8 times higher than heat and power, 0.9 times higher than solar, and 0.9 times higher than nuclear energy. Freshwater eutrophication findings with Environmental Footprint Method can be seen in Figure 12. It can be determined, the environmental load is drastically less in the case of nuclear and renewable energies compared with the electricity high voltage.

Figure 13 represents the IPCC 2021 GWP100 approach with the six energy resources.

As indicated in Figure 13, renewable energy resources reduce the fossil-based environmental effect, which is equal to the previous results. Renewable energy sources can vastly reduce fossil-based environmental impacts and CO_2 emissions [15]. The best energy sources with lower environmental effects and the best reuse processes were identified, as seen in Figures 3–13.

The outcomes of the Monte Carlo investigations are presented in Figures 14 and 15, with Environmental Footprint Method climate change, acidification, eutrophication freshwater, human toxicity cancer with two different energy sources, electricity high voltage, and heat and power. The procedure is recreated an excessive number of times, and after ten thousand iterations, the ultimate result is formed [36].

In the Supplementary Materials, more figures represent the results of the Environmental Footprint Method with solar, nuclear, and also wind energy.

The confidence interval of 95% was used as MCS, and accorded the outcomes of environmental effect in terms of 4 impact classifications (climate change, acidification, eutrophication freshwater, human toxicity cancer) [54].

SD expresses the standard deviation, and SEM expresses the standard error of the mean. From the data produced in MCS with Environmental Footprint approach, and with an energy resource of electricity high voltage, the climate change has a median of 63.8 kg CO_2, with SD = 14.3 and CV = 22.4%. Figure 14 revealed that 95% of environmental impacts as characterization would fall within the range of 40.3 to 96.4 kg CO_2.

The acidification has a median of 0.409 mol H^+eq, with SD = 0.0121 and CV = 2.95%. The 95% environmental impact as characterization would fall within the range of 0.388 to 0.435 mol H^+eq. The eutrophication freshwater has a median of 0.0709 kg Peq, with SD = 0.0662 and CV = 74.8%. The 95% environmental impact as characterization would fall within the range of 0.0221 to 0.255 kg Peq. The human toxicity cancer has a median of 9.75×10^{-9} CTUh, with SD = 8.49×10^{-9} and CV = 78.9%. The 95% of environmental impacts as characterization would fall within the range of 3.87×10^{-10} to 3.2×10^{-8} CTUh.

