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Review Article

Wind farms through the lens of sustainability and circularity: Integrating environmental, economic, and social dimensions

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ABSTRACT

The development of a sustainable energy transition is one of the strategic objectives in Europe, and wind energy plays a key role, as its production capacity has increased significantly in recent decades. However, to verify that wind farm projects are indeed sustainable, it is necessary to apply appropriate methodologies to assess the three pillars of sustainable development: environmental, social and economic. In addition, a comparison with traditional energy resources of fossil origin is necessary, seeking to identify the benefits and challenges associated with these renewable energy alternatives, as well as the study of how wind farms adhere circular economy principles. The idea of this analysis is to avoid past mistakes, such as the depletion of essential resources, for example the depletion of rare elements, used for the construction of renewable energy facilities. It is in this framework that this comprehensive and critical review is developed, with the aim of providing information on the actual production of wind energy in the European context, its potential environmental benefits and effects, the socio-economic constraints and benefits that wind farm projects could bring, as well as the gaps and challenges identified in the value chain. It is hoped that this critical review can be considered as a guide for policy makers, researchers and stakeholders on the main constraints that could slow down wind energy technologies, on the environmental footprint of wind farms and its comparison with fossil energy, on the potentialities of wind projects to increase employment opportunities and economic growth, and on the main concerns of social communities.

1. Introduction

As society becomes more demanding in terms of goods and services, as well as more technologically advanced, the gap between energy demand and supply capacity gradually increases every year (Li et al., 2022). Energy consumption and the consequent depletion of fossil resources, which are characterized by a very negative impact on environmental quality (Olabi and Abdelkareem, 2022), pose a challenge for a more sustainable energy transition, in which non-renewable resources must be gradually substituted. In this sense, it has been reported that the development of renewable energies, increasing their share in the electricity mix of the regions, as well as optimizing energy efficiency, implies a higher degree of sustainability compared to conventional energy sources. The objective is to achieve a green energy transition towards productive models with lower environmental impact, reduced climate degradation, less dependence on oil and gas reserves and avoid the depletion of finite fossil fuels (Bhattarai et al., 2022).

There are several renewable energy alternatives for energy production. The installation of one or another should be selected based on environmental conditions (such as solar intensity, wind speed, proximity to residual biomass generation facilities, tidal energy intensity, etc.), societal needs (adaptability and maintenance of the quality of life of social communities surrounding renewable energy facilities), effect on the environment (proximity to agricultural areas, landscape pollution, maintenance of air quality, human toxicity effects) and impact on the country economy (promotion of economic growth). Some of the alternatives include solar energy (especially for regions with high solar intensity throughout the year) (Castillo et al., 2016), hydropower energy (Ridgill et al., 2021), tidal energy (Bhatia, 2014), biomass energy (based on the energy valorization of biomass in combustion or anaerobic co-digestion processes) (Kiehbadroudinezhad et al., 2023), geothermal energy (Nkinyam et al., 2025) and wind energy (Mahmoud et al., 2023).

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Among all of them, it has been reported, and according to energy country reports, that wind, solar and tidal energy are the most prominent compared to other renewable resources (Aleixandre-Tudó et al., 2019).

With respect to the wind energy, the focus of this research, its production in Europe and the European Union (EU-27) has increased significantly in recent years, as shown in Fig. 1. There is an exponential trend in the increase of wind capacity in the period 2010–2020, after which there is a slowdown in the installation of new wind farms.

According to IRENA, the amount of onshore wind power produced in Europe in 2022 has been 188 GW (representing 92 % of the total wind power produced), while for offshore wind it has been 16 GW. This trend of increasing production in onshore wind farms can also be seen in Fig. 2, where onshore power production is more prominent in countries where wind power is already an important part of the electricity mix. In the specific case of Germany, which by a significant difference is the country with the highest level of wind power production, an analysis of renewable electricity production was performed. According to this, wind energy accounts for 37 % of the total renewable energy produced in the country, followed by solar energy with a share of 16 %, bioenergy with 15 %, biogas with 10 % and hydroelectric energy with 14 %, while the remaining 8 % is made up of solid biofuels and renewable municipal waste, among others.

Regarding the companies with the highest wind energy production in Europe, ENEL Green Power stands out, with a production of 65.9 TWh from wind and solar energy in 2022, IBERDROLA, which represents a total of 17.4 GW of installed capacity, increasing its annual production in Europe by 34.8 % in a decade. It is capable of producing a total of 437 TWh of wind energy, covering 15 % of the EU electricity demand, of which 12.2 % is offshore wind and 2.8 % onshore wind. ACCIONA S.A., characterized by an installed capacity of 11,826 MW, in 2022, of which 74 % are onshore wind farms, while 16 % is represented by solar photovoltaic, 7 % by hydroelectric and 3 % by solar thermal and biomass. VESTAS is present in almost all European countries, with a range of production capacity from the highest, reached in Germany, amounting to 18,327 MW, to the lowest, represented by Belarus, with 4 MW. Another important company is ORSTED, based mainly on offshore wind energy, with a total installed capacity of 561 MW in Denmark, 2988 MW in the UK, 673 MW in Germany and 376 MW in the Netherlands. This company has prepared an interesting report that also

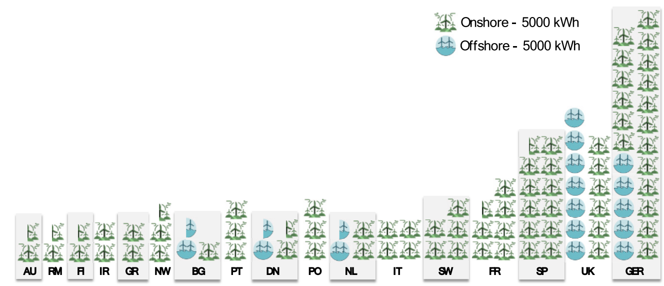

Fig. 2. Onshore and offshore wind energy production in 2022. Data source: Our World in Data and IRENA. Acronyms: GER (Germany), UK (United Kingdom), SP (Spain), FR (France), SW (Sweden), IT (Italy), NL (Netherlands), PO (Portugal), DN (Denmark), PT (Portugal),

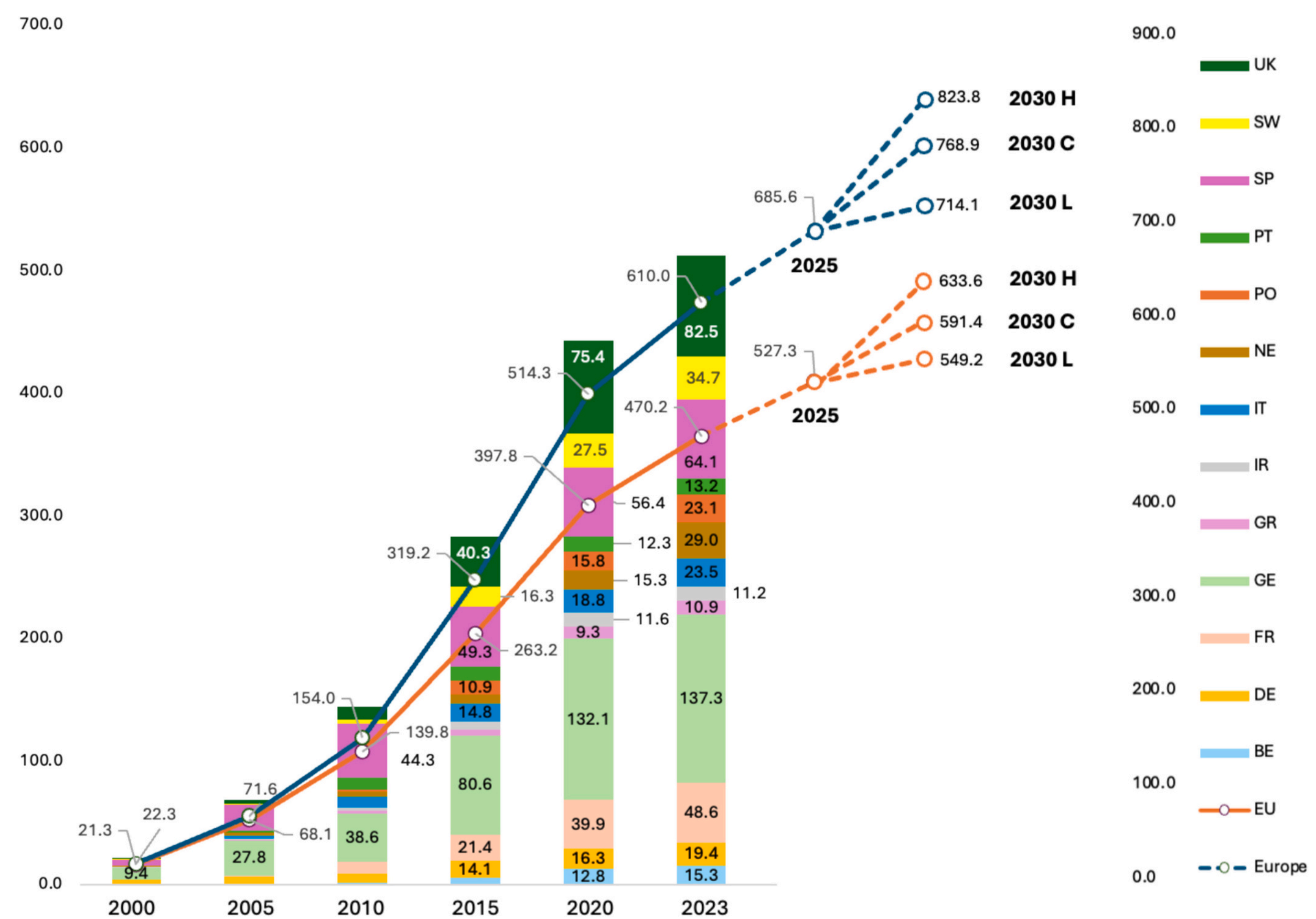

Fig. 1. Trends in wind production (GW) on Europe (Δ) and EU-27 (o). Details of wind energy capacity for some European countries are shown. Data source: IRENA (2022) and Ember (2025). Acronyms: L – low scenario, C – central scenario and H – high scenario according to Wind Europe.

