WIND FARMS WASTE: NON-CALCULATED ENVIRONMENTAL IMPACT?

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Introduction

The need to transform the energy matrix to reduce pollutant emissions has caused the renewable sources to gain more relevance, because of their low negative effect in the environment, its energetic independence, as well as the economic and social benefits generated by an industrial network in employments and access to energy in remote places, among others (EPA, 2021; SEMARNAT, 2018; Vergara et al., 2014).

The so-called other sources of energy, wind and solar energy (Table 1) have increased significantly in the last decades. However, the proportion of this energy matrix in the world order, is still small, to the extent that to this day, the supply of energy still depends 80% on fossil fuels. In the year 2020 11% of the electricity at a global level was generated by renewable sources (BP, 2021), and for the first time in the European Union more electricity was generated through renewable energies than from fossil fuels (GWEC, 2021). Particularly, wind and solar energies contributed with 63% of the electricity production in Denmark, 43% in Uruguay, 38% in Ireland, while in Germany and Greece it was with a close 30% (REN21, 2021).

Table 1. Total supply of energy at a world level

Source	Participation in the energy matrix (%)			Increase in exajoules (EJ)	
	1973	**2010**	**2019**	**1973-2019**	**1973-2019**
Oil	46.4	32.2	30.9	55	69
Coal	24.6	28.5	26.8	90	100
Natural gas	16.1	21.3	23.2	74	100
Nuclear	0.9	5.6	5.0	28	28
Hidro	1.8	2.3	2.5	8	11
Biofuels and waste	10.1	9.2	9.4	23	31
Other	0.1	0.9	2.2	5	13
Total	**100**	**100**	**100**	**282.1**	**352.3**

Own elaboration based on data from (IEA, 2021a)

In spite of the disruptions in the energetic supply chains accentuated by COVID-19, wind and solar energy increased their global capacity in 2020 to 93GW and 139GW, with sustained growth in the last decades with an annual rate over 10% of the wind energy (BP, 2021; GWEC, 2021; IEA, 2021b). Particularly, wind energy has reached a global accumulated capacity of 707GW (GWEC, 2021), and it is estimated that the land-based wind energy will accumulate 5,044 GW in 2050 (IRENA, 2019). The sustained growth that

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has maintained this sector is explained by the maturity its technology has reached, becoming competitive to the conventional sources (GWEC, 2021; IRENA, 2021). This technology has expanded to countries that were alien to wind mills, generating changes in the communities due to their installation (Avila, 2018; Martínez-Mendoza et al., 2021).

The wind energy has been promoted at a macro level by national or state governments as a response to the fulfillment of international agreements like the Kyoto Protocol and the Paris Agreement. The stimulus to this source of energy is emphasized as a window of opportunity to attract investment or as part of a national policy of environmental care. However, this approval at a macro level does not imply that the installation of wind turbines at a micro level is accepted, which has been proven with opposition events to the installation and to the encouragement for new wind farms (EJAtlas, 2021; Martínez-Mendoza et al., 2021). This opposition to the development of wind farms is not surprising. (Wolsink, 2007). It is important to emphasize that the attitudes towards wind energy are different to the ones for wind projects (Wolsink, 2007), because of it, understanding this difference is relevant to improve planning processes from their conception up to their development. This opposition is the one that has stimulated, demanded in many cases, the improvement of the development processes. The study of social acceptance to wind projects becomes more relevant in places where it has led to violence or social attitude (Dunlap, 2017; EJAtlas, 2021; Lehmann, 2018).

In the face of these events, although wind energy has obtained social support, in different parts of the world it has gone through complicated scenarios, due to tensions, polarization, protests, and social conflicts. These protests revolve, mainly, around landscape alteration, levels of noise, damage to birds, benefits distribution at a local level, and the lack of social inclusion in the decision making for the installation or development of this industry where installed. (Arifi et al., 2017; Martínez-Mendoza et al., 2021; Nazir et al., 2020; Pavlowsky & Gliedt, 2021; Wolsink, 2007; Zárate-Toledo et al., 2019). These topics are recurring due to the changes generated by the wind farms in the communities, events that have been taking place for decades in the world order. However, in America we find externalities that need to be dealt with, for example, the management of wind turbines waste at the end of their useful life. This is a topic that, even among the opposing groups, has no relevance because, in general, the wind farms in Latin America have not reached enough years of operation life.

