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Life Cycle Environmental Impacts of Wind Turbines: A Path to Sustainability with Challenges

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Abstract: This study aims to evaluate in detail the environmental impacts of the turbines used for electricity generation by wind energy, from a life cycle perspective. For this purpose, a comprehensive literature review is conducted and the life cycle environmental impacts of two sizes of wind turbines, namely 3.6 and 4.8 MW, in Turkey are analyzed. Sustainability studies, especially life cycle assessment (LCA) findings, yield healthy results only if the data used are site-specific. The system has been modeled using GaBi software and the Ecoinvent database. The functional unit is defined as 1 kWh of generated electricity. The impacts have been estimated using the CML 2 Baseline 2001 method. The 4.8 MW turbine has lower environmental impacts than the other turbine. The construction of wind turbines has the greatest share of the environmental impacts of all the options considered. Recycling materials at the end of plant life can reduce unwanted environmental impacts by up to 49%. Similar studies based on site-specific data will help to inform electricity producers and policymakers about wind energy's current impacts and environmental hotspots. Conducting analogous studies is critical to reducing the environmental impacts of wind energy, which will play an important part in the future of the energy sector.

Keywords: environmental impact; life cycle assessment; renewable energy; sustainability; wind turbine; climate change

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1. Introduction

Energy is a critical component for improving societal well-being because it is a basic component of all products and is used in almost every aspect of life. Rapid increases in energy demand are being driven by a variety of factors, including global population growth, urbanization, industrialization, and technological advances [1]. Global demand for primary energy increased by 31 EJ in 2021, the largest increase in history, more than reversing the sharp decline seen in 2020. Primary energy consumption in 2021 increased by 8 EJ from 2019. The primary energy consumption of emerging economies has grown by 15 EJ since 2019, with China accounting for the majority of this growth at 13 EJ [2]. Meeting the rising energy demand presents a significant challenge for global policymakers, businesses, and societies.

A wide range of technologies are available or in development to provide affordable, dependable, and long-term renewable energy sources [3]. Between 2019 and 2021, renewable energy sources accounted for all of the primary energy increases. In this period, the total amount of energy consumed—coal, oil, and natural gas—remained constant [2]. The growing population, fast urbanization and industrialization, the finite nature of energy resources, and the potential environmental risks associated with fossil fuel production are all contributing factors to the growing interest in renewable energy sources [4]. In 2021, the amount of renewable primary energy (which includes biofuels but excludes hydro) grew by about 5.1 EJ, or an annual growth rate of 15%, which was higher than the 9% growth rate in the year prior and more than any other fuel in 2021. In 2021, there was a sharp increase in solar and wind capacity of 226 GW, almost matching the record increase of 236 GW observed in 2020 [2]. China dominated the global markets for concentrating solar thermal power, hydropower, solar PV, and wind power, accounting for nearly half of all installations in recent years [5].

One of the most significant global issues that needs to be resolved in the modern world is the supply of sustainable energy. Climate change, pollution, and energy poverty are among the sustainability impacts of energy production and consumption. The combustion of fossil fuels emits large amounts of greenhouse gases, as well as other harmful gases and solids, into the atmosphere, resulting in climate change, acid rain, and soil and water pollution [6]. In 2022, the world's energy-related CO_2 emissions increased by 0.9%, or 321 Mt, and hit a record high of over 36.8 Gt [7]. The fastest growing energy source globally, renewable energy is crucial to achieving net zero emissions worldwide. Using renewable energy sources to generate electricity instead of fossil fuels reduces energy-related emissions. The technologies and low-carbon energy sources (biofuels, wind, solar, geothermal, hydropower, and carbon capture) required to accomplish rapid and deep decarbonization are currently accessible.

Current trends in the energy sector emphasize the importance of obtaining energy from renewable sources, rather than non-renewable ones. Among renewable energy sources, wind farms yield substantial reductions in unwanted environmental impacts, ranging from global warming and acidification potential to human toxicity [8–11]. Mainly due to these environmental benefits, the number of wind installations has substantially increased, especially over the last decade on a global basis.

Wind power generation is recognized as a critical technology for energy security, climate change mitigation, and other environmental impacts. Among other things, the strong growth in today's markets and the prospects for exploiting resource potential contribute to the expectation that wind energy will play an important role in facilitating the transition from fossil-based power generation to renewable energy in the coming decades [12].

Wind is a renewable and sustainable source of energy that has been utilized for centuries, with modern wind turbines being more efficient and reliable than previously. Wind turbines can transform wind energy into electrical or mechanical power. To harness the power of the wind, wind turbines typically consist of blades mounted on shafts and towers. Wind drives the rotor blades on modern wind turbines, which transform kinetic energy into mechanical energy. A shaft carries this mechanical energy to a generator, where it is converted into electrical energy [13].

Wind turbines are promising sources of renewable energy. Since 2000, the use of wind power as a clean, renewable energy source has grown significantly as a result of research and development, supportive legislation, and improvements in efficiency, dependability, and cost [5]. Figure 1 presents the global cumulative installed wind power capacity from 2001 to 2023. In 2023, the global installed wind power capacity was estimated to be around 1021 gigawatts [14]. Wind power generation reached over 2302 TWh in 2023 [15]. After solar photovoltaics, this was the renewable power technology with the second-highest growth [13].

In Turkey, wind power plants generated 34,945 GWh of energy in 2022, accounting for nearly 11% of the country's electricity generation [16].

Although wind energy is among the fastest growing renewable energy sources, it is also known that unwanted environmental effects are generated during the installation, operation, and end-of-life stages of wind farms. One should keep in mind that, apart from the environmental impacts, there are social concerns related to the development of the wind energy sector, as indicated by Chomać-Pierzecka [17]. The social impacts of adopting sustainable energy sources, such as quality of life, employment opportunities, accessibility of energy, etc., have been addressed for especially socio-economically disadvantaged societies [18]. The relationship between public acceptance and the development of power systems for wind energy has been investigated [19]. The impact of green finance on wind power development is also stated in the literature [20]. Nevertheless, this study concentrates on the environmental impacts of wind energy. Therefore, by developing strategies to reduce the undesirable environmental impacts caused by wind turbines at their various life stages, it is of importance as well. For this purpose, life cycle sustainability evaluations can be used. The most prominent and critical issue in such evaluations is running a sustainability study on case-specific data, as each case has its own limitations, geographical considerations, etc. In other words, feeding site-specific data will lead to a case-specific appraisal, which is a prerequisite for deriving robust outcomes. This fact is emphasized by [21] in a general sense, especially for countries that have not adopted the life cycle mindset from a sustainability perspective.