includes the impact on biodiversity protected areas, as well as actions to be taken, also including potential GHG emissions from electricity production. Finally, ENGIE and TotalEnergies also stand out, with 8.1 GW of total wind power capacity and 1936 MW of gross installed wind turbine capacity in Europe in 2022, respectively.

However, despite wind energy high production and its renewable nature, it is important to keep in mind that conducting sustainability assessments is key to evaluate the potentiality of wind renewable energy production sites, considering the entire value chain, from equipment production, installation, energy production phase, maintenance activities, to final decommissioning. It is necessary to evaluate, analyze and demonstrate the carbon and water footprint, as well as the impact on soil quality, the effects on social welfare and economic viability, and even improve them, identifying the main critical points that are leading to a greater effect on the environment. In addition, the absence of policy instruments, such as energy policies or action plans, as well as the lack of financial support have also been a key aspect in the further development of renewable energy projects (Lundy, 2019; Azevedo et al., 2019).

In this sense, this critical review is based on the assessment of environmental impacts, social effects and economic potentialities of wind farms, both onshore and offshore (Hevia-Koch and Jacobsen, 2019), in order to analyze their sustainability potential. The focus on wind farms is due to the expectation that, from a long-term perspective, wind energy will become the main source of renewable electricity, with its share projected to increase by 42 % by 2030 (Bogdanov et al., 2021). To this end, it is important to be aware of the real challenges and issues that need to be improved and enhanced to avoid unexpected problems in the future, as happened with fossil fuels, whose unlimited use ends up almost running out.

It also offers some ideas on how wind farms could help in the transition to a circular economy by considering the recovery, recycling and reuse of wind turbines. In this aspect, some actions are starting to take shape, such as the European Wind Energy Action Plan, updated in October 2023, in which the main concern is the availability of raw materials for the construction of wind turbines, as well as the fluctuation of their prices and dependence on third countries. One of the most important actions of this plan is the standardization of the wind farm sector, in which the circular economy plays a key role, so it requires a deep and effective analysis of the entire value chain of the wind sector. In this sense, thinking about life cycle analysis could be a starting solution, since this methodology is based on the consideration of all the stages required for a productive process, from the extraction of materials to the production of the required equipment, up to the final dismantling of the activity.

To this end, the main objective of this critical review is to provide some insights to stakeholders, industry players, policy makers and interested researchers on the benefits, challenges and gaps of wind energy production, in the approach of sustainable development and life cycle assessments, as well as to provide an overview of the available literature reports on this topic.

2. Methodology

In order to analyze the main aspects of environmental, social and economic sustainability of wind farms, as well as their progression in the economic value chain, an initial literature search was conducted using the Scopus database, considering the PRISMA guidelines. Four keywords were used: (1) wind farms AND carbon footprint, (2) wind farms AND life cycle analysis, (3) wind farms AND sustainability, and (4) wind farms AND energy transition.

The first set of keywords seeks to establish an analogy between wind farms and carbon emissions, which is directly related to environmental sustainability, while the second set of keywords focuses on the aspect of assessing the entire value chain of wind farms, thus allowing to analyze their impact on environmental, economic and social sustainability at all stages of their life cycle. The third set of keywords has been developed to provide an overview of sustainability and its relation to wind energy production, and the fourth set aims to analyze how wind farm projects have developed and grown over time. For cluster (1) a total of 132 documents were found, for cluster (2) 217, for cluster (3) a total of 1977 documents were found and for cluster (4) 56 documents were found, in the period from 2000 to 2024. In addition to these reports, other articles found in the bibliography, databases, reports from wind energy companies and governmental action plans and policies were also used.

Among the documents mentioned, those that were duplicated were disregarded, as well as those that belonged to abstracts of congresses, symposia, forums and proceedings, leaving a total of 115 documents that were thoroughly analyzed (Fig. 3). On the other hand, all the documents found in the bibliography were used to evaluate the interaction between the keywords chosen by the authors, using the VosViewer® tool, which produces clusters of connections between keywords. Fig. 1SM[Supplementary material]A shows a total of 102 interactions with 6 clusters for clustering (1), where the interaction between wind farms and carbon footprint, carbon dioxide, climate change and renewable energies can be clearly observed.

One of the aspects driving the development of renewable energies is to achieve an energy sector with lower carbon emissions, in order to promote the transition to energy resources that do not involve climate change and also reduce the consumption of fossil resources (Niu et al., 2024; De La Peña et al., 2022; Watari et al., 2021). On the other hand, a large presence of offshore wind farms is also observed, which seems to be indicative of a greater tendency to evaluate offshore wind farms compared to onshore wind farms (He et al., 2023; Li and Yu, 2018). In addition, the publication date of the articles was also analyzed to be aware of when the analysis of wind energy started to be the focus of evaluation, being more intense from 2016 to the present.

As for cluster (2), a strong interaction between wind farms and life cycle analysis has been observed, which makes sense in order to show the potential of wind energy for a green and more sustainable energy transition (Fig. 1SMB). Life cycle analysis allows identifying which stage of the process leads to the highest environmental, social or economic impact, which allows proposing improvement actions in order to minimize the impact-generating capacity of wind energy projects (Kristjanpoller et al., 2023; Moussavi et al., 2023; Xu et al., 2022; Abid-Saeed et al., 2020).

In addition, it was also observed that the keyword "decision making" appears prominently among the clusters, which is indicative of how life cycle analyses can be useful in any of the design, production and decommissioning phases of wind farms. As for the time frame, in this case, the highest number of articles has been observed between 2017 and 2021.

Cluster (3) is the one with the highest number of research reports found in the literature, which implies a higher number of clusters, specifically 10, as could be observed in Fig. 1SMC, representing a total of 167 keywords linked among the articles found. In addition to the analogy between wind energy, renewable energies and sustainability, which are the clusters that stand out, other interesting aspects have emerged in this graph: the development of energy and exergy analysis, thinking about increasing the efficiency of wind farm projects (Tahir et al., 2022; Esfandi et al., 2020), and also the association with other renewable energies, such as solar and hydro, which are other prominent renewable energy sources, thinking about combined and hybrid renewable energy systems (Hassan et al., 2023; Ercan and Kentel, 2022; Memon et al., 2021). As for the time frame, it is analogous to the previous one, approximately from 2017 to 2021 is the area in which the largest number of research articles has been developed.

Finally, cluster (4) presented a total of 56 articles, where again a strong analogy with previous analyses is observed, although in this case the connection of wind farms with social and economic effects, as well as the comparison with fossil fuels, is present to a greater extent (Fig. 1SMD). As expected, when talking about energy transition, new heat chains based on renewable energies should not only be analyzed