With this purpose, in this article we concentrate on the world revision concerning the practices of final disposal, especially of wind turbine blades, that leading countries are doing in the wind industry with an emphasis on those who are already facing the management of

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the waste generated by this industry. On the other hand, and to evaluate the environmental impact generated by this industry, we carried out a projection of this waste in the following years based on the number of turbines installed in Latin America.

The results of this research, on one hand, have the purpose of highlighting the importance that a wind project plan should have, the implied costs of reusability and the type of cost implied for not taking care of that waste in the mid-term; as well as the necessity of including in the public discussion the management and final disposal of the waste of composite material of the wind turbines at the end of their useful life for the generation of clean energy.

The wind turbine waste

The impact of the wind industry that affects the environment comes from the materials and its supply chain (Psomopoulos et al., 2019); such as concrete and composite material used in the blades, which are the biggest environmental challenges of the wind energy (Liu & Barlow, 2017). To this waste we add the waste generated during the life cycle of the blades, that is, during the manufacturing, transportation, installation, operation, and maintenance (Hoffman, 2017; Liu & Barlow, 2017; Wind Europe, 2020). These externalities along the supply chain of the wind industry have motivated the need to study the final disposal of the material waste, specifically the blades and parts of the nacelle in Latin America, mostly, now that the wind turbines are at the end of their useful life. While the tendency of the world energy matrix is to increase the participation of renewable energies; in Latin America this process of transition is still in its infancy. In any case, the development of the energy matrix has centered in the accumulation of the installed capacity. However, although it is true that there are efforts for the development of a wind industrial sector friendly with the environment, it is also true that only long term local regulatory documents can be found for this topic. On the other hand, even though Brazil and Mexico have shown leadership, Mexico has been questioned because of the negative social and environmental impacts (Chaves et al., 2018; Martínez-Mendoza et al., 2021; Nahmad-Sitton et al., 2014; Turkovska et al., 2021).

Approximately, the average life of the wind turbines is 20-25 years, and up to 35 years; then, the wind farms installed at the beginning of the XXI century, when wind energy accelerated its growth at a world level, would have little time to reach the period of dismantling. In 2020, 388 MW of wind energy in Europe were dismantled, from which 57% were dismantled in Germany (Wind Europe, 2021). Until this year, in the wind sector in the world order, 2.5 million tons of composite material had been employed, while around 14,000 wind blades

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(4700 turbines) could be dismantled by the year 2023. This represents 40,000-60,000 tons (Wind Europe, 2020). Each GW of installed capacity requires approximately 10,000 tons of material in blades (Deeney et al., 2021). Other estimations indicate that by the year 2025 the wind sector will have generated 66,000 tons of thermal-composite materials, that correspond to 10% of the total installed (Wind Europe, 2020) generating 400,000 tons of blade waste between 2029-2033, and 800,000 tons by 2050 (Andersen et al., 2014). This waste represents an accumulation of 43 million tons by the year 2050 (Ekstrand, 2020).

With all this, until now the best practice to recycle thermal-composite materials at an industrial scale has not been defined (Chiesura et al., 2020; Psomopoulos et al., 2019); and a clear legislation does not exist for its circular management. However, different re-use alternatives have been used for relatively small volumes, and in discontinuous amounts (Chiesura et al., 2020). In this sense, in the last years, the European community has created legislation to forbid composite material landfills (Psomopoulos et al., 2019). With this experience, Latin America and countries that have not reached the aging years of their wind turbines, should anticipate today the dismantling of those installations.

Around 80-90% of the wind turbines total material can be recycled (Jensen, 2019; Wind Europe, 2020), the pieces like the tower, foundation, components of the gearbox, and the generator, can be recycled properly (Jensen & Skelton, 2018). However, since the blades are manufactured in fiberglass, and the nacelle, made of fiberglass coated steel, these still pose challenges due to the fact that they are manufactured with composite materials (Chiesura et al., 2020; Jensen & Skelton, 2018), although they can be recycled by chemical, thermal, or mechanical processes (Joustra et al., 2021; Wind Europe, 2020). However, the current processes are not yet capable to dealing with high volumes or being economically profitable (Joustra et al., 2021; Wind Europe, 2020), which is why, most of the composite materials are incinerated or placed in landfills (Joustra et al., 2021).