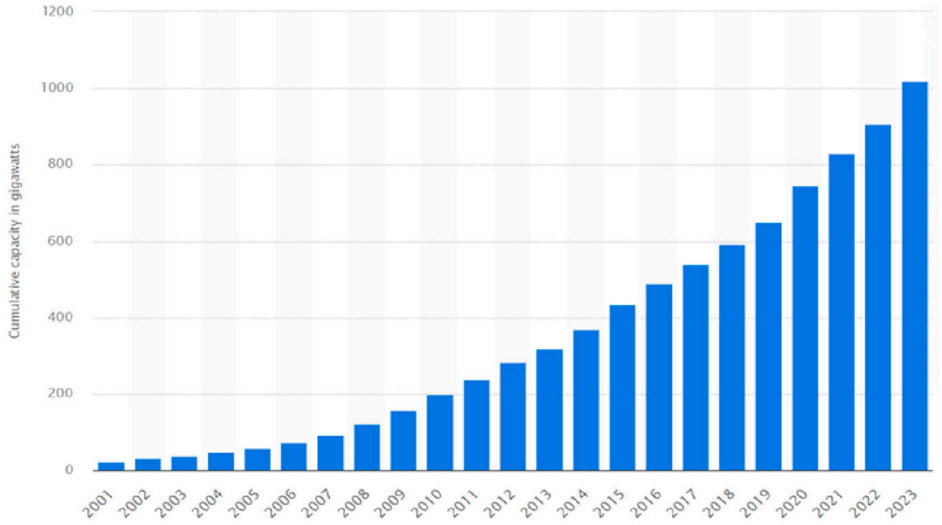

Figure 1. Cumulative installed wind power capacity worldwide from 2001 to 2023 [14].

In this context, the objective of this study is to display the environmental impacts of wind turbines in detail within a life cycle perspective by presenting a comprehensive literature review and analyzing a case study from Turkey. The importance of the quantification of sustainability and case-specific sustainability appraisal are emphasized in this study. Instead of directly transferring the sustainability results obtained from other geographical locations, the significance of case-specific evaluations dealing with various recycling alternatives during decommissioning, the input of energy from different sources, and usage of various materials for construction, etc., are underlined. Running similar studies will make decision-making easier, as addressing the specific hotspots in the life cycle of wind turbines will reduce the efforts required to deal with unwanted environmental impacts.

This study is critical to the future of the renewable energy sector. The LCA methodology is described in detail in this study, and the environmental sustainability of electrical energy from two different turbine sizes, which are expected to be widely used in the future, is examined in conjunction with an extensive literature review on the life cycle environmental impacts of wind energy.

2. Wind Energy and Life Cycle Sustainability

It is a known fact that quantifying sustainability in an objective and robust manner is of importance. With growing environmental awareness, renewable energy sources have gained importance as energy sources. Assessing an energy system's direct environmental effects, however, does not solve the issue. The environmental effects of renewable energy sources, such as wind energy, can differ greatly based on several variables, such as the materials used, transportation, plant capacity, and maintenance needs [22]. Because of this, evaluating environmental sustainability should be conducted by using a life cycle approach. Life cycle assessment (LCA) is an environmental management tool based on this approach. The LCA method investigates the potential impacts on the environment of a product, process, or service, from raw material extraction to production, transportation, use, and waste management [23]. LCA evaluates the impact on the environment of all relevant inputs (raw materials, water, energy, and land use), as well as emissions into the air, water, and land. ISO 14040 [24] describes the “principles and framework for LCA”, whereas ISO 14044 [25] “specifies requirements and provides guidelines” for LCA.

Wind energy has emerged as one of the world’s most important renewable energy sources due to its rapid growth, significant contribution to electricity generation, and potential for future expansion [26]. Although their operational phase has resulted in a reduction of greenhouse gas emissions, it is imperative to evaluate the environmental impact of their manufacturing and installation processes in order to determine their overall sustainability. Some studies in the literature have been conducted by using the LCA method to assess the environmental impacts of producing electricity using wind energy. This section of the paper examines studies that use the life cycle analysis method to evaluate onshore wind energy systems’ environmental effects.

When the literature review is considered as a whole, it becomes clear that there are LCA studies on the life cycle sustainability of wind turbines in the literature. Figure 2 compares energy life cycle analysis studies and wind life cycle analysis studies in the literature by year. Figure 3 presents the current state of LCA for wind energy studies in the literature.

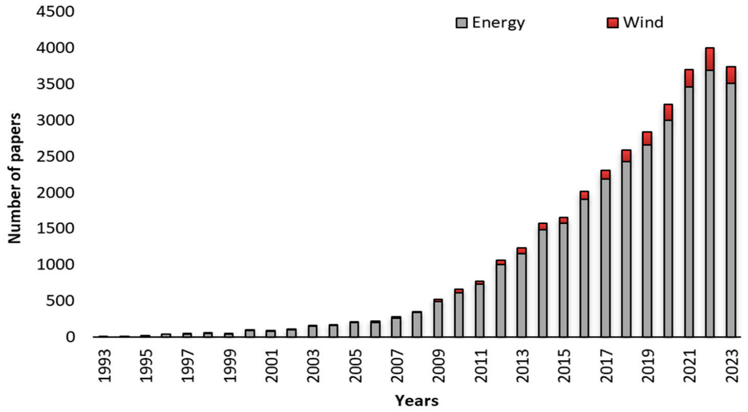

Figure 2. Comparison of the publications in the WoS database (Keywords: energy and life cycle assessment; wind and life cycle assessment).

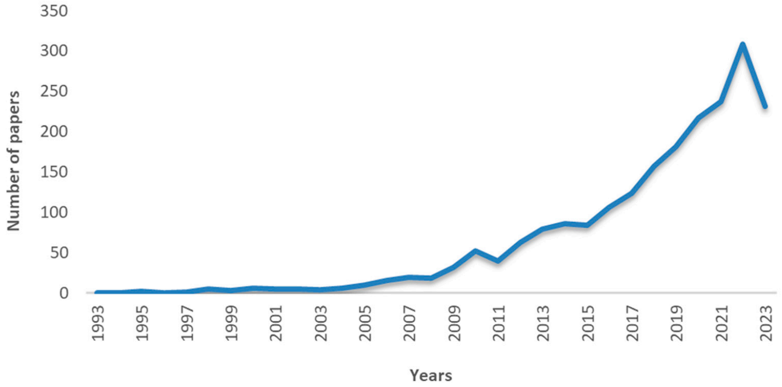

Figure 3. Results of searching for publications in the WoS database (Keywords: wind and life cycle assessment).

In a thorough literature search of the Web of Science database, the number of scientific articles discovered with the keywords (wind energy and life cycle assessment) were examined and the results revealed that there has been a significant increase in the number of studies prepared in this field. The decrease in 2023 was caused by articles that were still in the publication process. In the first month of 2024, 14 articles containing these keywords were published.

Selected LCA studies related to wind energy are tabulated in Table 1. This table presents the locations of the wind turbines, types and sizes, functional units adopted, and environmental impact categories investigated.

Table 1. Selected LCA studies related to wind energy supply.