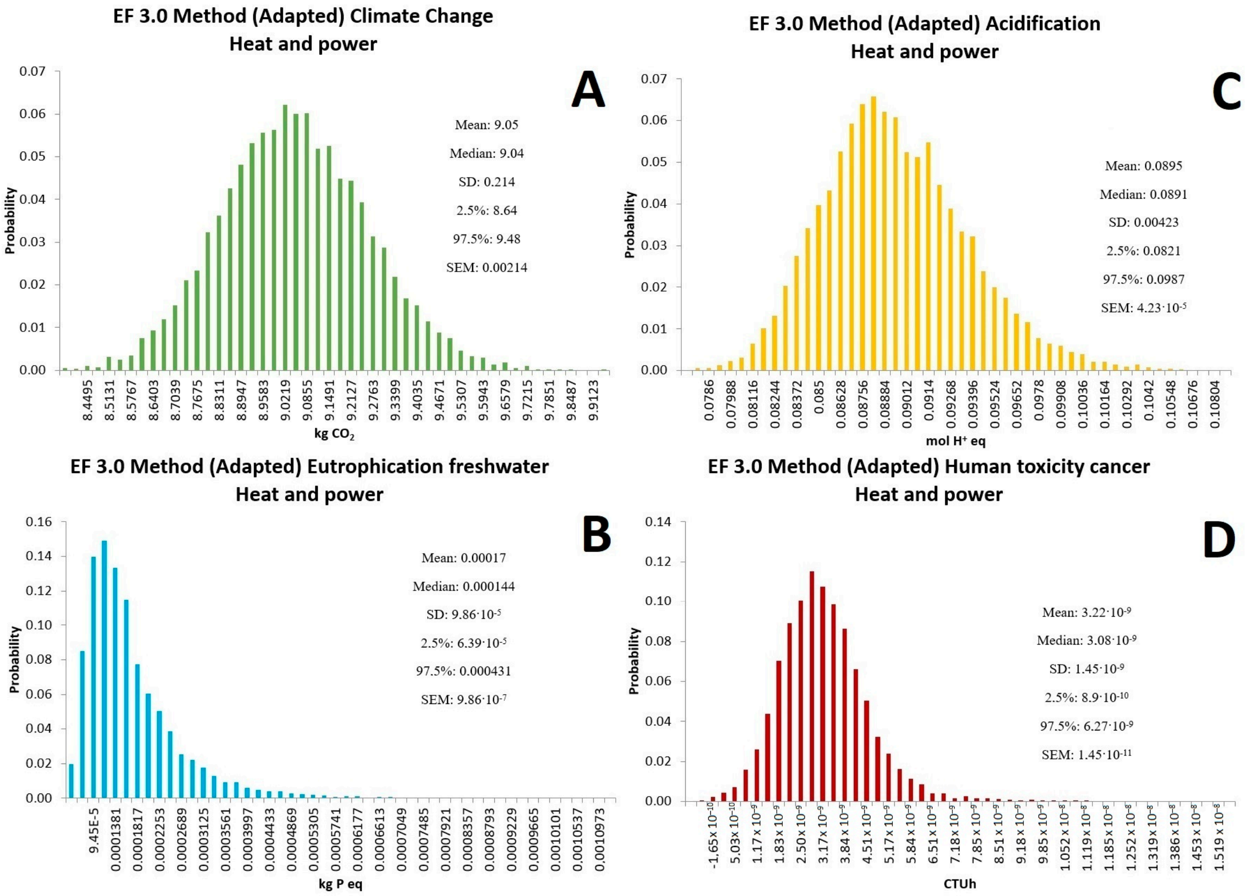

Figure 15. Monte Carlo analysis of EF 3.0 Method (Adapted) using heat and power in the case of different environmental effects: Climate change (**A**), Eutrophication (**B**), Acidification (**C**), and Toxicity (**D**).

Other energy resources, like heat and power, were also investigated with the Environmental Footprint Method in MCS. The calculation results show that the climate change has a median of 9.04 kg·CO_2, with SD = 0.214 and CV = 2.36%. Figure 15 revealed that 95% environmental impact as characterization would fall within the range of 8.64 to 9.48 kg CO_2. The results of the uncertainty analysis represented that the acidification has a median of 0.0891 mol H^+eq, an SD = 0.00423, and CV = 4.73%. Characterization data would fall within 0.0821 and 0.0987 for 2.5% and 97.5% possibility stages, respectively.

Examining the eutrophication of freshwater, the results are SD = 9.86×10^{-5} and CV = 51.1% with a median value of 0.000144 kg Peq. The 95% environmental impact would fall within the range of 6.39×10^{-5} to 0.000431 kg Peq. Human toxicity cancer has a value of SD = 1.45×10^{-9} and CV = 45%, and the 95% of environmental impacts would fall within the range of 8.9×10^{-10} to 6.27×10^{-9} CTUh with a median of 3.08×10^{-9} CTUh. According to previous studies, when CV (coefficient of variation) is below 30%, this means the model has great expectation results and is sufficient for engineering utilization [55].

Further literature examines the life cycle of some other nitrogen removal processes. Xue et al. [56] investigated, for the first time, the LCA of ReNOx (converting nitrogen oxides to ammonia). In this paper, the environmental impacts of ReNOx under various circumstances were studied. Designers and engineers can use the results for technological estimations. Their work found that more than 90% of urban area air pollution and acidification are contributed by the emissions of NOx. Critical points from the point of view of the eco-index were determined; in order of importance, they are as follows: catalyst production, NOx emission, waste treatment service, CO_2 emission, methane production, and adsorption material production.

Kar et al. [15] studied ammonia recovery with air stripping technology from WWTP sidestreams at varying sidestream nitrogen concentrations. Also, it was investigated with techno-economic analysis. It was established that air-stripping technology provides an environmentally beneficial option for nitrogen recovery, even with varying ammonia concentrations and high sidestream volume. It was also determined that the greenhouse gas emission of the hydrocarbon-based Haber–Bosch method is six times higher than the air stripping technology.