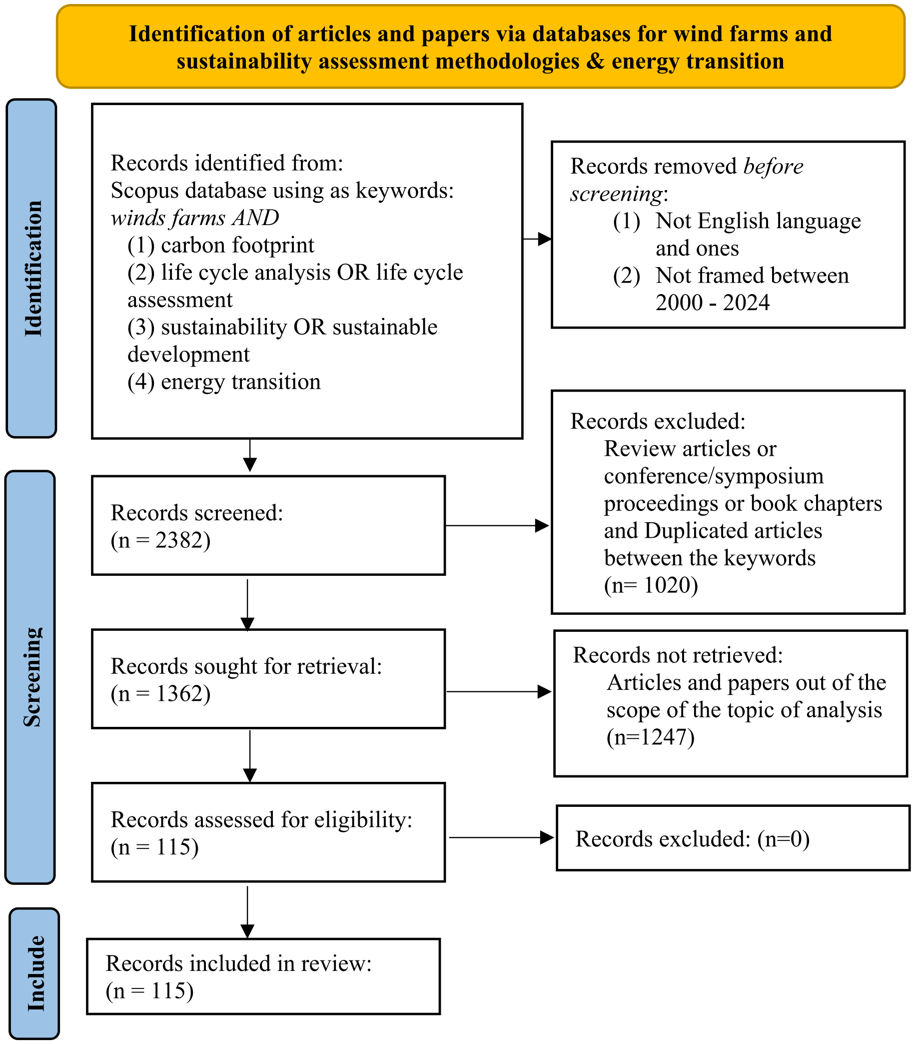

Fig. 3. Methodological approach for the selection of articles to be further analyzed considering PRISMA guidelines.

from the point of view of environmental sustainability, but also from the aspect of effects on economic growth and social welfare (Hussain et al., 2023; Yasmeen et al., 2023; Ahn et al., 2021). Furthermore, these impacts and effects should be compared with fossil energy sources in order to analyze whether improved solutions to the problems caused by non-renewable energy sources are really being proposed.

3. Results and discussions

3.1. *Wind farms under a sustainability perspective*

3.1.1. *Environmental sustainability of wind farms*

In the aspect of environmental sustainability, three main aspects are analyzed: the carbon footprint, seeking to evaluate the direct and indirect carbon emissions related to the wind farms, the effects on soil quality and soil carbon cycles, focusing also on the possible consequences on agricultural areas, the variation of climatic conditions in the areas surrounding the wind farms, and impacts on the landscape.

3.1.1.1. Carbon footprint and its comparison with fossil fuels. Table 1 shows the analysis of research reports that have used the life cycle analysis (LCA) methodology to calculate the carbon footprint associated with wind farms. As can be seen, most of them are considering a cradle-to-grave approach as system boundaries, in order to analyze the total life cycle of wind farms: construction of the equipment (i.e. turbines, blades, tower, etc.), transportation, installation phase, electricity production phase, maintenance activities and decommissioning of the wind farms.

Regarding the functional unit, most LCA studies use “1 kWh” of wind energy produced, which is easily comparable with fossil energy and even with other renewables such as wind or solar, among others, and allows for simpler data handling. In some studies, such as Ramos Júnior et al. (2023) or Weinzettel et al. (2009), the wind turbine capacity factor, expressed in MJ or GJ, has been considered as a functional unit, while others take a long-term view, i.e. a prospective LCA (Ji and Chen, 2016), or focus on the level of emissions generated by the construction, installation phases, maintenance and decommissioning of turbines (Osorio-Tejada et al., 2022; Walmsley et al., 2017). In these cases, the comparative analysis with fossil fuel-based energy production models is more complex.

Diversity was observed in the databases and impact calculation methodologies used, with the use of EcoInvent as the background activity inventory database and the use of emission factors, ReCiPe and IPCC as the main methodologies. Comparing the values obtained, for the same system boundary (cradle to grave) and the same functional unit (1 kWh), the studies that used EcoInvent as a database reported a carbon footprint in the range of 8.3 g CO_2eq/kWh (Fonseca and Carvalho, 2022) and 49 g CO_2eq/kWh (Pulselli et al., 2022), both using IPCC as methodology. On the other hand, those based on emission factors and using reports and primary data as a database obtained a carbon footprint value in a similar range, between 6.6 g CO_2eq/kWh (Liu et al., 2021) and 26.7

Table 1
Analysis of LCA research reports on wind farms.

Reference	Onshore or offshore	System boundary	FU[1]	Database	Method	CF[a] [CO_2 eq.]	Sensitivity assessment	Comparison with fossil	Gaps and challenges
Arvesen and Hertwich, 2012	Both	Various	1 kWh	Various	Various	12 g	–	Lower CF in comparison with nuclear, hydropower and solar.	Design of wind turbines, installation and dismantling phases
Xie et al., 2020	NA	Cradle-to-grave	1 kWh	Primary data	–	3.9 g	–	–	Demand of materials for construction
Pulselli et al., 2022	Offshore	Cradle-to-grave	1 kWh	EcoInvent	IPCC 2013 GWP 100	49 g	Quantity of steel used for wind blades and amount of recycled steel	Lower CF compared to national electricity grids	Reducing steel requirements and use of recycled steel
Ramos Júnior et al., 2023	Both	Cradle-to-gate	1 GJ	EcoInvent	ReCiPe and IPCC 2021 100-y GWP	0.21 kg offshore 1.37 kg onshore	Capacity factor of turbine blades and its lifetime, and material substitution.	–	Technological and financial viability of wind farms
Ji and Chen, 2016	NA	Cradle-to-grave	Wind farm over 21-year lifetime	Primary data	CO_2 emission factors	14.5 g	Peak regulation	–	Use of predictive methods for wind variability
Liu et al., 2021	Both	Cradle-to-grave	1 kWh	Primary data and reports	Carbon emission factors	6.57 g	–	CF 148.45 times less than coal, 71.91 less than natural gas, 127.85 less than oil and 3.50 times less than nuclear power.	Promotion of wind farms in grasslands
Nassar et al., 2024	NA	Cradle-to-grave	1 kWp (plant capacity)	Various	Various life cycle indicators (i.e. GHG emission factor, carbon payback time, energy payback ratio)	46.88 g	–	CF lower than biomass, biogas, solar and thermal power plants	Identification of appropriate site for wind farms installation
Rajaei and Tinjum, 2014	NA	Cradle-to-gate	1 kWh	EcoInvent	–	9.5 g	–	CF of natural gas in almost twice compared to wind energy	–
Diez-Cañamero and Mendoza, 2023	Onshore	Cradle-to-grave	160 t wind blades, 20 years	EcoInvent	Product circularity indicator and ReCiPe	467 t	Efficiency and performance of EoL strategies	–	Assessment of circularity and environmental indicators for wind blades optimization
Walmsley et al., 2017	NA	Cradle-to-gate	1 ton of CO_2	Datasets and reports	Energy Return on Energy Invested (EROI) and Energy Return on Carbon Emissions (EROC)	477 GJ/t	Capacity factor, wind speed, blade diameter and number of turbines	The energy production capacity per ton of CO_2 is 56 times higher for wind energy compared to combined cycle natural gas power	Decreasing the maintenance requirements of turbines and predicting models for wind variability
Arvesen and Hertwich, 2011	Both	Cradle-to-grave	1 kWh	EcoInvent	ReCiPe	22.5 g onshore and 21.2 g offshore	Capacity factor and wind blades lifetime.	CF of wind energy lower than the fuel-chain emissions for fossil power	–
Yuan et al., 2023	Offshore	Cradle-to-grave	1 kWh	EcoInvent and Chinese core life cycle database	ReCiPe and CML 2002	25.76 g	Amount of steel required	CF significantly lower compared to photovoltaic and biomass power	Monitoring system for marine environment to install offshore wind farms
Fonseca and Carvalho, 2022	Onshore	Cradle-to-grave	1 kWh	EcoInvent	IPCC 2013 GWP 100y and Cumulative Energy Demand	8.3 g	–	–	Wind speed data and best location predictions
Arvesen et al., 2014	Offshore	Cradle-to-grave	1 kWh	EcoInvent and Exiobase	ReCiPe	2.49 g	–	–	Power losses and effect of offshore grids on the surrounding marine life

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Table 1 (*continued*)