Not having methods capable of attending high volumes, problems are being generated for the efficient environmental management, for example, in the United States landfills that add thousands of wind turbines are identified (Martin, 2020; Sneve, 2019). Although it is argued that the reception of this waste generates local benefits of $675,000 dollars (Martin, 2020) when fixing a fee of $59 dollars per ton received (Lachance, 2019), this strategy is not a sustainable solution.

In the face of minimizing the negative externality of these wind components, the incineration as a source of energy in production processes (Wind Europe, 2020) has been a practice

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that seems to solve the environmental problem that is caused by wind waste, but it should also be mentioned that this activity of incineration entails other negative externalities like the generation of toxic gases (Cooperman et al., 2021; Joustra et al., 2021), and the generation of up to 60% of incinerated material in ashes (Jensen & Skelton, 2018), from which no utility is reported. Another disposal destination that has been given to these elements of the wind turbines is in the production of cement (Wind Europe, 2020). It is a method that is applicable to the blades of fiberglass reinforced compounds (GFRP, carbon-fiber-reinforced polymer), but not for the carbon fiber reinforced blades (CFRP, carbon-fiber-reinforced polymer) (Cooperman et al., 2021; Yazdanbakhsh & Bank, 2014).

The reconditioning as an element for the construction of houses, transmission network towers, bridges, furniture, among others, is another alternative that has been explored with the wind turbine blades (Bank et al., 2018; Joustra et al., 2021; RE-WIND, 2021; Wind Europe, 2020). (Guzzo, 2014) shows the use of dismantled wind blades as an alternative to build a children's' playground in Rotterdam, or as a parking lot for bicycles, bridges, or urban furniture (Wind Europe, 2020).

(Bank et al., 2018) present architectural alternatives in Yucatán-México to build houses out of wind blades, considering in the design the affectations of flooding and hurricanes, which are present in this area.

In recent years, the disposal destination of the blades and elements of the wind nacelle have gained relevance. The wind sector has undertaken actions to transit towards a management under the perspective of a circular economy, making developments of new materials that facilitate wind blades recycling (Barsoe, 2021; Gamesa, 2021); although because they are new technologies, they will still take time to be applied. Meanwhile, the volume generated by the wind turbines installed in recent decades, which will be dismantled continuously in the following years, must be dealt with.

For thermal-composite materials recycling two main processes are distinguished: mechanical and thermal. The mechanical processes require less use of energy and their cost is lower in comparison to thermal processes (Wind Europe, 2020). However, grinding this waste requires great consumption of energy (Jensen, 2019). This method has the disadvantage that the value of the materials decreases significantly (Jensen, 2019; Wind Europe, 2020). In this treatment the size of the material is reduced by means of crushing or grinding, among others, to later separate it into resins or fibers (Yazdanbakhsh & Bank, 2014). Among the recycling thermal treatments for these materials, we can find: pyrolysis,

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solvolysis, heat recovery, the process of fluidized bed (Psomopoulos et al., 2019; Wind Europe, 2020), even if it is estimated that recycling these composite materials will quadruple in 2030, nowadays it presents difficulties at an industrial scale (Psomopoulos et al., 2019). Currently, technologies for their recycling still pose difficulties at an industrial level (Wind Europe, 2020).