Vineyard et al. [57] investigated electrodialysis, nitrification–denitrification, and anammox to recover nitrogen as an ammonium-based fertilizer. In this study, OpenLCA 1.8 software was used with ecoinvent 3.5 database. The theoretical LCA results in this article show that the electrodialysis appears to be the preferable environmental choice of nitrogen removal technologies. The different midpoint environmental impact categories were calculated and these are the following: Carcinogens, Ecotoxicity, Eutrophication, Non-Carcinogenics, Respiratory Effects, Acidification, Fossil Fuel Depletion, Global Warming, Ozone Depletion, and Smog. In the case of the latter five, a net negative value was determined for electrodialysis.

As mentioned earlier, the reject water stream used as feed was collected from Brisbane, Australia's Luggage Point municipal WWTP. Thus, the Australian conditions were used in the PESTLE analysis. In 2021, 29% of Australia's total electricity production originated from renewable energy resources, including solar energy (12%), wind energy (10%), and hydropower energy (6%). Recently, large-scale solar energy production has begun to expand rapidly. Large-scale solar energy production has increased from 2016 neglectable levels to 4% of all Australian electricity production by 2021. It means a five-year growth rate of 1.75% [58].

AEMO (Australian Energy Market Operator) determined that there are basically no obstacles to supplying the energy needs of the country from 100% renewable energy resources, despite the fact that the stability and security of the current system would be fully covered by the change. In the future, most energy production would be achieved using the most affordable technologies, i.e., devices using wind and solar energy. The electricity produced here would be transferred to Australian industry, to transport, cities, and it even would be exported. Wind and solar power plants would be scattered throughout the country, and according to their plans, these devices would share the energy they produce with each other. The Australians would plan the energy use of the future to be much more dynamic and efficient: during sunshine and wind, specially developed software would send a signal to the energy users to switch on the batteries and charge them, then when the wind becomes weaker, the software would also signal the batteries, to switch off. In the Australian plans, even isolated urban and agricultural areas will be able to supply themselves with energy for at least 6–12 h without any help. This will result in stronger resistance and a more reliable energy supply system for them [59].

According to the Powering Australia Plan, the government will raise the share of low-cost renewables to 82% by 2030 in the National Electricity Market. Powering Australia is the cornerstone for intuiting Australia as a renewable energy superpower. The plan includes up to 3 billion AUD to invest in renewable metals, renewable energy section manufacturing, renewable hydrogen electrolysers, 85 solar banks, and 400 community batteries across Australia and to attain new zero emissions by 2030. The fast price decrease in the solar and renewable energy means that Australia can comfortably reach a 50% mitigation in emissions by 2030 [60].

During the selection of a treatment plan for a municipal WWTP, GHG emissions, land consumption, and energy consumption play a significant part during the selection process [61]. To reach a sustainable and cleaner operation, we should concentrate on social and environmental conditions since these criteria may have a significant and positive effect on the technology [51].

The legal and political study indicates that solar energy and wind energy offshore are most intense, followed by wind energy onshore, heat and power, and, eventually, electricity high voltage and nuclear energy. The social review demonstrated the highest value of wind energy offshore and onshore, followed by solar energy, with the lowest score in the electricity high voltage. According to the environmental and economic reviews among all the schemes, wind energy offshore and onshore and solar energy were the ones with the highest values.

Figure 16 shows our TOPSIS analysis with the values in the range of 0.116–0.947, as the higher values correspond to the wind energy offshore and solar energy, indicating them as the best options with the TOPSIS score of 0.947 and 0.866. The results of our analysis and the actual facts are equivalent, as solar energy production in Australia has begun to expand rapidly, and most of the future energy production would be achieved using devices with wind and solar energy.