Reference	Onshore or offshore	System boundary	FU[1]	Database	Method	CF[a] [CO_2 eq.]	Sensitivity assessment	Comparison with fossil	Gaps and challenges
Oebels and Pacca, 2013	Onshore	Wind park	1 kWh	Emission factors	NA	7.1 g	Capacity factor	–	–
Sun and You, 2024	Offshore	Cradle-to-grave	1 kWh	Emission factors	Emission factors	26.72 g	Maximum wind speed, vulnerability of wind turbines and emission factors	CF of wind farm account for only 3.22 % compared to coal-fired electricity	Design of wind turbines and peak regulation.
Kaldellis and Apostolou, 2017	Both	NA	–	NA	–	–	–	–	–
Hossain et al., 2019	NA	Cradle-to-grave	1 kWh	EcoInvent	ILCD 2011 MidPoint	–	–	–	Increase of wind energy on electricity mix
Farina and Anctil, 2022	Both	Cradle-to-gate	1 MW	US-EI 2.2	IPCC 2013 GWP100 and Cumulative Energy Demand		–	–	Availability of metals and rare elements
Rojas-Michaga et al., 2023	Offshore	Well-to-waste	1 MJ of SAF	EcoInvent	ReCiPe	21.43 g	–	–	–
Osorio-Tejada et al., 2022	NA	Cradle-to-gate	1 kg of NH_3	EcoInvent	ReCiPe–100y	−0.52 kg	–	Impact on land use is 650 times reduced when compared to biomass-based power	–
Zhao et al., 2017	NA	Cradle-to-grave	1 kWh	EPiC database	Emission factors and IPCC 2006	12.51 g		CF is reduced significantly compared to coal-fired plant, amounting to 810.35 g CO_2/kWh	–
Heng et al., 2021	Both	Gate to grave	Ton of blade waste	EcoInvent	NA	IMSW[1] 0.90 t MRL[1] 0.28 t MRI[1] 0.09 t	Total waste inventory variations	–	Recycling of wind turbines and blades is the best EoL scenario for long term.
Zimmermann and Gößling-Reisemann, 2012	–		1 kWh	GaBi	Harvest factor and carbon footprint equations	7.9 g	Service and maintenance intensity and wind conditions	–	Identification of site specific for wind farms installation
Weinzettel et al., 2009	Offshore	Cradle-to-grave	Wind farm of 5 MW, 1 MJ	Primary data and EcoInvent	CML 2 baseline 2000 V2.03	3.4 g	–	–	Use of recycled materials for construction
Kabir et al., 2012	–	Cradle-to-grave	1 kWh	Reports and primary	–	17.8 g	–	–	Increase energy efficiency
Querini et al., 2012	Onshore	Well-to-wheels	Driving 1 km	ELCD, GaBi, EcoInvent	–	1.5 g	–	Lower than gasoline (104 g CO_2/km) and diesel (118 g CO_2/km)	–
Raadal et al., 2014	Offshore	Cradle-to-grave	1 kWh	EcoInvent	ILCD	18–31.4 g	Wind conditions, blades lifetime, steel and fuel needs	Wind power entails small carbon footprint	Land use, visual aspects, biodiversity and noise effects should be assessed.
Reimers et al., 2014	Offshore	Cradle-to-grave	1 kWh	EcoInvent	IPCC 2007	16.8 g	Power yield, site conditions, maintenance required, wind speed.	–	Manufacturing emissions should be reduced and location of wind farm.
Vargas et al., 2015	–	Cradle-to-grave	1 kWh, 2 MW capacity, 20 years	EcoInvent	CML 2001	493.56 t 20 y	–	–	Improvement of wind turbines design
Wagner et al., 2011	Offshore	Cradle-to-grave	1 kWh	EcoInvent	–	32 g	Increase on lifetime, wind conditions, energy converters.	Electricity mix carbon footprint amounts to 665 g CO_2/kWh	Fluctuating wind conditions effects on assuring wind energy supply
Arvesen et al., 2013	Offshore	Cradle-to-gate	1 kWh	EcoInvent	ReCiPe	10 g	–	CF about 25 % and 90 % lower compared to coal	Inventories for installation and maintenance needs to be improved

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Table 1 (*continued*)

Reference	Onshore or offshore	System boundary	FU[1]	Database	Method	CF[a] [CO_2 eq.]	Sensitivity assessment	Comparison with fossil	Gaps and challenges
								and natural gas, respectively	
Bonou et al., 2016	Both	Cradle-to-grave	1 kWh	EcoInvent	ReCiPe	7 g onshore 11 g offshore	Steel recycling, efficiency, lifetime and wind speed	CF for coal (530 g CO_2 eq/kWh) and natural gas (530 g CO_2 eq/kWh)	EoL strategies are crucial, thus requiring investment for technologies to recycle materials.

[a] FU: functional unit, CF: carbon footprint, IMSW: incineration with municipal solid waste, MRL: mechanical recycling with landfilling, MRI: mechanical recycling with incineration.

g CO_2eq/kWh (Sun and You, 2024). This discrepancy between the values indicates that (1) each wind farm project should be treated distinctively, as there are several conditions that can affect the environmental profile of the project, and (2) it is important to identify all the parameters considered when performing the LCA, as several reports in the literature did not include the assumptions considered, nor essential elements of the LCA, such as direct indication of the system boundaries considered, or the functional unit, or even the LCA itself, or the functional unit, or even the calculation methodology or the basis of the LCA, and (3) it is important to identify all the parameters considered when performing the LCA, since several reports in the literature did not include the assumptions considered, nor essential elements of the LCA such as the system boundaries considered, the functional unit, or even the LCA calculation methodology.

On the other hand, many articles analyzed made a comparison with the carbon footprint of energy from fossil resources, clearly showing that the environmental impact associated with wind energy is significantly lower, with carbon footprint values 148.5 times lower than those of coal, 71.9 times lower than those of natural gas, 127.9 times lower than those of oil and 3.5 times lower than those of nuclear energy (Liu et al., 2021). Some have also made comparisons with other impact categories and other renewables, such as land use and biomass-based energy, concluding that the impact of wind power is reduced by 650 points compared to biomass-based energy (Osorio-Tejada et al., 2022).

Finally, several gaps and challenges have been identified to promote further development of wind energy, the first and perhaps the most important of which is to ensure the technological and financial viability of wind farms (Ramos Júnior et al., 2023). The development of renewable energy projects must be backed by adequate financial resources, and policies must promote their integration into national value chains and electricity mixes. In addition, work should also be done on models that can adapt to or predict air variability, as this has a direct impact on energy production capacity (Yuan et al., 2023; Ji and Chen, 2016). In this sense, artificial intelligence and machine learning could bring great benefits to achieve greater energy efficiency. It is also necessary to continue working on the technological improvement of wind turbines to avoid or reduce maintenance activities as much as possible, as these also involve environmental impacts that could be avoided with more optimized technology (Sun and You, 2024; Walmsley et al., 2017; Vargas et al., 2015). In addition, it has been observed that technological developments are also needed to improve wind turbine dismantling and recycling activities, thus promoting more circular wind energy (Heng et al., 2021; Bonou et al., 2016).

3.1.1.2. Effects on soil quality and soil carbon cycles. One of the main concerns when implementing a new facility is its impact on soil quality and natural carbon cycles. The installation of wind farms involves biological disturbance due to the need to remove tree cover, which also has an impact on soil erosion. This direct impact is the result of changes in rainfall patterns and soil vegetation, which also affects photosynthesis and thus carbon cycling (Murray, 2012). Therefore, site selection for new facilities is key to promoting more sustainable development and avoiding negative impacts on the vegetation and agricultural capacity of the area. For this reason, several studies point out that areas with lower agricultural productivity are the ones that should be considered, at least in the first place, for the installation of wind farms, since areas without vegetation are the optimal for their implementation (Pekkan et al., 2021). Another aspect to take into account is the soil type characteristic of the area where the wind farms are to be installed, as this can have an important effect on the energy efficiency and productivity of the turbines. According to the study by Abhinav and Saha (2015), soil conditions are a key factor in siting decisions, since while soft soils induce excessive movements leading to turbine failure.

Regarding impacts on soil quality, it is also important to note that losses and emissions during construction, production and decommissioning of the facility have an impact on soil quality. The wastewater generated, as well as oil losses during wind turbine transport and maintenance activities, can reach the ground soil and water flows and thus cause significant environmental impacts. However, it should be noted that these impacts are not exclusive to the installation of a wind farm but are generic to any other type of industrial facility. Therefore, it is not considered as a factor specific to wind energy, but as a general factor that should be improved as much as possible, as well as opting for soil protection mechanisms to reduce the negative impact on soil quality and natural nutrient cycles.

On the other hand, there is some concern from social communities and industrial sectors about the location of wind farms due to their potential impact on agricultural yields. According to the research articles reviewed, the implementation of wind energy production systems does not seem to have a negative effect on crop quality and yields, quite the contrary. According to the study by Liu et al. (2022), the installation of a wind farm about 4 km from crops increases the growing season in both windward and leeward areas. The reason for this increase is because the installation of the wind farm increases the local land surface temperature to some extent, which also influences soil moisture and thus benefits crops (Liu et al., 2022). Regarding evapotranspiration, a previous study by Armstrong et al. (2014) concluded that the effect of wind turbines on this soil property is very small, around 0.2 mm/h under steady-state conditions, so it should not have a negative impact on soil quality (Armstrong et al., 2014).