Study	Location	Turbine Type	Turbine Size	Aim	Scope	Functional Unit	Impact Categories
Lenzen and Wachsmann [27]	Germany, Brazil	Onshore	0.5 and 0.6 MW	Provide an example of geographical variability, examine the energy and CO_2 embodied in a wind turbine	Cradle to gate	1 kWh	Cumulative energy demand, CO_2 emission
White [28]	US	Onshore	0.345, 0.75 and 0.60 MW	Update to a life cycle net energy and CO_2 emissions of three different wind systems	Cradle to grave	1 GWh	Net energy, payback time, CO_2 emissions
Peacock, Jenkins [29]	UK	Onshore	0.4, 0.6, 1.5 and 2.5 kW	Assess the economic and carbon performance of microturbines	-	-	Net savings (energy cost), simple payback, discounted payback, emissions savings, emission savings to investment ratio
Ardente, Beccali [30]	Italy	Onshore	660 kW	Analyse the environmental and energy effects of wind electricity	Cradle to grave	1 kWh	Wastes, air and water emissions, payback indexes, energy and CO_2 intensity
Tremeac and Meunier [31]	France	Onshore	250 kW and 4.5 MW	Compare life cycle impacts for a high-power turbine and a small one	Cradle to grave	1 kWh	Cumulative energy demand, solid waste, air and water emissions
Fleck and Huot [32]	Canada	Onshore	400 W	Compare the environmental and economic effects of small wind turbines and diesel generator systems	Cradle to grave	162.5 kWh electricity/month	Payback period, intensity index, embedded energy, annual energy production, greenhouse gas emissions
Kabir, Rooke [33]	Canada	Onshore	5, 20 and 100 kW	Compare three wind turbine configurations that produce a nameplate power of 100 kW	Cradle to grave	1 kWh	Global warming, acidification, ozone depletion, price of electricity, simple payback, simple payback period under current electricity price in Alberta within turbine lifetime
Garrett and Rønde [34]	-	Onshore	2 MW	Examine potential environmental impacts and other non-impact indicators	Cradle to grave	1 kWh	Abiotic depletion potential—elements, abiotic depletion potential—fossil, acidification, eutrophication, freshwater aquatic ecotoxicity, global warming, human toxicity, marine aquatic ecotoxicity, photochemical oxidant creation, terrestrial ecotoxicity

Table 1. *Cont.*

Study	Location	Turbine Type	Turbine Size	Aim	Scope	Functional Unit	Impact Categories
Greening and Azapagic [35]	UK	Onshore	6 kW	Compare the environmental sustainability of micro-wind turbines to grid electricity and solar PV	Cradle to grave	1 kWh	Global warming, abiotic depletion (elements, fossil), acidification, eutrophication, human toxicity, ozone layer depletion, terrestrial eco-toxicity, freshwater aquatic eco-toxicity, marine aquatic eco-toxicity, photochemical ozone creation
Rashedi, Sridhar [36]	-	Onshore and offshore	5 MW	Assess the impacts of three 50 MW wind farms with vertical axis turbine	Cradle to grave	1 kWh	Carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer depletion, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels
Oebels and Pacca [37]	Brazil	Onshore	1.5 MW	Identify and demonstrate sources of CO_2 emissions	Cradle to grave	1 kWh	CO_2 emissions
Demir and Taşkın [38]	Turkey	Onshore	330, 500 810, 2050 and 3020 kW	Evaluate and compare environmental impacts of five different rated power wind turbines	Cradle to grave	1 kWh	Acidification, eutrophication, global warming, freshwater aquatic ecotoxicity, human toxicity, photochemical ozone creation, terrestrial ecotoxicity
Uddin and Kumar [39]	Thailand	Onshore	300 and 500 W	Assess the impacts of grid-connected 300 W vertical axis and 500 W horizontal axis turbines	Cradle to grave	1 kWh	Global warming, acidification, and eutrophication
Glassbrook, Carr [40]	Thailand	Onshore	400 W, 2.5 kW, 5 kW and 20 kW	Calculate global warming impacts and embodied energy of four small wind turbines	Cradle to grave	50 kWh of electricity per month for 20 years	Annual energy production, embedded energy, payback period, annual energy production
Haapala and Prempreeda [41]	USA	Onshore	2.0 MW	Compare the environmental effects of two wind turbine designs over their life cycles.	Cradle to grave	2.0 MW wind turbine	Fossil-water-metal depletion, natural-urban-agricultural land occupation, marine-freshwater-terrestrial ecotoxicity, terrestrial acidification, climate change-ecosystems, ionising radiation, freshwater eutrophication, particulate matter formation, photochemical oxidant formation, human toxicity, ozone depletion, climate change-human health

Table 1. *Cont.*

Study	Location	Turbine Type	Turbine Size	Aim	Scope	Functional Unit	Impact Categories
Vargas, Zenón [42]	Mexico	Onshore	2.0 MW	Compare the environmental impacts of different materials and electricity used in the manufacture of components of two wind turbines	Cradle to grave	1 kWh	Global warming, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, abiotic depletion, photochemical ozone creation, acidification, eutrophication
Atilgan and Azapagic [43]	Turkey	Onshore	2.0 MW	Estimate environmental impacts of electricity generation from wind, hydro, and geothermal energy	Cradle to grave	1 kWh	Global warming, abiotic depletion (elements, fossil), acidification, eutrophication, human toxicity, ozone layer depletion, terrestrial eco-toxicity, freshwater aquatic eco-toxicity, marine aquatic eco-toxicity, photochemical ozone creation
Wang and Teah [44]	Taiwan	Onshore	600 W	Assess the environmental impacts of wind turbine	Cradle to grave	-	Energy consumption, global warming, energy, and greenhouse gases payback time
Xu, Pang [45]	China	Onshore	1.5 and 0.75 MW	Evaluate environmental impacts of wind power plant	Cradle to grave	1 kWh	Global warming, abiotic depletion (elements, fossil), acidification, eutrophication, human toxicity, ozone layer depletion, terrestrial eco-toxicity, freshwater aquatic eco-toxicity, marine aquatic eco-toxicity, photochemical ozone creation
Ozoemena, Cheung [46]	Wales	Onshore	1.5 MW	Assess the environmental impacts of a 114-MW onshore wind farm comprised of design variants for a 1.5-MW wind turbine	Cradle to grave	1 kWh	Global warming, abiotic depletion (elements, fossil), acidification, eutrophication, human toxicity, ozone layer depletion, terrestrial eco-toxicity, freshwater aquatic eco-toxicity, marine aquatic eco-toxicity, photochemical ozone creation
Jiang, Xiang [47]	China	Onshore	2.0 MW wind turbine gearbox	Analyse the life cycle environmental impact of wind turbine gearbox	Cradle to grave	Gearbox service life 20 years, transmission efficiency 96%	Global warming, acidification, photochemical ozone formation, eutrophication, environmental impact load