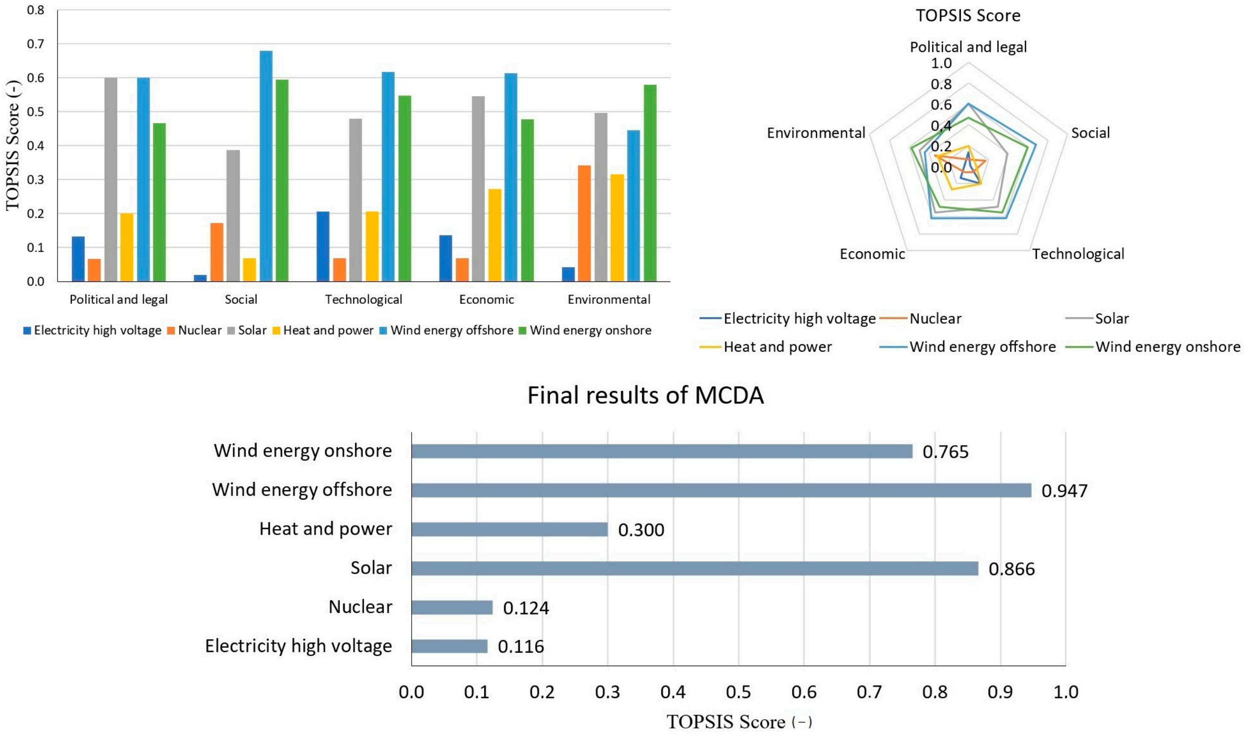

Figure 16. Findings of MCDA for PESTLE factors using TOPSIS methodology, TOPSIS score: the higher the preferable.

This study found a context to classify the best energy resource for nitrogen recovery from wastewater by regarding the parameters of the wastewater, the energy demand, and the flow rate. This study used the MCDA framework regarding economic, social, technical, and environmental perspectives of the process and utilised fuzzy TOPSIS to regard the uncertainty of criteria weighting values of the process [53].

Further research could focus on different aspects, like using solar and/or wind energy, for example, wind–solar hybrid power as well, for wastewater technologies and apply and develop hybrid models to investigate the impacts of renewable resources. For example, wastewater treatment with solar energy decreases the emission of GHG, and the solar thermal electrochemical method and the photocatalysis can entirely degrade contamination with solar power [62]. Also, there is a need to work on economic studies that consider which solar energy-based technology is more cost-effective [63]. It would also be useful to find out which MCDA method is the best fit for the kind of study case. As for our study, TOPSIS can be the better option with its different criteria and score system.

4. Conclusions

Life Cycle Analysis (LCA) can play an important role by evaluating the environmental sustainability of new techniques and procedures, like nitrogen recovery processes from wastewater. The environmental effects of combining electroconcentration and stripping methods were examined with LCA, including Monte Carlo simulation, PESTLE, and Multi-Criteria Decision Analysis (MCDA). Five indicator methods (climate change, global warming, acidification, eutrophication freshwater, human toxicity) were used with six different energy sources in our study. In wastewater treatment, the energy-consumption costs are one of the significant costs and life cycle analysis is useful to calculate the process with different energy resources.

As for MCS, the total replicated number of runs were ten thousand, and the confidence interval was 95%. CV (coefficient of variation), SEM (standard error of mean), SD (standard deviation), and median and mean values at 2.5% and 97.5% probability levels were also calculated. When the CV results are below 30%, this means the model has great expectation results and is sufficient for engineering utilizations. In our calculations, the electricity high voltage energy resource and the factor of climate change (CV = 22.4%) and acidification (2.95%) have achieved such results, as well as heat and power with climate change (2.36%) and acidification (4.73%).