Regarding the carbon cycle, the study by Heinatz and Scheffold (2023), which analyzed several offshore wind farms covering an area between 6.17 and 34.59 km^2, which, at the same time, implies an affected area between 38 and 160 km^2, concluded that their installation implies an increase in the transfer and stock of organic carbon in the surrounding area during the energy production phase. On the other hand, carbon emissions increase during the construction and decommissioning phases, but at a much lower percentage compared to their ability to generate benefits in terms of natural carbon cycling and CO_2 emissions reduction (Heinatz and Scheffold, 2023).

3.1.1.3. Variations in climate conditions and species. The main changes in the surrounding climate that have been analyzed and discussed by other researchers focus on the following aspects: changes in wind speed, air temperature, land surface temperature, soil evapotranspiration and vegetation index. While wind speed has decreased with wind farm construction by about 16 %, air temperature has increased during the day and decreased at night by about 0.35 °C per decade, while land surface temperature has increased at an average of 0.52 °C per decade (Luo et al., 2021). These differences in temperatures could also be important when analyzing the impact on the carbon cycle, as changes in air and land surface temperatures have a direct impact on the carbon cycle (Armstrong et al., 2014). To this end, although this is not a significant variation, it should be considered as an aspect to be assessed when locating a wind farm near areas destined for livestock farming, and social communities, and see if this difference could affect them. In the case of soil evapotranspiration, the effects are more significant, as it has increased from 34 to 95 mm in the environment closest to the wind farm, while for buffer zones, defined as the minimum distance from other sectoral activities and social communities (European Commission, 2023), it has increased from 44 to 92 mm (Luo et al., 2021). Given this significant difference, further analysis is needed to assess whether the variation in evapotranspiration could be considered a negative environmental impact.

Air quality in the surrounding area could also be adversely affected, as emissions from construction, maintenance, and decommissioning activities are expected to occur both onshore and offshore. However, these impacts are predicted to be mostly local, rather than large in magnitude (Kaldellis et al., 2016). In addition, some effect on soil composition has been observed, particularly with regard to chemical concentrations of Co, K, Ti and V, which are significantly increased when wind farms are installed. Specifically, Co and Ti are the compounds where the largest perturbations are observed, while Co concentration could increase by 1 to 4 times compared to the soil composition before wind farm development, for Ti the range could be between 1 and 10 times higher (Luo et al., 2021). Further evaluations in this aspect should be developed in order to avoid as much as possible the possible toxicological effects that this increase in metal concentration could have on soil quality.

Focusing more on the effects on animals, the species habitats could be disturbed by construction, operation and decommissioning activities, as the size of the habitat is altered. A reduction in species abundance and diversity could also be observed, due to emigration, but also due to collisions with shovels and flight disturbance in the case of birds, and noise effects for all types of species, both during construction and operation. In the specific case of birds, which are the most affected species, the annual mortality per wind turbine in onshore wind farms in Denmark or Spain, two of the largest producers, is 0.8 for Denmark and between 0.03 and 0.45 for Spain. The values certainly increase when evaluating offshore wind farms, in the case of the Netherlands it is 16.1 (Kaldellis et al., 2016). Given these significant differences between regions, further analysis should be conducted to assess these discrepancies between land and sea, as well as between the location of wind farms, as it is not clear which is the best in terms of environmental protection and maintenance of species diversity.

3.1.1.4. Landscape effects. The importance of this impact is notorious also at the level of policy makers, as it has been the main focus of the European Landscape Convention, which considers landscape quality as a key aspect of the natural and cultural heritage of European identity (Lloret et al., 2022; Glasson et al., 2022). As for wind farms, significant landscape disturbance could occur in both onshore and offshore wind farms, in fact, according to surveys, it is more about onshore projects, given their proximity to social communities. In fact, about 75 % of respondents to surveys being conducted in this regard, consider this to be a key negative effect of wind energy, which could influence on tourism and, consequently, on the economic growth of local communities (Glasson et al., 2022; Kaldellis et al., 2016). According to the research report developed by Sæþórsdóttir and Ólafsdóttir (2020), it appears that residents are not as concerned as tourists about the effect of onshore wind turbines on the landscape, with tourists considering a greater intrusive effect on the natural landscape. In the case of offshore wind farms, the concern is less, as 64 % of the total respondents showed a positive consideration of the installation of wind farms, indicating that no optical disturbance is observed, while only 11 % have a negative attitude and still prefer to avoid their installation (Gkeka-Serpetsidaki and Tsoutsos, 2023).

3.1.2. Socioeconomic sustainability of wind farms

In addition to environmental sustainability, it is important to demonstrate the social benefits of establishing wind farms as well as job creation, social community concerns, potential health effects and economic growth. The idea is to give an overview of the benefits and challenges of wind farms in promoting social welfare, economic stability and diversification.

Wind energy, together with solar PV, is expected to be the renewable energy capable of creating the largest number of jobs in the energy transition period, considered from 2015 to 2050 (Ram et al., 2020), reaching a total of 35 million direct jobs related to these renewables in 2050 (Sovacool et al., 2023). In addition, it is also believed that the expansion of bio-based energies will also have an effect on the European labor force, with an expected reallocation of about 1.3 %, as the labor intensity of bio-based energies is higher compared to that of fossil fuels (Fragkos and Paroussos, 2018). With this in mind, the energy transition will not have a negative effect on employment-related economic growth: jobs lost in the fossil fuel sector are expected to be fully replaced by the bioenergy sector.

Focusing on the analysis of job creation for wind energy projects, opting for onshore or offshore wind energy production entails differences, while with onshore job creation derives from the construction of wind turbines, as well as their transportation and maintenance, in the case of offshore, the construction, installation, control and maintenance of foundations and cables is also required. The number of jobs related to onshore wind energy has increased by 33.33 %, while for offshore they have tripled in the same period of time (Ortega-Izquierdo and del Río, 2020). In terms of wind energy employment, the regions of Denmark, Germany, Spain, the Netherlands and the United Kingdom are the European countries that stand out in job creation, as shown in Table 2.

When assessing the potential effects of wind energy on social welfare, several aspects must be assessed, which are considered essential to evaluate whether or not the wind farm project is accepted by the social communities (Vuichard et al., 2022): impacts on the wind farm environment, location of the facility and its effects on the landscape, the ultimate goal of the project (i.e., national or local use of the wind energy produced or export of the same), distributive justice (i.e., potential benefits for social communities located near the wind farms), renewable energy prices, and health effects (Table 3).

With respect to the impacts on the wind farm environment and the location of the facility, those aspects have already been discussed above, as they are associated with the environmental effects of wind farms. Something important when starting up a new project is to think about who is going to use the services provided by the activity, in this case, which community is going to take advantage of the renewable wind energy produced. In this aspect, it has been reported that, in general, social communities prefer the local use of locally produced energy, or at least to be included in the national grid, rather than its export to other countries (Brennan and van Rensburg, 2020). Regarding the preference between onshore and offshore, there is no definite agreement, but in general, social communities report greater concern regarding onshore than offshore wind farms (Linnerud et al., 2022).

Transparency and adequate information on new wind farm projects is also a key factor in ensuring the acceptance of social communities, in addition to those in close proximity. It has been reported that a thorough

Table 2
Wind energy employment by European country. Data source: IRENA (2022). Highlighted in green the countries that stand out on job creation.

Country	Jobs created ($\cdot 10^3$)	Country	Jobs created ($\cdot 10^3$)
Austria	2.7	Montenegro	0.08
Belarus	0.106	Netherlands	25
Belgium	3	New Zealand	0.27
Croatia	1.4	North Macedonia	0.031
Czechia	0.54	Norway	2
Denmark	22.6	Poland	14.5
Finland	7.4	Portugal	5.4
France	30.7	Romania	2
Germany	139	Russian Federation	3
Greece	4.7	Serbia	0.359
Iceland	0.001	Slovakia	0.028
Ireland	3.6	Slovenia	0.1
Italy	8.3	Spain	27.7
Latvia	0.155	Sweden	15.9
Lithuania	2.3	Switzerland	0.025
Luxembourg	0.1	Türkiye	13
Malta	0.094	Ukraine	2.2
Moldova	0.061	United Kingdom	75.1

analysis of the location selected for the wind farm installation, including topographic analysis, in order to identify potential impacts on nearby areas, could increase citizens' trust and, therefore, public acceptance (le Maitre et al., 2024). In addition, maintaining a collaborative attitude and promoting public discussions between industrial stakeholders and social communities could also be beneficial to gain acceptance and overcome negative attitudes against wind farm installation (Skjølsvold et al., 2024). On the other hand, the implementation of financial benefits for the surrounding social communities also enhances the acceptance of wind farm project development, in the range of 14–21 % (Knauf, 2022).

Regarding wind energy prices, it depends on the region and the type of wind farm: offshore or onshore. In the period from 2010 to 2022, onshore wind premiums have decreased significantly, from 0.107 USD/kWh in 2010 to 0.033 USD/kWh in 2022, according to the global report prepared by IRENA (IRENA, 2023). This could have been the result of two main factors: (1) the total wind farm installation, which decreased from 2179 USD/kW in 2010 to 1274 USD/kW in 2022, and (2) the capacity factor, which has increased by 10 % in the same period. In the particular case of Europe, installed costs varied from 2692 USD/kW in 2010 to 1626 USD/kW in 2022, while the cost of energy decreased from 0.137 USD/kWh in 2010 to 0.045 USD/kWh in 2022 (IRENA, 2023).