Table 1. *Cont.*

Study	Location	Turbine Type	Turbine Size	Aim	Scope	Functional Unit	Impact Categories
Schreiber, Marx [48]	Germany	Onshore	3.0 MW	Compare environmental impacts of the geared converter with a doubly-fed induction generator, direct driven synchronous generator, direct-drive permanent magnet synchronous generator	Cradle to grave	1 kWh	Acidification, climate change, ecotoxicity freshwater, eutrophication freshwater, eutrophication marine, eutrophication terrestrial, human toxicity, ionizing radiation, land use, ozone depletion, particulate matter/respiratory inorganics, photochemical ozone formation, resource depletion (mineral, fossils and renewables)
Alsaleh and Sattler [49]	United States	Onshore	2.0 MW	Assess the environmental impacts of large wind turbines	Cradle to grave	1 kWh	Global warming, depletion of ozone, tropospheric ozone formation, acidification, eutrophication, ecotoxicity, human health carcinogens, non-carcinogens, respiratory effects resource depletion, fossil fuel depletion, water depletion index, cumulative energy demand
Troullaki, Latoufis [50]	Greece	Onshore	900 W	Examine the environmental effects of wind turbines and off-grid pico hydroplants	Cradle to grave	1 kWh	Non-renewable primary energy, global warming, eutrophication; acidification and abiotic depletion
Stavridou, Koltsakis [51]	UK	Onshore	2.0 MW	Compare environmental impacts of tubular and lattice wind turbine towers	Cradle to grave	20 years	CO_2 emissions, cumulative energy demand, energy payback time
Teffera, Assefa [52]	Ethiopia	Onshore	Four turbines: between 1 and 1.67 MW	Estimate environmental impacts of currently operational wind farms	Cradle to grave	1 kWh	Climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, metal depletion, marine ecotoxicity, particulate matter formation, photochemical oxidant formation, terrestrial acidification
Nagle, Delaney [53]	Ireland	Onshore	850 kW	Determine the most sustainable disposal method for Irish blade waste	Gate to grave	Disposal of 5.7 tonnes of blade waste	Human health, ecosystem quality, climate change, resources

Table 1. *Cont.*

Study	Location	Turbine Type	Turbine Size	Aim	Scope	Functional Unit	Impact Categories
Kouloumpis, Sobolewski [54]	Poland	Vertical axis onshore	5.0 kW	Investigate the impacts of electricity generated from small-scale vertical axis wind turbines (VAWT)	Cradle to grave	1 kWh	Depletion of abiotic resources non-fossil, depletion of abiotic resources fossil, acidification, eutrophication, freshwater ecotoxicity, global warming, human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical ozone creation, and terrestrial ecotoxicity
Doerffer, Bałdowska-Witos [55]	Poland	Onshore	15 kW	Assess the impacts of production and use of a special drag force-driven wind turbine	Cradle to gate	Productivity of wind plant at the stage of its production	Carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels
Li, Duan [56]	China	Onshore	2.0 MW	Evaluate the environmental impacts and economic benefits of wind power	Cradle to grave	1 kWh	Greenhouse gas emissions
Vélez-Henao and Vivanco [57]	Colombia	Onshore	19.5 MW wind farm	Quantify the environmental performance of an operating wind farm with a focus on the role of services	Cradle to grave	1 kWh	Freshwater and terrestrial acidification, climate change, carcinogenic effects, ecotoxicity, marine eutrophication, non-carcinogenic effects, ozone layer depletion, photochemical ozone creation, respiratory effects, inorganics, and terrestrial eutrophication
Yildiz, Hemida [58]	-	Offshore	2.0 MW barge-type floating wind tower	Analysis of environmental impacts of the barge-type floating wind turbine	Cradle to grave	1 kWh	Global warming, acidification, and energy payback time
Verma, Paul [59]	India	Onshore	1.65 MW	Examine the environmental impacts of wind energy	Cradle to grave	1 MWh	Global warming potential, acidification potential, photochemical oxidant potential, and particulate matter formation
Nagle, Mullally [60]	Ireland	Onshore	-	Assess differences by replacing construction material with discarded turbine blades	Gate to grave	Utilization for 60 years of 30 × 22 m blades	Human health, ecosystem quality, climate change, resource depletion

Table 1. *Cont.*

Study	Location	Turbine Type	Turbine Size	Aim	Scope	Functional Unit	Impact Categories
Das and Nandi [61]	India	Onshore	1.65 MW	Compare the environmental impact of various types of generators used in wind turbines and their relationship with wind speed	Cradle to grave	1 MWh	Climate change, acidification potential, human toxicity, abiotic resources depletion, eutrophication potential, photochemical oxidation
Garcia-Teruel, Rinaldi [62]	Scotland	Offshore	6.0 and 9.5 MW	Evaluate the environmental impacts of a floating offshore wind farm	Cradle to grave	1 kWh	Fine particulate matter formation, fossil resource scarcity, freshwater ecotoxicity, freshwater eutrophication, global warming, human carcinogenic toxicity, human non-carcinogenic toxicity, ionising radiation, land use, marine ecotoxicity, marine eutrophication, mineral resource scarcity, ozone formation-human health, ozone formation-terrestrial ecosystems, stratospheric ozone depletion, terrestrial acidification, terrestrial ecotoxicity, water consumption, cumulative energy demand
Ozsahin, Elginoz [63]	Turkey	Onshore	2.5 MW	Investigate the environmental impacts of a full-scale wind farm	Cradle to grave	1 kWh	Global warming, abiotic depletion (elements, fossil), acidification, eutrophication, human toxicity, ozone layer depletion, terrestrial eco-toxicity, freshwater aquatic eco-toxicity, marine aquatic eco-toxicity, photochemical ozone creation
Feng and Zhang [64]	China	Onshore and offshore	1.5, 2.0, 2.5, more than 3.0 MW	Compare 60 wind plant systems' GHG intensities	Cradle to grave	1 kWh	Greenhouse gases
Cong, Song [65]	China	Onshore	49.5 MW wind farm	Identify the main emission process of different end-of-life blade disposal scenarios	Grave to cradle	Weight of a single blade	Carbon reduction

Table 1. *Cont.*

Study	Location	Turbine Type	Turbine Size	Aim	Scope	Functional Unit	Impact Categories
Elmariami, El-Osta [66]	Libya	Onshore	2.0 MW	Analyse the life cycle effects on the environment of producing electricity from a 20 MW onshore wind farm	Cradle to grave	1 kWh	Energy consumption and air emissions
Gennitsaris, Sagani [67]	Greece	Onshore	Vestas 52 wind turbines	Evaluate impacts of different end-of-life material management for decommissioning	Gate to grave	Turbine (rotor diameter of 52 m and a hub height of 50 m)	Climate change, land occupation, fossil and nuclear energy
Zajicek, Drapalik [68]	Austria	Onshore	0.4 and 5.0 kW	Assess the environmental impacts of wind turbines in rural and suburban areas	Cradle to grave	1 kWh	Freshwater ecotoxicity, human carcinogenic toxicity, global warming potential, land use, total and non-renewable energy demand, nominal capacity, annual production, energy payback time
Brussa, Grosso [69]	Italy	Offshore	14.7 MW	Analyse the environmental performance of a floating offshore wind farm	Cradle to grave	Delivery of 1 GWh of electricity to the onshore grid	Acidification, eutrophication, global warming, photochemical oxidant formation, abiotic depletion of elements and fossils, water scarcity, ozone layer depletion, and cumulative energy demand
Chen, Mao [70]	China	Offshore	Eight turbines (5.0–6.7 MW)	Examine the effects that various materials have on the environment in order to support offshore wind power's green design.	Cradle to grave	1 kWh	Global warming, abiotic depletion (elements, fossil), acidification, eutrophication, human toxicity, ozone layer depletion, terrestrial eco-toxicity, freshwater aquatic eco-toxicity, marine aquatic eco-toxicity, photochemical ozone creation
Cao, Meng [71]	China	Offshore	5.0 MW	Evaluate the LCA effects of large-scale offshore wind farms	Cradle to grave	1 kWh	Acidification, climate change, ecotoxicity, energy resources, eutrophication, human toxicity, material resources, ozone depletion, particulate matter, disease incidence, water use