In the case of MCDA, the TOPSIS score was applied to estimate the alternatives, and the most appropriate wastewater treatment was selected, using six various energy process options. Analysed global warming and climate change showed that the electricity high voltage has the most dominant values; it is 7–179 times higher than the other resources. The dominant electricity high voltage values appear during the examination of human toxicity. Also, it is 2–106 times higher than other resources. Ultimately, the acidification electricity high voltage values are 0.9–132 times higher than the other values. Our TOPSIS analysis had the values in the range of 0.116–0.947, as the higher values correspond to the wind energy offshore and solar energy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15183231/s1, Figure S1: Monte Carlo analysis of EF 3.0 Method (Adapted) using electricity high voltage in the case of human toxicity non-cancer effect, Figure S2: Monte Carlo analysis of EF 3.0 Method (Adapted) using heat and power in the case of human toxicity non-cancer effect, Figure S3: Monte Carlo analysis of EF 3.0 Method (Adapted) using nuclear energy in the case of climate change effect, Figure S4: Monte Carlo analysis of EF 3.0 Method (Adapted) using nuclear energy in the case of acidification effect, Figure S5: Monte Carlo analysis of EF 3.0 Method (Adapted) using nuclear energy in the case of eutrophication freshwater effect, Figure S6: Monte Carlo analysis of EF 3.0 Method (Adapted) using nuclear energy in the case of human toxicity cancer effect, Figure S7: Monte Carlo analysis of EF 3.0 Method (Adapted) using nuclear energy in the case of human toxicity non-cancer effect, Figure S8: Monte Carlo analysis of EF 3.0 Method (Adapted) using solar energy in the case of climate change effect, Figure S9: Monte Carlo analysis of EF 3.0 Method (Adapted) using solar energy in the case of acidification effect, Figure S10: Monte Carlo analysis of EF 3.0 Method (Adapted) using solar energy in the case of eutrophication freshwater effect, Figure S11: Monte Carlo analysis of EF 3.0 Method (Adapted) using solar energy in the case of human toxicity cancer effect, Figure S12: Monte Carlo analysis of EF 3.0 Method (Adapted) using solar energy in the case of human toxicity non-cancer effect, Figure S13: Monte Carlo analysis of EF 3.0 Method (Adapted) using wind energy offshore in the case of climate change effect, Figure S14: Monte Carlo analysis of EF 3.0 Method (Adapted) using wind energy offshore in the case of acidification effect, Figure S15: Monte Carlo analysis of EF 3.0 Method (Adapted) using wind energy offshore in the case of freshwater eutrophication effect, Figure S16: Monte Carlo analysis of EF 3.0 Method (Adapted) using wind energy offshore in the case of human toxicity cancer effect, Figure S17: Monte Carlo analysis of EF 3.0 Method (Adapted) using wind energy offshore in the case of human toxicity non-cancer effect, Figure S18: Monte Carlo analysis of EF 3.0 Method (Adapted) using wind energy onshore in the case of climate change effect, Figure S19: Monte Carlo analysis of EF 3.0 Method (Adapted) using wind energy onshore in the case of acidification effect, Figure S20: Monte Carlo analysis of EF 3.0 Method (Adapted) using wind energy onshore in the case of eutrophication freshwater effect, Figure S21: Monte Carlo analysis of EF 3.0 Method (Adapted) using wind energy onshore in the case of human toxicity cancer effect, Figure S22: Monte Carlo analysis of EF 3.0 Method (Adapted) using wind energy onshore in the case of human toxicity non-cancer effect.

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Abbreviations

AEMO	Australian Energy Market Operator
AEM	Anion Exchange Membrane
CEM	Cation Exchange Membrane
DALY	Disability Adjusted Life Year
Decerns	Decision Evaluation in Complex Risk Network System
EF	Environmental Footprint Method
GHG	Greenhouse Gases
Global	GLO
LCA	Life Cycle Analysis
MCDA	Multi-Criteria Decision Analysis
MCS	Monte Carlo Simulation
PAF	Potentially Affected Fraction
PESTLE	Political, Economic, Social, Technological, Legal, and Environmental Analysis
RoW	Rest of the World
SD	Standard deviation
SEM	Standard Error of the Mean
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
WWTP	Wastewater Treatment Plant

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