In the case of offshore wind farms, as expected, installed costs are significantly higher, which implies a reduction in economic benefits, resulting in higher electricity costs. Although the values on installed cost and energy price have decreased significantly over the same time period, these are higher compared to onshore, amounting to a total of USD 3461/kW for total installed costs and USD 0.081/kWh for energy price, both values for 2022. In the case of capacity factor, the improvement is not as significant as onshore, achieving a 4 % improvement (IRENA, 2023).

On the other hand, in addition to the aforementioned aspects, social sustainability is also concerned with maintaining the best possible quality of life, and in this aspect the health effects of the wind farm installation project should be evaluated. The analysis of available reports on this topic indicated the following potential impacts on human health given the installation of wind turbines in the environment of social communities:

- Noise emissions: the operation of wind turbines involves some noise: around 45 dB, which could end up causing sleep disturbances if the wind farm is located close to dwellings (Kaldellis et al., 2016). Therefore, wind farm projects should consider this potential effect at the initial design stage.
- Incidence of discomfort such as headache has been reported in 41–44 % of the respondents living in an area less than or equal to 2.5 to 10 km. Additionally, fatigue and stress, mostly given difficulties in falling asleep, with percentage values in the range of 47–52 % and 31–35, respectively (Turunen et al., 2021a).
- Some respondents have felt dizziness and nausea due to the effects of turbine infrasound, but only if the noise levels are above the permitted threshold. Therefore, these health effects are not expected if the regulations on wind farm projects are followed (Turunen et al., 2021b).

In general terms, these potential effects on human health could easily be avoided by maintaining adequate distances from wind farms to populated areas. Most European regions have established minimum distances for the installation of small and large wind turbines. To give some examples, in the case of Germany, for small turbines, the distance ranges from 200 m in the region of Mecklenburg-Western Pomerania to 1000 m in the region of Saxony, while for large turbines once the range increases from 1000 m to 1250 m in most regions. Whereas, in the case of Spain, for both types of turbines, the minimum set distance is 500 m (Dalla Longa et al., 2018).

Table 3
Analysis of social assessments on wind farm projects.

Reference	Onshore/ offshore	Location	Social analysis		Main outcomes		
			Type of assessment	Methodology			
Lindvall et al. (2025)	Both	Sweden	Surveys to 5280 respondents aged between 18 and 84.	Type of questions: "Wind farm construction in the municipality" or "within 5 km from their home". Numerical scale: (1) completely disagree – (4) neither/not – (7) completely agree	Strong support to wind farms projects for more than 20 % of respondents	Strong correlation between governmental trust and wind energy projects opinions. As higher trust, as higher support.	Ideological orientations affect over the support or resistance to wind energy projects
Caporale et al. (2020)	Both	None	Interviews to renewable energy experts from science and industry sectors	Analysis of people perception using qualitative and quantitative analysis using interviews and Optimized-Analytic Hierarchy Process and Monte Carlo analysis	The distances for wind farms constructions are not a sensitive aspect for social acceptance	Transparency on wind projects and adequate regulatory procedures are important for people living nearby wind farms	The dismantling process of wind projects is a key factor to be analyzed for a positive acceptance of wind farms
Yiridoe (2014)	Both	Australia	Multicriteria analysis, considering mixed methods	Qualitative research: six interviews with stakeholders. Structured survey research: survey to 20 respondents using numerical scales.	Social acceptance increases if key aspects are being quantified and showed, as increasing the stakeholder consultation	Consumer confidence is a key factor in order to ensure that wind farms projects are accepted	More public education is needed, 27 % of respondents didn't consider that wind energy is environmental-friendly
Lienhoop (2018)	Both	Germany	Quantitative and qualitative research methods and 4 focus research groups	Each group consisted of 15 market research institute participants. Also, a web survey with 388 persons from rural areas with wind farms energy establishment potential	Some profit of the wind energy farms should be kept on the region in which those are located	Communities' participation and cooperation on wind farms projects decision should be encouraged	Compensation on electricity bills for the communities around wind farms projects
Windemer (2023)	Onshore	Great Britain	Two wind farms survey cases provided to respondents within a circumference distance of 3.5 km	Various topics were asked: attitude against wind farms projects, perceptions about place attachment, current wind farm, life extension of the project, awareness in a 25-years frame	50 % of respondents are against wind farms project, while 31 % support them	Visual impact and noise disturbances are the main negative comments on the wind farms projects nearby	Increasing the lifetime of the wind farms project is not seen as a positive aspect from respondents
Karakislak and Schneider (2023)	Both	Bavaria	23 surveys with German wind energy project developers. 4 case studies on wind projects	Two-dimensional framework considering various factors and variables related with social aspects, policies interactions and wind projects	Mediation between project developers and social communities in highly influential on local responses	Communication strategies could help on the social acceptance for the establishment of wind farms projects	Stakeholders and political representatives have a huge effect over the positive acceptance of wind farms project
Lindvall (2023)	Both	Sweden	20 interviews over 18 municipalities in Sweden	The high number of municipalities was selected in order to consider those that have approved and rejected wind farms projects	Visual and noise disturbances of wind farms are the main factors reducing local acceptance	Monetary compensation of communities' nearby wind farms could be effective to increase social acceptance	Cooperation and collaboration between wind farm stakeholders and social communities is a good strategy
Bidwell, 2023	Both	USA	Surveys to permanent and seasonal residents, and visitors to Block Island	1095 surveys were completed, which were speciated between wind farm preconstruction (531), construction (384) and operation (180)	The visual impact is a more important negative effect for tourist/seasonal residents	Social welfare should be kept in all the wind farm project stages	Some respondents don't believe on the benefits of wind energy, so more education is needed to enhance understanding
Knauf (2022)	Both	Germany	Online survey to analyze the level of acceptance and the attitude towards wind energy projects	811 respondents have been used as baseline for analysis, using a choice-based conjoint and a seven-point Likert scale	The location of the wind farm and the distance are one of the most important factors	For wind farm project developers, increasing project acceptance is quite dependent on financial benefits	A discounted tariff for electricity price is seen as the most preferred action
Rodríguez-Segura et al. (2023)	Onshore	Spain	Survey divided in 3 blocks: (1) multiple-choice questions on general wind energy trends, (2) scale degree of agreement on wind technologies and (3) multiple-choice on acceptance or rejection of wind energy projects	329 interviewees around 60 municipalities out of the 97 on Jaen province (Spain), with a balanced representation of sex and age ranges	The size of the production site for establishing the wind farm project affects over the degree of acceptance from the respondents, preferring medium-size or small projects	The protection of natural areas for non-constructing wind farms projects is an option been preferred for respondents, so preference for non-environmental value areas	Agricultural and livestock farming areas are seen as the locations with the lowest rating in terms of acceptance, mostly given economic reasons.

(*continued on next page*)

Table 3 (*continued*)

Reference	Onshore/ offshore	Location	Social analysis		Main outcomes		
			Type of assessment	Methodology			
Liebe et al. (2017)	Both	Germany and Poland	Factorial survey experiments based on a hypothetical wind farm construction plan in the 10 km area around the respondents' residences	Six factors evaluated: number of turbines, type of investor, electricity use, opportunity to participate in the wind farm planning, tax revenues and number of turbines. Total amount of respondents: 1800	Poland showed a higher acceptance rate of wind farms projects compared to Germany	The strongest factor to increase the acceptance rate of wind farms projects is the participation on the decision-making process	Consuming the electricity produced in the wind farms by the nearby communities is seeing as a positive aspect
Sirr et al. (2023)	Both	Ireland	The survey was based on 4 positively framed statements and 5 negatively ones about wind energy	Participation of 2023 Irish citizens. The possible answers are quantitative ones: agree, disagree or don't know.	More than a half of the Irish respondents are willing to invest in local wind projects	The establishment and presence of a sustainable energy community is a critical factor for investment	The development of policies around wind farms projects increases also the rate of invest
Höltinger et al. (2016)	Both	Austria	Participatory modelling of potential areas for the construction of wind farm projects	28 experts encompassing public authorities, federal state authorities, wind farms developers, environmental and nature conservation groups, and other stakeholders	Social and political barriers, as well as market ones, are key aspects for the widespread of wind farm projects	Defining specific criteria for the selection of suitable areas for wind farms projects construction is essential	The potential of wind energy production could be reduced drastically by social barriers (92.8 to 3.9 TWh)
Cranmer et al. (2023)	Offshore	USA	262 surveys for the coastal region countries of 12 US states using visual-only choice experiment	Twelve choice tasks with respect to distance from the coast, wind farm project size and turbine size	The distance from the coastal zones is the most important factor for the respondents	There is more preference for small wind farm projects, but less care about the turbine sizes used	Coastal residents are more worried about the effects of the offshore wind farms on the landscape than tourists
Vergine et al. (2024)	Offshore	Italy	Surveys with guided interviews consisted of 19–21 questions aiming at analyzing the acceptance level of offshore wind plants	585 interviews on a wind farm planned project based on 90 floating turbines at an average distance of 18 km from both coast sides, with an estimated annual production of 4 TWh.	The climate change concern of the respondents is key for the acceptance of wind farms on long term perspective	According to the results of the survey, residents are not cared about the distance between the coast and the offshore wind farm	Education on climate change, renewable energies and on the project itself enhances the acceptance of the wind farm project
Stephens and Robinson (2021)	Both	Scotland and South Africa	Qualitative analysis to compare the willingness to accept wind farm projects on both countries	Semi-structured interviews, concretely 11 in South Africa and 12 in Scotland. Three topics were discussed: relationship between wind farms and national government, attitudes towards ownership and community consultation & benefits	While in Scotland the investment on the wind farms projects is a key facilitator, in South Africa the investment should be placed on the communities	The social communities' acceptances on wind energy projects is directly related with the national policies	In both countries, the enhancement of the communities interests and benefits increases the support of the wind farm projects
Devine-Wright and Wiersma (2020)	Offshore	United Kingdom	Survey in form of questionnaires to evaluate (1) wind farm place attachment, (2) production capacity, (3) general characteristics of the project	A final data set of 468 questionnaires were distributed, with an overall response rate of 41 %. Different locations have been considered for respondents, thus being representative of all the island territory.	The acceptance of the wind farm project depends on the location: lowest acceptance in the south-west zone of the island.	Educational level provides a higher acceptance rate, while the effects on the landscape are seen as a negative factor for establishing the wind farm project	Support on wind farm project has been seen in terms of increasing the security of the energy system and allowing autonomous source of energy for the region