Wind turbine blade waste management

Five main routes for the destiny of wind turbine blades are identified: reuse, reconditioning, incineration, co-processing in cement plants, and recycling (Jensen, 2019; Wind Europe, 2020). Because of its negative environmental impact, placement in landfills or incineration are the less desirable alternatives (Deeney et al., 2021; Nagle et al., 2020; Psomopoulos et al., 2019). Reusing elements of the wind generators at the end of their useful life opens up the opportunity to extend the usefulness of the dismantled wind turbine blades, which has to be accompanied by an analysis of structural conditions and subsequent management based on the international standard guidelines, like DNVGL-ST-0262 or EC TS 61400-28 (Wind Europe, 2020).The reconditioning alternative provides the chance to give another use to the wind turbine blades, which is beneficial due to the challenges that are still present in the recycling methods. However, although some demonstrations have initiated for their use in urban places, (Guzzo, 2014) these alternatives would hardly deal with the high volume of generated waste in the next decades. Recycling and recovery offer greater advantages when transforming the wind generator blades in new products, although these processes imply the use of more resources and energy. For example, the recovery that is carried out in the cement production processes reduces the carbon footprint of the cement, it is scaleable, and its logistics are not complex (Wind Europe, 2020).This process requires the blades to be grinded in small parts and mixed with recovered solid fuels, where, the polymer portion of the blade works like a substitute for fossil fuels for the oven up to 850°C, in this point; when the oven increases its temperature up to 1450°C (Image 1), the elements of the fiber are calcified without leaving waste that requires a landfill (Nagle et al., 2020).

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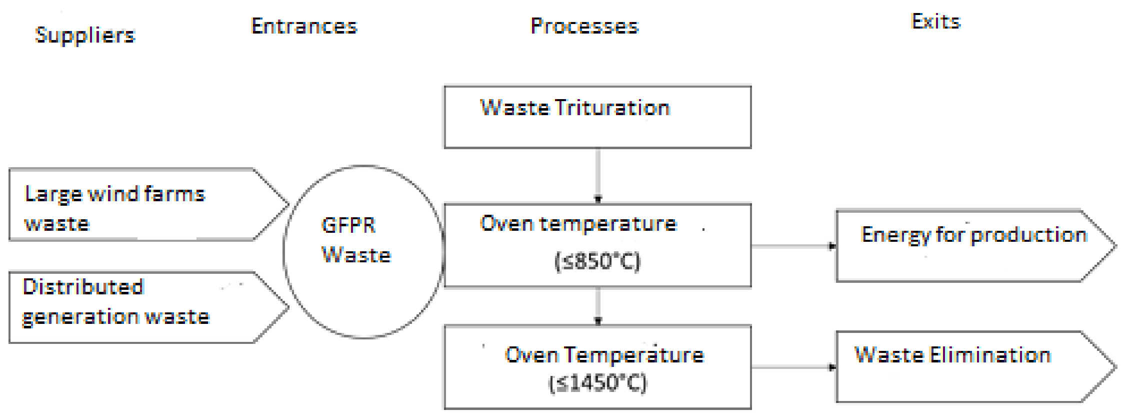

Image 1. Treatment in cement ovens

Own elaboration based on (Nagle et al., 2020; Wind Europe, 2020)

Image 2 shows the hierarchy for the prevention and waste management. In the prevention technical recommendations have been given (DNV GL, 2016; Siemens Gamesa, 2016) and have started actions to extend the life span of the wind turbine blades. In some cases up to 35 years (Sharpley, 2013). Other actions are related with new technological developments to facilitate wind turbine blades recycling (Gamesa, 2021; Vestas, 2020).

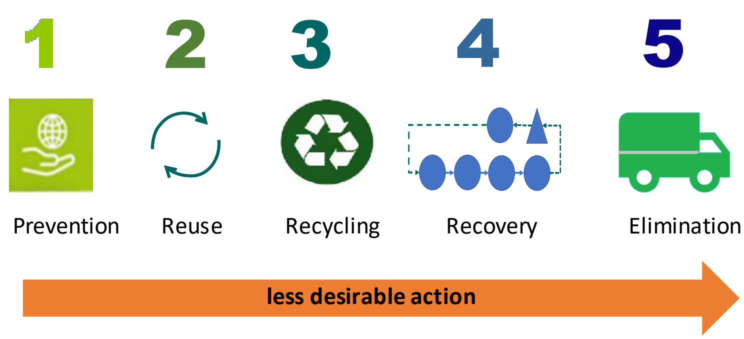

Image 2. Waste hierarchy

Source: Own elaboration based on (European Comission, 2021)