Table 1. *Cont.*

Study	Location	Turbine Type	Turbine Size	Aim	Scope	Functional Unit	Impact Categories
Juhl, Hauschild [72]	Denmark	Offshore	-	Assess the life cycle sustainability performance of wind turbine coating	Cradle to grave	1 m^2 turbine tower coated	Global warming, stratospheric ozone depletion, fossil resource scarcity, mineral resource scarcity, terrestrial acidification, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, ozone formation, human health, ozone formation, terrestrial ecosystems, fine particulate matter formation, ionizing radiation, water consumption
Nassar, El-Khozondar [73]	Libya	Onshore	100 MW capacity wind farms at 12 sites	Examine various energy, economic, and environmental indicators for potential wind farm installations in a variety of locations	Cradle to grave	1 kWh	Total energy consumption, GHG emissions, carbon payback time, energy payback time, energy payback ratio, energy intensity, capital cost, annual productivity, levelized cost
Henao, Grubert [74]	USA	-	-	Evaluate the financial and environmental effects of using wind turbine blades as the main load-bearing components of high-voltage transmission line structures at every stage of the process	Gate to end-of-life	60-year life span, 30 m transmission pole	Global warming, eutrophication, acidification, particulate matter formation, fossil fuel depletion, respiratory effects, cost

As evident from Table 1, both onshore and offshore turbines with sizes ranging from big to small and micro turbines are covered. Although different scopes are identified for the studies, the majority are from cradle to grave.

There are LCA studies dealing with various components of wind turbines as well. Jiang and Xiang [47] investigated the environmental burdens of the gearbox by adopting the LCA methodology. The results show that the main source of impacts is the manufacturing phase. Reusing components at the decommissioning stage is devoted to lowering the impacts by 10%.

Similar to all other energy sources, wind farms have a limited lifetime. The turbines reaching their end-of-life stage should be handled in a proper way to lower their unwanted environmental impacts. There are studies in the literature related to this issue. In the study performed by Nagle and Delaney [53], composite wind turbine blade wastes generated from the decommissioning stage of a wind farm were investigated in terms of alternative scenarios of co-processing in cement kilns and landfilling via LCA. Another study on Chinese wind turbine blades at the end-of-life stage with various disposal scenarios was performed Cong and Song [65].

The challenges associated with blade waste from on-shore wind farms were examined by Nagle and Delaney [53]. In the aforementioned study, repurposing blades into second-life structures was evaluated via LCA. Not clearly stating the assumptions, calculations, and conversions applied to LCA studies involving wind farms is quoted as a problematic issue by Davidsson and Höök [75]. The uncertainties related to the decommissioning stage of wind farms is emphasized by Mello et al. [72].

Arvesen and Hertwich [22] mentioned certain points to focus on for future perspectives on the LCA of wind energy as geographical areas other than Europe; large turbines; offshore technologies; construction and operation; and maintenance phases of the life cycle.

3. Case Study: Life Cycle Environmental Impacts of a Wind Turbine

The LCA methodology followed here is the ISO 14040/44 methodology [24,25]. Accordingly, iterative steps of goal and scope definition; inventory analysis; impact assessment; and interpretation are conducted [23,24]. The goal, boundaries, and functional unit of the study are all clearly defined in the goal and scope definition step of the process. This is followed by the life cycle inventory phase, which entails gathering data on all inputs (such as energy and raw materials) and outputs (such as emissions and waste) throughout the product's life cycle. In the life cycle impact assessment phase, these data are analyzed to determine their potential environmental impacts, which are classified and characterized into impact categories such as global warming potential and resource depletion. The final phase is interpretation, which involves analyzing the results to identify significant impacts, drawing conclusions, and making recommendations for reducing environmental burdens [76].

One of the primary benefits of LCA is its ability to provide a comprehensive perspective, identifying significant environmental hotspots and facilitating informed decision-making for sustainable product design, process optimization, and policy development. However, conducting an LCA is frequently data-intensive and resource-intensive, necessitating extensive data collection and technical expertise, which can be expensive and time-consuming [77].

The LCA modeling was carried out in GaBi Software version V10.8 [78] and the CML (Centre of Environmental Science at Leiden University) 2001 impact assessment method [79] was used to estimate the environmental impacts. GaBi is a widely used tool for conducting LCA. It offers comprehensive solutions for modeling, analyzing, and optimizing the environmental performance of products and processes. GaBi software provides significant benefits, including comprehensive and up-to-date databases, detailed modeling, and support for a variety of impact assessment methods. However, the use of the software can be resource-intensive, necessitating significant time and financial investment [80]. The CML method is a widely used LCA approach. This method distinguishes itself by focusing on midpoint indicators, which represent environmental impacts at an intermediate point in the cause–effect chain, rather than endpoint indicators, which reflect long-term effects on human health, ecosystem quality, and resource availability [81].

The following sections define the research's goal and scope, as well as its data and assumptions.

3.1. Goal and Scope

The main goal of the study is to determine the environmental impacts associated with 3.6 MW and 4.8 MW onshore wind turbines installed in Turkey. Another objective is to provide recommendations for future energy planning by comparing the environmental impacts of wind turbines of different sizes.

As shown in Figure 4, the scope of the study is from cradle to grave, and it includes the following stages:

- extraction and processing of raw materials;
- manufacture and installation of the turbine;
- operation and maintenance over the lifetime of the system;
- decommissioning of the turbine; and
- all transportation.