3.1.2.1. Social acceptance of wind farm projects. To analyze the degree of acceptance of wind farms, many studies in the literature rely on surveys that include both quantitative and qualitative questions directed at expert groups, local communities, political representatives, and others. The objective is to assess which elements of wind farm projects influence their acceptance, either positively or negatively. It is generally observed that effective communication and participation, the economic benefits of the installation, the distance from local communities, and the political environment of the region are key factors in promoting the development of wind energy.

On the other hand, it is worth mentioning that the attitude towards the installation of wind farms by social communities differs depending on the territories, as analyzed by Vuichard et al. (2022), who have evaluated various social parameters related to wind energy in three different European countries: Switzerland, Estonia and Ukraine. The elements with the most negative social position are those related to ecological impacts, the most affected, with the effect on landscapes and protected areas, the installation of foreign energy companies and the lack of revenue sharing among surrounding communities. In these aspects, the most negative attitude has been observed for Ukraine, with a "final preference score" of −105.8 for the ecological impact aspect, while, for the same element, Switzerland showed a value of −63.23. On the contrary, when assessing the "effect on landscape and protected areas", Switzerland showed the highest concern, while for the "installation of foreign companies", Ukraine seems not to be concerned compared to the other two countries (Vuichard et al., 2022).

But this variation in attitudes does not only occur at the intercontinental level, but also within regional settings, as could be seen in the evaluation developed by Windemer (2023), focusing on two regions of Great Britain. While one region really cares about the surrounding landscape and how it could be affected, with 91 % of respondents, the other region only achieved 49 %, with 35 % of respondents having a neutral attitude on this aspect. Furthermore, regarding the opinion on the installation of a wind farm and a possible repowering (extension of the lifetime of the wind farm in km), one region supports or has a neutral attitude at 88 % and 89 %, while the other region provides significant reduced values, amounting to 50 % and 39 %, respectively (Windemer, 2023).

According to D'Sousa and Yiridoe (2014), the social acceptance of a wind farm project depends directly on the following aspects: concerns, understood as the effects on the environment and health of social communities, nuisance, related to the effects of wind turbine noise that can cause sleep disorders and with visual effects on the landscape, and consultation, which refers to the consideration of social communities in the development of decisions about the project (D'Sousa and Yiridoe, 2014).

3.1.2.2. Ocean environment and food security. Wind energy projects could also have an effect on other affected sectors such as the fishing sector for offshore wind farms. The fishing rate decreased 1.32 $h \cdot km^{-2} \cdot year^{-1}$ comparing the fishing activities before and after construction of the offshore wind farm and 0.31 $h \cdot km^{-2} \cdot year^{-1}$ when compared with operation stage. The largest differences are observed in the distances between the 5 km and 15 km buffer zones and, on average, a 77 % reduction in fishing rate capacities has been observed in almost all offshore wind sites assessed (Dunkley and Solandt, 2022). The installation of offshore wind farms also implies the modification of fishing vessel routes, which usually implies an increase in the transport distance to make catches. According to the evaluation developed by Chaji and Werner (2023), an increase in 18.5 km of distance per transit implies an increase in 9.76 M$ per year in the sector, fuel being the main contributor to these costs, representing 54 % of the total expenses. However, this aspect also affects fishermen, since the increase in transit distances implies an increase in fuel requirements, and therefore higher costs that result in lower economic benefits. To this end, a direct effect on the fishing sector is being faced with the implementation of offshore wind farm projects, being the direct impact on economic benefits the one that most concerns fishermen and members of the sector related to the industry (Chaji and Werner, 2023).

On the other hand, apart from the effect on fishing activities, certain impacts were also observed by other researchers on how species are being altered by the implementation of offshore wind farm projects. According to Watson et al. (2024) the following effects could be faced, which could be both negative and positive depending on the fish species: integration or displacement of species and physical energy effects (mostly related to the inclusion of electromagnetic fields). In addition, as to when the greatest negative effects are observed, these could be framed in the construction phase, rather than the operation phase (Watson et al., 2024).

For example, with respect to the species integration/displacement effect, it has been reported that in the buffer zones around the wind farm installation, between 500 m and 4 km, a reserve effect could be observed, since fishing activities are limited in these areas. In this sense, considering the ecosystem services, an improvement in ecological quality is observed in the sense of increased fish communities around the farm, thus being a positive effect (Baulaz et al., 2023). The problem is that, at the same time, it is having a detrimental effect on the fisheries sector, given the ban on catching fish. In addition, changes in how fish species are adapting to the ecosystem surrounding wind farms could end up in the need to adapt catching practices by fishermen, which could imply a reduction in profits as well as a problem for the food value chain (Baulaz et al., 2023).

A possible mitigation measure or compensatory action, in order to reduce the negative effect on the value chain and food availability, is the implementation of aquaculture plants around wind farms. This strategy is believed to have a positive economic effect, and also a social benefit, for both the energy and food sectors (Danovaro et al., 2024; Van den Burg et al., 2020). However, this strategy for areas with high extractive fishing production should take into account the potential alterations of the nearest ecosystem.

Regarding physical effects, Genç et al. (2021) have stated that electromagnetic fields created by offshore wind farms, as well as vibrations, negatively affect fishing activities in the country. This is why the Turkish government, in collaboration with UNESCO, has established marine protected areas in order to regulate the establishment of offshore wind farm projects (Genç et al., 2021). In this aspect, it was thought to analyze whether marine protected areas have changed from 2012 to 2021, and certainly could be related to the objective of controlling the installation of wind farms for energy production as reported by Stephenson (2023) and Genç et al. (2021). As could be observed, marine protected areas have increased significantly in the evaluated time frame, which demonstrates the concern for maintaining ecosystem services and establishing a balance between the maintenance of marine species, fishing activities and energy production. In this sense, it is important to monitor the economic implications of considering the protection of a marine area for fishing activities rather than for energy production projects, and also how this affects social communities and the food-related sector (Gorayeb et al., 2024).

3.2. Circular economy and wind farms

Alignment with the principles of a circular economy involves action going forward, in which the involvement of entrepreneurs, stakeholders, investors and policy makers will play an important role. It has been reported that, continuing with the same model of wind energy construction and production, will end up with 43 million tons of turbine blade waste by 2050 (Liu and Barlow, 2017), which is a real problem that needs to be solved before it happens.

According to a report prepared by Green Purposes Company, three main levels of concern should be analyzed when evaluating wind farms under a circular economy approach: design, reuse or proper end-of-life management of wind turbines, and work on regulatory and financial barriers. The first and second levels are really related. Asset design could allow extending the lifetime of wind turbines and could also help in the decommissioning and reuse of critical materials required for their construction (Spini and Bettini, 2024). One of the main concerns, in the short term, is the extensive use of critical raw materials, which can lead to their depletion, among which copper, rare earths and zinc are the ones in the spotlight, as they are required for the construction of wind turbines (Rueda-Bayona et al., 2022). Regarding rare earth elements, neodymium, praseodymium and dysprosium, are the ones that are required at a higher level (Huber and Steininger, 2022) as neodymium and praseodymium are used to improve the resistance of wind turbines, while dysprosium increases their resistance to demagnetization. But in addition, other metals such as nickel, chromium or platinum are needed, so their proper demand and management should also be an aspect of concern (Calvo and Valero, 2022).