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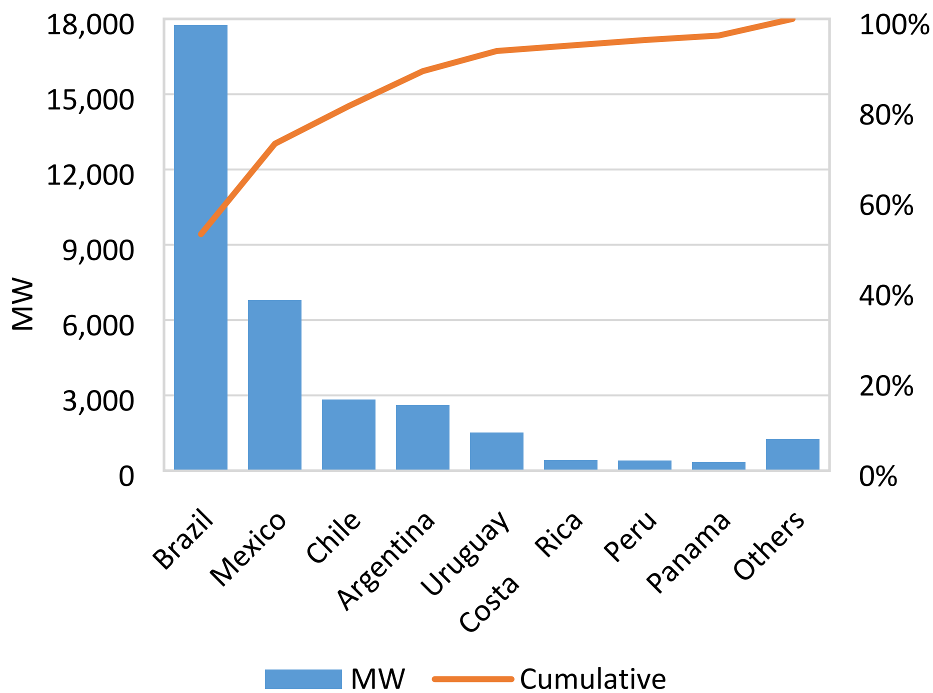
For example, the dismantled wind turbine blades have been recycled as aggregate in the construction of buildings or highways, furniture, acoustic insulation (Deeney et al., 2021; Wind Europe, 2020). Recycling allows the recovery of materials, but it loses the effort invested in manufacturing (Joustra et al., 2021), and so incineration has become the last alternative (Joustra et al., 2021; van Buren et al., 2016).

Wind energy in Latin America

Until year 2020, the installed global wind energy capacity was 707.4 GW, from which, 33,906 MW belonged to Latin-American countries (GWEC, 2021), that is, they represented less than 1% of the globally installed capacity, and, among them, Brazil has 52% of that installed capacity, followed by Mexico with 20% (Graph 1). In the case of Uruguay, although its installed capacity is lower compared to other countries, in terms of accumulated MW (1484MW); this capacity covers 40% of its national electricity demand (AUGPEE, 2021).



Graph 1 Accumulated wind capacity in Latin America

Source: Built with data from (GWEC, 2021; The Wind Power, 2021)

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Table 2 shows the wind power installations identified in Latin America. Brazil and Mexico stand out as the countries with a greater number of wind generators installed with 73% from the total.

Table 1. Wind power installations in Latin America

Country	Wind Generators	Wind Farms
Brazil	8500	726
Mexico	3012	70
Argentina	1104	36
Chile	945	40
Uruguay	600	44
Costa Rica	343	18
Peru	193	8
Dominican Rep.	157	6
Panama	128	3
Honduras	114	3
Nicaragua	96	4
Venezuela	88	2
Cuba	74	4
Jamaica	60	4
Puerto Rico	52	4
Bolivia	40	4
Guatemala	38	3
Ecuador	33	4
Curazao	15	2
Colombia	15	1
San Cristóbal y Nieves	8	1
Granada	4	2
Bahamas	1	1
Total	**15,620**	**990**

Source: Built with data from: (ABEEólica, 2021; Comisión Nacional de Energía, 2021; Ministerio de Economía, 2021; The Wind Power, 2021)

Because most installed turbines until last decade were of 2MW; and based on the fact that a typical 2MW turbine, whose 50 meters blades have an approximate weight of 20 tons FRP (Bank et al., 2018); it can be estimated that at least 312,400 tons of composite material in the turbines are the ones that have been installed in this region of Central America. Image 3 shows the distribution of wind farms in Brazil, Mexico, and Argentina, the countries with the largest amount of wind generators installed in Latin America.