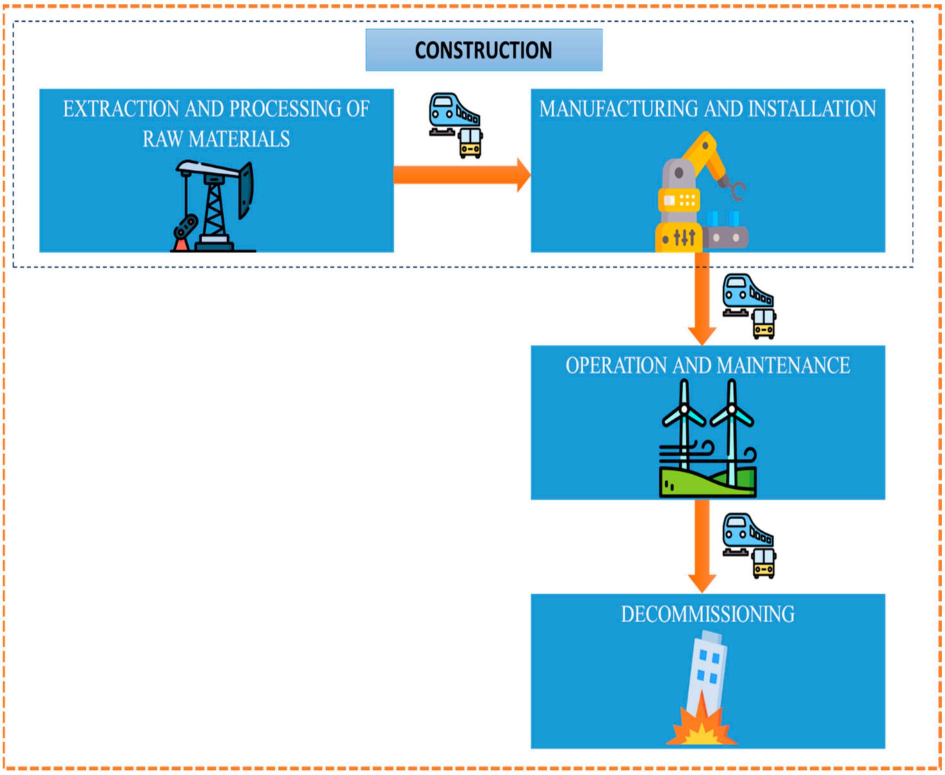

Figure 4. Wind turbine life cycle stages.

The functional unit is 1 kWh of electricity generated from selected onshore wind turbines.

3.2. Inventory Data

The data used in this analysis were obtained from a variety of sources and 2022 has been selected as the time reference. The wind turbine capacity factors used in the assessment are based on wind-installed capacity and wind-based electricity generation in Turkey in 2022 [16].

In this study, two different sizes of onshore wind turbines are modeled and their environmental effects are assessed. Table 2 presents the technical specifications of the

3.6 MW and 4.8 MW wind turbines selected for this study. The 3.6 MW onshore wind turbine is chosen as it is the average size of wind turbines in Turkey in 2022, while the 4.8 MW onshore wind turbine is selected considering it has recently become the most popular turbine size in the country. The inventory data for onshore wind turbines are taken from Atilgan and Azapagic [43].

Table 2. Technical specifications of the assessed wind power turbines.

Installed Capacity (MW)	Lifetime (Years)	Rotor Diameter (m)	Hub Height (m)
3.6	Fixed parts: 40 Moving parts: 20	131	site-specific
4.8	Fixed parts: 40 Moving parts: 20	133	site-specific

A summary of the data used in the study is given in Table 3. The primary data were gathered from government and industry reports, as well as the academic literature. The background life cycle inventory data were obtained from Ecoinvent but were modified for the model conditions.

Table 3. Assumptions and summary of inventory data (per kWh).

Life Cycle Stage	Turbine—3.6 MW	Turbine—4.8 MW
Construction (per kWh) Only included the main inputs	Moving Parts Epoxy resin 1.6×10^{-5} kg Aluminium 9.3×10^{-6} kg Cast iron 1.1×10^{-4} kg Chromium steel 7.1×10^{-5} kg Copper 1.6×10^{-5} kg Glass fibre 1.1×10^{-4} kg Lubricating oil 1.6×10^{-6} kg Polyethylene 4.2×10^{-6} kg Polypropylene 1.4×10^{-7} kg Polyvinylchloride 3.0×10^{-6} kg Steel 1.7×10^{-4} kg Synthetic rubber 1.5×10^{-6} kg Zinc 1.1×10^{-6} kg Electricity 9.4×10^{-4} MJ Fixed Parts Concrete 9.3×10^{-7} m^3 Electricity 2.3×10^{-7} MJ Diesel 2.6×10^{-4} MJ Epoxy resin 1.5×10^{-6} kg Reinforcing steel 7.2×10^{-5} kg	Moving Parts Epoxy resin 1.0×10^{-5} kg Aluminium 5.8×10^{-6} kg Cast iron 6.9×10^{-5} kg Chromium steel 4.4×10^{-5} kg Copper 1.0×10^{-5} kg Glass fibre 7.2×10^{-5} kg Lubricating oil 1.0×10^{-6} kg Polyethylene 2.6×10^{-6} kg Polypropylene 8.8×10^{-8} kg Polyvinylchloride 1.9×10^{-6} kg Steel 1.0×10^{-4} kg Synthetic rubber 9.3×10^{-7} kg Zinc 6.8×10^{-7} kg Electricity 5.9×10^{-4} MJ Fixed Parts Concrete 5.8×10^{-7} m^3 Electricity 1.5×10^{-7} MJ Diesel 1.6×10^{-4} MJ Epoxy resin 9.4×10^{-7} kg Reinforcing steel 4.5×10^{-5} kg
Transportation	Raw material Freight train 150 km Lorry 100 km Turbine Freight train 2500 km Lorry 150 km Maintenance Passenger car 100 person·km/year	Raw material Freight train 150 km Lorry 100 km Turbine Freight train 2500 km Lorry 150 km Maintenance Passenger car 100 person·km/year
Operation and Maintenance	Lubricating oil 30.2 mg	Lubricating oil 25.9 mg
Plant decommissioning The system has been credited for recycling	Metals and concrete: 50% recycled, 50% landfilled Plastics: 20% recycled, 80% landfilled	Metals and concrete: 50% recycled, 50% landfilled Plastics: 20% recycled, 80% landfilled

The construction stage includes the raw material extraction and processing of materials such as the concrete, aluminum, steel, and glass fiber required to manufacture the fixed (tower and basement) and moving parts (rotor, nacelle and hub, yaw, and mechanics), turbine manufacturing, all transportation, and installation. The transportation stage considers the transportation systems required to provide raw materials for the production of the various wind turbine components, the transportation of turbine components to the specific wind farm site, and transportation during operation. For fair comparisons, it is assumed that the turbines are manufactured in Germany and installed in Canakkale, Turkey. The operation stage is concerned with turbine maintenance, which includes oil changes, lubrication oil, and transportation of people during the maintenance. When the wind turbine is no longer in service, the decommissioning process begins. The current scenario involves recycling some components (see Table 3 for the details). The raw materials for turbine parts made in Germany are transported 100 km by road and 150 km by rail. The turbine is shipped to Turkey (2500 km by rail and 150 km by road), and 150 km of railroad and 100 km of road transportation are used to deliver the raw materials needed for the fixed part to the installation location.

3.3. Results

The following environmental impact categories based on CML methodology [79] are considered: abiotic depletion potential (ADP elements and fossil), acidification potential (AP), eutrophication potential (EP), fresh water aquatic ecotoxicity potential (FAETP), global warming potential (GWP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone layer depletion potential (ODP), photochemical ozone creation potential (POCP), and terrestrial ecotoxicity potential (TETP). The results are discussed in the following sections.