In this sense, opting for more durable and efficient designs, thus requiring less maintenance or replacement, would imply a reduction in the demand for these critical raw materials. In addition, opting for waste management strategies for their valorization would imply the possibility of their reuse, recycling and revaluation, which would increase their useful life, thus converting wind energy production technology into a more circular model and, therefore, also more sustainable. Wind turbine recycling is the most analyzed in the literature and has proven to be the most circular and sustainable EoL strategy (Diez-Cañamero and Mendoza, 2023; Pulselli et al., 2022). The reason behind this is based on the fact that by recycling materials, less virgin resources are required, thus avoiding their depletion. In fact, several research works have been carried out in this aspect, seeking to avoid the mistakes of the past, as happened with fossil resources, whose uncontrolled use has ended in their depletion and their detrimental effects on the environment. An example is the report prepared by the European Commission in 2020, with the aim of developing efficient recycling technologies and promoting research on adequate infrastructures for the collection, separation and dismantling of rare elements.

Some authors have also analyzed these aspects, such as the article developed by Mendoza and Pigosso (2023), in which six priority areas have been identified to enhance circularity in the wind industry, among which are the consideration of circular economy indicators and criteria from an early design stage, the monitoring of the entire life cycle of wind turbines, or the improvement of materials and technologies to increase their recycling rate while maintaining their quality (Mendoza and Pigosso, 2023). Design aspects were also the main element of concern in the research developed by Jensen and Skelton (2018), concluding that an effective and adequate dismantling, in which the recovery and recycling of materials and equipment must be the priority to ensure the durability, valorization and recovery of wind turbine components (Jensen and Skelton, 2018).

On the other hand, with respect to the monitoring of the entire life cycle of wind farms, it has also been pointed out by other authors in the literature that material flow analysis, LCA, Data Envelopment Analysis, and the use of circularity indicators could help in the identification of gaps, in the analysis of the efficiency of wind production, on the analysis of hotpots and on pinpointing valorization opportunities on the end-of-life stages of wind turbines and wind farms (Gast et al., 2024; Gennitsaris et al., 2023).

Regarding regulatory and financial barriers identified in the Green Purposes Company report, it has also been reported that, among all the barriers that wind farm development has faced and is facing, including technical, economic, social and environmental issues, experts have pointed out that regulatory and administrative barriers have the highest impact. Some of those identified were the following: lack of regulation on how to manage and develop wind farm projects, as well as repowering projects, lack of investment and financial support from the government, absence of specific auction procedures, tax credits and denial for the installation of new wind farms, among others (Hansen et al., 2024; de Simón-Martín et al., 2022). On the other hand, another important aspect to consider, as it is also seen as a regulatory barrier, is the fact that social communities located around wind farms are not perceiving adequate benefits (Hvelplund et al., 2017). The implementation of adequate and regulated financial supports, as well as job creation, could improve the acceptance of communities for the installation of wind farm projects, thus helping their expansion and reducing the dependence on electricity from non-renewable resources, which are far from being considered as circular (Zwarteveen and Angus, 2022).

Therefore, after discussing the aspects of the circular economy and the development of wind farm technologies, it can be stated that regulatory and policy frameworks have played a pivotal role in promoting more sustainable value chains and facilitating the green energy transition. However, in terms of circularity, existing frameworks fall short of addressing the specific requirements necessary for enabling a fully circular economy. While certain initiatives have emerged, they tend to be general in scope and lack the sector-specific depth required—such as in the case of wind energy. A notable illustration of this gap is the fact that ISO 59040, the first standard dedicated to the circular economy, was only published in 2025, while ISO 14040, which addresses sustainability aspects, has been in place since 2009.

In the specific context of wind farm projects, current policies and regulations predominantly focus on accelerating deployment, rather than integrating circular design principles—such as designing wind turbines with full life cycle considerations. There is still a significant lack of standards and guidelines concerning the reuse, refurbishment, or recycling of turbine components. This gap is particularly concerning given that several materials used in turbine construction are classified as Critical Raw Materials by the European Union. In many cases, these components are inaccurately classified as non-recyclable waste, despite being recyclable, which ultimately discourages investment in circular solutions.

From a financial perspective, economic support mechanisms are predominantly geared towards the installation of new wind farms, with limited funding allocated to activities such as dismantling, material recovery, or product redesign aimed at enhancing circularity. This lack of targeted funding limits the circularity potential of wind turbines and perpetuates linear production models that are fundamentally unsustainable. Moreover, the absence of additional economic instruments—such as Extended Producer Responsibility (EPR) schemes or landfill taxes for turbine waste—further limits the incentives for manufacturers and operators to adopt circular business models.

Addressing these gaps through targeted policy reforms and dedicated financial incentives is crucial for fostering the adoption of circular strategies within the wind energy sector. Such measures would significantly contribute to a more circular and resilient renewable energy transition.

4. Conclusion

The objective of this critical review was to evaluate wind farms from a sustainable development perspective. The assessment considered environmental impacts, with particular emphasis on carbon footprint, soil quality, carbon cycles, climatic conditions, and biodiversity. The analysis also examined the broader socio-economic effects of wind farm projects, recognizing both their positive and negative implications, including potential impacts on the health of communities.

Although the circularity dimension is no longer the primary focus, the review highlighted the potential of wind energy to support circular production models. This includes improving the production chain, adopting systemic thinking that promotes the recycling and valorization of construction materials, and implementing continuous monitoring of the environmental impacts of energy production. These elements are essential to advancing more sustainable practices in the sector. Furthermore, the analysis emphasized the need for strong governmental support, the creation of comprehensive regulatory frameworks, and the development of financing mechanisms to encourage renewable energy production. Such measures are critical to increasing wind energy integration into electricity grids and reducing dependency on fossil fuels.

Like other renewable energy sources, wind energy is inherently variable and, to some extent, unpredictable. Fluctuations in wind power generation necessitate flexible grid infrastructure to maintain system balance. One major challenge is that wind energy does not inherently contribute inertia to the grid, which increases its vulnerability to disturbances. However, advancements in control systems and power electronics are helping to mitigate these limitations, improving voltage and frequency regulation and enhancing overall system reliability. These developments are expected to reduce the risk of unexpected outages and support better management of demand surges. Importantly, wind energy has the potential to contribute to more favorable electricity pricing due to its low marginal costs. This can lead to reductions in electricity prices and, consequently, lower electricity bills for consumers in both the short and long term.

Given the intermittency of wind energy, energy storage systems are essential for maintaining the balance between supply and demand. When wind production exceeds demand, surplus energy can be stored and later used during periods of low production or high demand. These systems enhance grid stability, reduce reliance on fossil fuels, and lower the risk of power outages. However, their deployment involves significant capital costs and environmental concerns related to the extraction of key minerals such as lithium, cobalt, and nickel used in battery manufacturing. Additionally, the need to periodically replace storage infrastructure contributes to operational and maintenance expenses.

The successful development and deployment of wind energy depends on supportive policies, regulatory frameworks, and favorable political conditions. These factors shape national energy strategies, influence the renewable energy share in the grid, and affect international trade in critical materials. While Europe hosts several wind energy manufacturing projects, it remains reliant on imports of essential construction materials. This dependency exposes wind energy development to geopolitical tensions and trade restrictions, which could hinder project execution and increase costs. Without adequate political and financial incentives, the competitiveness and viability of new wind farm projects may be compromised. Therefore, advancing wind energy requires strong political cooperation, affordable tariffs, and favorable trade agreements.

In conclusion, wind farm projects have the potential to serve as catalysts for sustainable value chains, offering significant carbon footprint reductions compared to fossil fuel-based systems, along with proven economic advantages. Looking ahead, efforts should prioritize the sustainable and efficient decommissioning of wind farms, responsible consumption of critical raw materials, enhanced social benefits for local communities, and the development of more durable technologies. In parallel, effective regulatory and policy frameworks—featuring tariffs, tax incentives, social benefits, and financial support—are essential to drive the widespread adoption and implementation of wind farm projects.

In conclusion, this critical review offers a multidisciplinary and integrative analysis that identifies emerging opportunities and systemic challenges frequently overlooked in the literature. It also evaluates the potential social well-being effects of wind farm projects, as well as the associated geopolitical dependencies of raw material supply chains. Combining social equity and resource resilience is crucial for the development of future wind energy policies and enhancing this renewable energy source. Furthermore, the review emphasizes the technical and regulatory innovations required to address grid instability, variable supply and storage-related environmental concerns. By synthesizing these interconnected elements, the review proposes a more comprehensive framework for evaluating wind energy systems — one that harmonizes sustainability objectives with technical feasibility and socio-political realities. In summary, the outcomes of this review could contribute to the reframing of wind farm projects within circular and sustainable paradigms, emphasizing the evaluation of social and geopolitical dimensions to ensure wind farms are adequate, and proposing new political and technological advancements to overcome current barriers and challenges to wind farm energy.

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CRediT authorship contribution statement

Ana Arias: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Maria Teresa Moreira:** Writing – review & editing, Supervision. **Gumersindo Feijoo:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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