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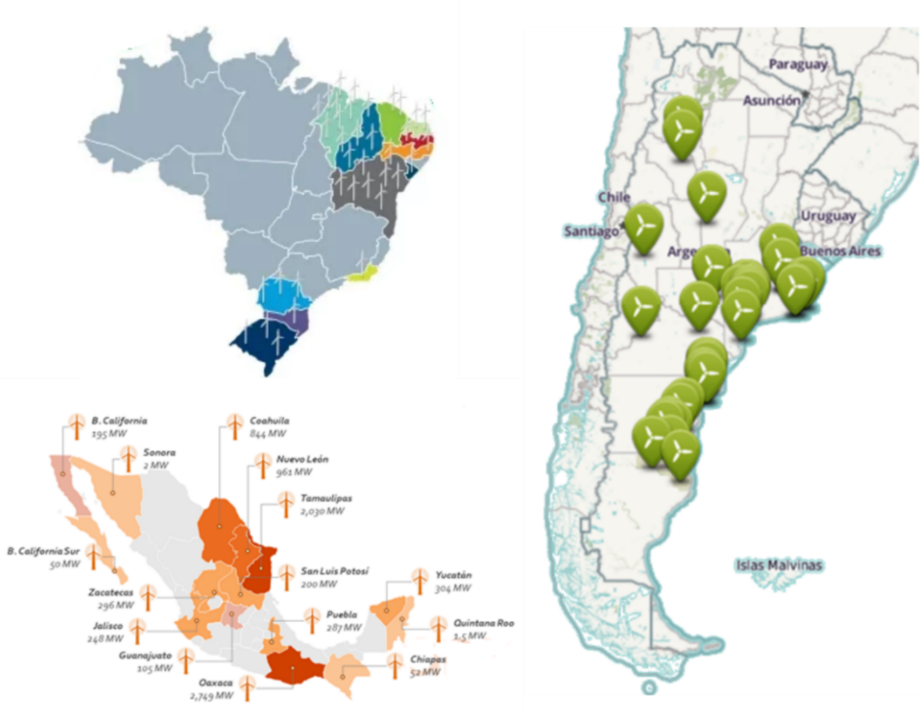

Image 3 Wind farms installed in the main countries in Latin America

(ABEEólica, 2017; AMDEE, 2018; Ministerio de Educación, n.d.)

Nevertheless, the amount of wind turbines installed in Latin America is less compared to countries like China, which until 2017 had installed 92,000; 7000 in only one wind farm (Koufakis, 2017), and in 2020 it added almost 50GW of capacity installed, which represents approximately almost 20 thousand turbines of 2.5 MW; or compared to the 29,608 installed in Germany (BWE, 2020). In spite of these differences, the problem for the management of this waste in Latin America is not less important due to the difficulties this continent faces for the waste management and the wind energy growth perspectives in the region. Brazil expects to reach an installed wind capacity between 110-195 GW by 2050 (MME, 2020), this would represent at least six times the installed up to 2020; Argentina, in the best scenario, could install 58 GW by the year 2040 (Beljansky et al., 2018), while Mexico would reach 15 GW of accumulated power in 2030 (SENER, 2016). This scenario of dismantling clean energy wind generators should be as of now, an environmental and potentially social concern in the following 15 years.

Discussion

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The generation of waste from composite materials reinforced with fibers has been present in the automotive, aerospace, medical, electronics, and construction industries, among other uses (Krauklis et al., 2021; Scribante et al., 2018). In 2025, the wind industry will contribute with 10% of the total thermostable waste, and with 5% if thermoplastics are considered. (Wind Europe, 2020). In this contrast, what alternatives have been defined for their treatment?