The life cycle environmental impacts of one kWh of electricity produced by 3.6 MW and 4.8 MW onshore wind turbines operating in Turkey are compared in Figure 5. As expected, the unwanted environmental impacts are reduced by around 63, 67, 65, 64, 63, 66, 63, 63, 70, 69, and 63% for ADP, ADP fossil, AP, EP, FAETP, GWP, HTP, MAETP, ODP, POCP, and TETP, namely when 4.8 MW onshore wind turbines are used instead of 3.6 MW ones.

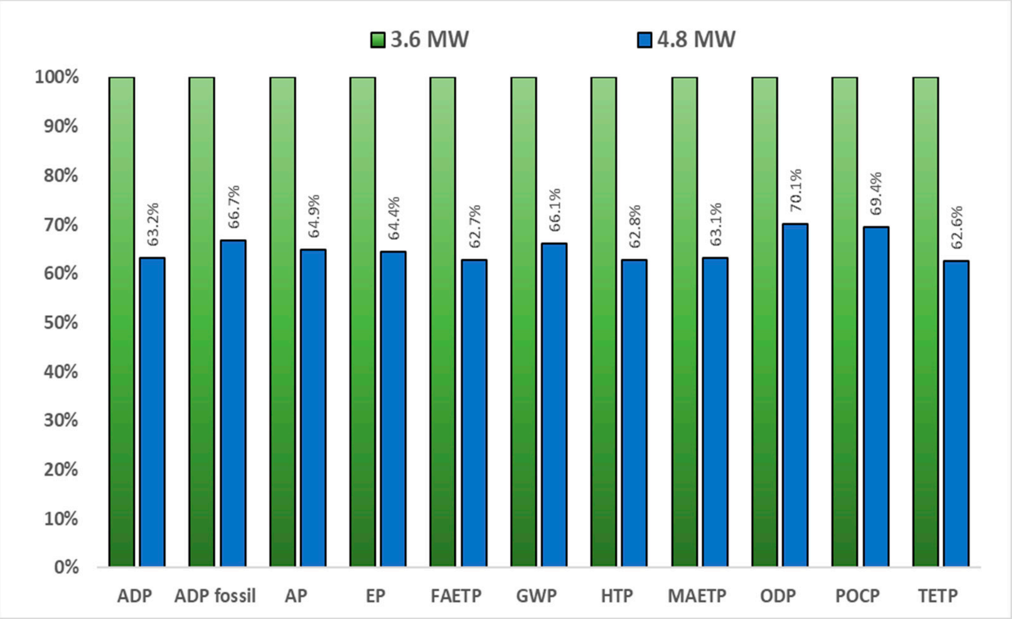

Figure 5. Environmental impacts from selected wind turbines.

The turbines under investigation have different capacity factors. The environmental impact values are obtained per functional unit. Elevated turbine sizes are expected to result in fewer negative environmental effects compared to smaller sized ones. Similar findings have been reported in the literature for various renewable energy sources [42].

Another main finding of this paper is that the construction phase is the main contributor to the environmental impacts. Moreover, as can be observed in Figure 6, unwanted environmental impacts are reduced by recycling for all the impact categories by up to 49%. Therefore, it is recommended to apply recycling as much as possible during the decommissioning stage. It should be noted that impacts arising from the transportation of materials are considered within construction.

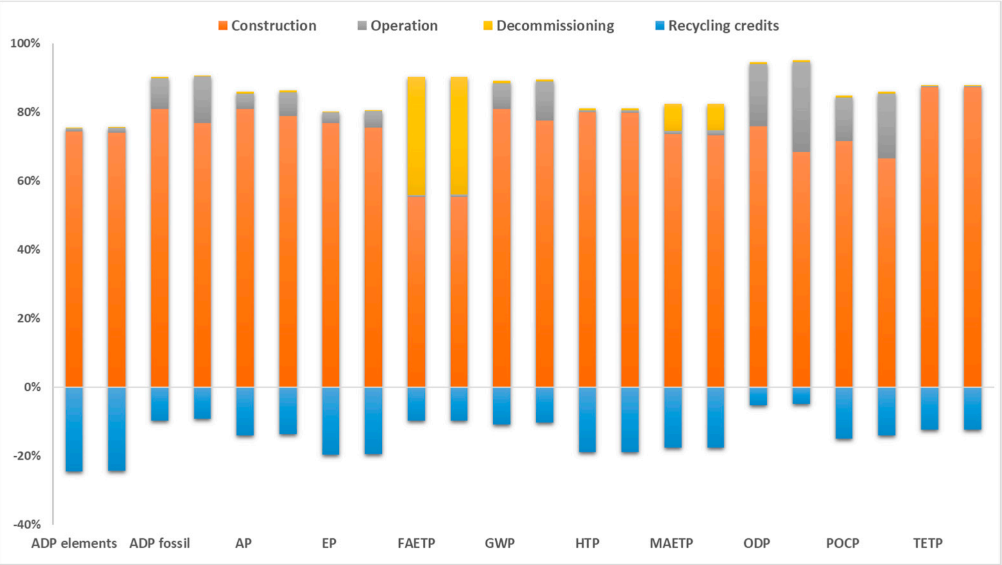

Figure 6. Distribution of environmental impacts for various life stages.

As presented in Figure 6 and Table 4, the wind turbine construction stage is almost entirely responsible for the ADP elements caused by the use of metals. The ADP fossil fuels produced for both sizes of turbine were primarily due to the energy used in the extraction and processing of construction materials. The emissions of SO_2 (around 72%) and NOx (around 25%) from the production of the metal parts contribute almost all the acidification potential. The EP of electricity from the wind turbines examined in this study came from the plant construction stage, particularly from phosphate emissions to freshwater (58%). The FAETP and MAETP for both sizes of turbines are primarily caused by metal emissions into fresh water during construction and decommissioning. The biggest contributors to GWP are the construction and operation of the power plant, due to the CO_2 (>91%) and CH_4 (>7%) emissions. Construction is responsible for nearly all of the HTP and TETP, primarily due to chromium emissions into the air and water. The most significant contributors to the ODP and POCP are the construction and operation of the wind turbines.

When the results from the literature are examined, a wide range of values are reported for each effect. This is primarily due to differences in background data and assumptions regarding geographical regions, installed capacities, capacity factors, recycling rates, and lifetimes. When our results are compared to those in the literature, we can see that they are within the expected range.

The annual environmental impacts from wind energy-based electricity generated in Turkey have been estimated using the impacts per kWh from the 3.2 MW onshore wind turbines and the total wind energy electricity generated from wind turbines in 2022 (34,945 GWh); the results are shown in Table 4.

Table 4. Distribution of environmental impacts for various life stages.

Category	**Unit**	**TOTAL**		**Construction**		**Operation**		**Decommissioning**		**Recycling**	
		3.6 MW	**4.8 MW**	**3.6 MW**	**4.8 MW**	**3.6 MW**	**4.8 MW**	**3.6 MW**	**4.8 MW**	**3.6 MW**	**4.8 MW**
ADP	kg Sb-eq.	3.1×10^{-8}	2.0×10^{-8}	4.6×10^{-8}	2.9×10^{-8}	6.0×10^{-10}	6.0×10^{-10}	3.6×10^{-11}	2.3×10^{-11}	-1.5×10^{-8}	-9.5×10^{-9}
ADP fossil	MJ	5.4×10^{-2}	3.6×10^{-2}	5.4×10^{-2}	3.4×10^{-2}	6.0×10^{-3}	6.0×10^{-3}	2.1×10^{-4}	1.3×10^{-4}	-6.6×10^{-3}	-4.1×10^{-3}
AP	kg SO_2-eq.	1.5×10^{-5}	9.8×10^{-6}	1.7×10^{-5}	1.1×10^{-5}	9.5×10^{-7}	9.5×10^{-7}	1.0×10^{-7}	6.2×10^{-8}	-3.0×10^{-6}	-1.8×10^{-6}
EP	kg PO_4-eq.	7.3×10^{-6}	4.7×10^{-6}	9.3×10^{-6}	5.8×10^{-6}	3.7×10^{-7}	3.7×10^{-7}	3.8×10^{-8}	2.4×10^{-8}	-2.4×10^{-6}	-1.5×10^{-6}
FAETP	kg DCB-eq.	5.4×10^{-3}	3.4×10^{-3}	3.7×10^{-3}	2.3×10^{-3}	3.4×10^{-5}	3.4×10^{-5}	2.3×10^{-3}	1.5×10^{-3}	-6.6×10^{-4}	-4.1×10^{-4}
GWP	kg CO_2-eq.	3.6×10^{-3}	2.4×10^{-3}	3.7×10^{-3}	2.3×10^{-3}	3.4×10^{-4}	3.4×10^{-4}	3.1×10^{-5}	1.9×10^{-5}	-5.0×10^{-4}	-3.1×10^{-4}
HTP	kg DCB-eq.	1.0×10^{-2}	6.3×10^{-3}	1.3×10^{-2}	8.1×10^{-3}	8.0×10^{-5}	8.0×10^{-5}	8.7×10^{-5}	5.5×10^{-5}	-3.1×10^{-3}	-1.9×10^{-3}
MAETP	kg DCB-eq.	5.9×10	3.7×10	6.7×10	4.2×10	9.2×10^{-2}	9.2×10^{-2}	7.0×10^{-1}	4.4×10^{-1}	-1.6×10	-1.0×10
ODP	kg R11-eq.	2.6×10^{-10}	1.8×10^{-10}	2.2×10^{-10}	1.4×10^{-10}	5.2×10^{-11}	5.2×10^{-11}	1.9×10^{-12}	1.2×10^{-12}	-1.5×10^{-11}	-9.6×10^{-12}
POCP	kg C_2H_4-eq.	2.1×10^{-6}	1.5×10^{-6}	2.1×10^{-6}	1.3×10^{-6}	3.8×10^{-7}	3.8×10^{-7}	1.9×10^{-8}	1.2×10^{-8}	-4.5×10^{-7}	-2.8×10^{-7}
TETP	kg DCB-eq.	3.2×10^{-4}	2.0×10^{-4}	3.7×10^{-4}	2.3×10^{-4}	1.1×10^{-6}	1.1×10^{-6}	9.0×10^{-8}	5.6×10^{-8}	-5.2×10^{-5}	-3.3×10^{-5}

Table 5 outlines the environmental impacts generated from wind-based electricity in Turkey for the whole year of 2022.

Table 5. Annual environmental impacts from wind-based electricity in Turkey in 2022.

Category	Unit	Annual Impact
ADP	kg Sb-eq.	1.1×10
ADP fossil	MJ	1.9×10^6
AP	kg SO_2-eq.	5.3×10^2
EP	kg PO_4-eq.	2.6×10^2
FAETP	kg DCB-eq.	1.9×10^5
GWP	kg CO_2-eq.	1.3×10^5
HTP	kg DCB-eq.	3.5×10^5
MAETP	kg DCB-eq.	2.1×10^8
ODP	kg R11-eq.	8.9×10^{-3}
POCP	kg C_2H_4-eq.	7.3×10^1
TETP	kg DCB-eq.	1.1×10^4

Turkey's total greenhouse gas (GHG) emissions as CO_2-equivalent (eq.) for the year from wind-powered electricity are 0.13 million tonnes (Mt). The greenhouse gas inventory results revealed that overall GHG emissions as CO_2-eq. for the year 2021 compared to the previous year increased by 7.7% to 564.4 Mt in Turkey. Total GHG emissions per capita were calculated at 4 tonnes CO_2-eq. for 1990, 6.3 tonnes CO_2-eq. for 2020 and 6.7 tonnes CO2-eq. for 2021. In 2021, the energy sector had the largest share of total GHG emissions with 71.3%. The energy sector was followed by the industrial processes sector, the agriculture sector, and the waste sector, with 13.3, 12.8, and 2.6% shares. The energy sector emissions were calculated as 402.5 Mt CO_2-eq. in 2021, which increased by 188.4% compared to 1990 and also increased by 9.8% compared to the previous year. Similarly, emissions from the industrial processes and product use sector were calculated at 75.1 Mt CO_2-eq. in 2021, which increased by 228.7% compared to 1990 and also increased by 10.6% compared to the previous year [82].

4. Conclusions

The following conclusions are driven from this study and put forth the environmental impacts of wind turbines from a life cycle sustainability standpoint.

Similar to all sorts of energy-generating installations, addressing specific environmental factors within the life cycle of wind energy facilities will guide strategy development for handling and reducing the unwanted environmental impacts.

The use of wind energy is one of the ways that will bring humanity to sustainability. Then again, there are obstacles to be tackled on the road. The most significant challenge can be quoted as the use of site-specific data to obtain a clear picture of environmental impacts. In this sense, location-specific issues such as geographical considerations, matters related to transportation, end-of-life recycling alternatives, various energy sources and materials used for, i.e., construction, etc., gain importance. The use of location-specific data is essential to achieve a sound case-specific evaluation.

The examples presented in this study indicate that the environmental impacts per functional unit are decreased by more than 63% in cases using 4.8 MW onshore wind turbines instead of 3.6 MW ones.

The construction phase contributes the main share of all environmental impacts. Recycling reduces all unwanted environmental impacts by up to 49%.

It is recommended to conduct similar studies with site-specific data for each wind installation. Also, future focus should be given to (i) large turbines; and (ii) the construction, operation, and maintenance phases of the life cycle.

A sustainability assessment that takes into account the life cycle environmental impacts, economic costs, and social aspects of these options will assist the energy sector in identifying and implementing the most sustainable energy solutions. Future studies should consider both the economic and social impacts, as well as the environmental impacts.

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