Wind energy is accepted as a source of clean energy that reflects the decrease of polluting emissions, non-existent use of water during the operation, among other benefits (GWEC, 2021; Kaldellis & Zafirakis, 2011; Saidur et al., 2011); although its development has not been free of questioning among the society of the communities where this industry is settled at a local level, with an emphasis on landscape, noise, wild life, among others (Arifi et al., 2017; Martínez-Mendoza et al., 2021; Nazir et al., 2020; Wolsink, 2007). However, until recently, there was little attention on the impact of the turbines waste, specially, the wind blades and parts of the nacelle, which are manufactured with composite materials, which, by nature are currently difficult to recycle in large quantities (Chiesura et al., 2020; Psomopoulos et al., 2019). It is important to highlight that the social opposition regarding wind farms has been about the local environmental alterations, and until now, the management of this type of waste has not gained relevance in the discussion in emerging countries.

For countries that started with the development of wind energy in the 1990s, the end of the useful life of the turbines has become a problem for its management, generating landfills of thousands of wind turbine blades. Although technologies for its treatment have been developed, there are no clear guidelines for its management yet (Wind Europe, 2020). If this topic is complicated to manage in countries which have proposed adaptations in their legislations, such as forbidding wind blades landfills (Wind Europe, 2020) and motivating a high sense of environmental care; this topic is even more complex in emerging countries, where the need of adapting the legal framework for this new challenge has not taken a stance yet in the public debate.

The opportunities of recycling the wind turbine blades as elements for the improvement of the urban space (Belton, 2020) can be significant, especially in underdeveloped countries, due to a lack of public spaces in the communities where wind farms have been installed. However, this alternative is not enough to deal with the volume of materials that will be generated in the future. The proposal of (Bank et al., 2018) to employ wind blades in the construction of housing is attractive because it would benefit disadvantaged social sectors;

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nonetheless, in these two proposals it should be determined since the beginning of the wind farm projects, which would be the management of those components at the end of their useful life; so that, when a wind farm is dismantled, a certain destination for this waste will already exist.

Although the waste volume related to the wind turbine waste in Latin America is smaller compared to the one generated in countries of Europe or the United States, the planning for the disposal destination of the dismantled wind turbine blades in Latin America does not represent a less important challenge.

Within the proposed alternatives, attention is drawn to the fact that with the current technological and economic conditions, a viable destination for the dismantled wind turbine blades waste is in the cement production processes. This disposal destination will allow dealing with the problem from the start, and at the same time, the recycling technologies are economic and industrially profitable.

Conclusions

The disposal destination of composite materials during the planning of wind farms has not yet been fixed in the discussion agenda in emerging countries. It is a relevant topic that should be discussed in the consulting processes, to the extent possible, starting from the communities where they are installed. This society-enterprise-government activity will provide more certainty to the inhabitants as a task of public transparency. Even more when it is necessary to anticipate opportune measures due to the aging of wind farms in order to decrease social tensions in communities and national and international environmental groups.

Latin American countries should make progress in the adaptation of their legal framework for the management of this waste taking as a reference the experience of the European community, especially Germany, who has established measures to avoid the proliferation of wind turbine blades landfills; a non-desired disposal destination due to its environmental impact and the impossibility of recovering materials or energy. One alternative that can be motivated in the Latin community, and that can make trends, is to take advantage of the wind turbine blades in the cement production processes as it allows the recovery of energy. However, it is necessary to motivate innovation in order to make the recycling methods profitable at an industrial level.

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In Latin American countries, due to social resistance and conflicts experienced in the development of wind projects, it is necessary to initiate the discussion regarding the processes for the management of wind generators waste, especially, composite materials, due to the existing challenges in the recycling processes. Dealing with this issue waiting for turbines to use up their life span can open up a space for the creation of resistance and social claims in communities in which this industry is settled.

Authors contributions

Martínez-Mendoza, E.: Conceptualization, Data curation, Writing-original draft preparation. **Fernández-Echeverría, E.:** Data curation, Visualization. **García-Santamaría, L.E.:** Investigation, Data curation. **Ruvalcaba-Sánchez, L.:** Supervision, Writing-original draft preparation. **Fernández-Lambert, G.:** Conceptualization, Writing-Reviewing and Editing.

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