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Published in:
Sustainability

Link to article, DOI:
10.3390/su15065496

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Magar, V., Pena, A., Hahmann, A. N., Pacheco-Rojas, D. A., Garcia-Hernandez, L. S., & Gross, M. S. (2023). Wind Energy and the Energy Transition: Challenges and Opportunities for Mexico. *Sustainability*, *15*(6), Article 5496. https://doi.org/10.3390/su15065496

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Article

Wind Energy and the Energy Transition: Challenges and Opportunities for Mexico

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Abstract: We present a review of wind energy development in Mexico, factors hampering this development, and proposals for solutions to address this hampering. This review is relevant in the context of climate change mitigation strategies and the achievement of the United Nations' sustainable development goals. Wind energy can be harvested at competitive costs to solve society's energy poverty and climate change problems. Firstly, we present the current wind energy installed capacity and wind power generation status globally and in Mexico and discuss why Mexico is lagging behind, particularly since 2020. Despite this lag, several state governors are still considering wind energy developments. The current economic context is then considered, with community wind energy as a solution forward for wind energy development, using a successful case study from the UK that has addressed energy poverty and provided an additional income source for an island community. Any community energy project using wind as its main energy resource relies on accurate wind energy assessment in its feasibility analysis. Thus, an evaluation of different wind energy atlases for Mexico was performed, which showed that models considering microscale processes could lead to a relative difference of more than 50% when compared to those that do not consider them. This led to the conclusion that microscale effects must be considered in wind energy characterization models. Furthermore, it is acknowledged that wind faces other challenges, such as the effect of future climate change scenarios, grid planning, and vulnerability and risk associated with tropical storms, which can be substantial in Mexico. Solutions are proposed in the form of possible wind power generation scenarios, planning and implementation of centralized and distributed transmission lines, and possible wind siting and technological choices to reduce the vulnerability and risk to tropical storms. Finally, we close with some future perspectives for researchers and decision-makers. The main conclusions are that sustainable growth can only be compatible with a transition to renewable sources of energy, energy community projects can address energy poverty and achieve sustainable development goals, wind energy feasibility studies need to include microscale effects, return of investment can be improved by siting the wind farms in regions of low vulnerability and risk to extreme events, and high-voltage transmission lines are crucial for sustainable development, even with the important role that distributed systems play. Finally, turbine growth and materials recycling, among other factors, must be considered when assessing the environmental impacts of wind farm decommissioning.

Keywords: wind energy; energy policy; sustainable development goals; social and economic development; environment and climate change; Mexico

Citation: Magar, V.; Peña, A.; Hahmann, A.N.; Pacheco-Rojas, D.A.; García-Hernández, L.S.; Gross, M.S. Wind Energy and the Energy Transition: Challenges and Opportunities for Mexico. *Sustainability* **2023**, *15*, 5496. https://doi.org/10.3390/su15065496

Academic Editor: Byungik Chang

Received: 14 January 2023
Revised: 13 March 2023
Accepted: 14 March 2023
Published: 21 March 2023

1. Introduction

Energy production from wind turbines constitutes a suitable alternative to fossil fuels. From utility-scale plants to small turbines in residential areas, technically-viable wind solutions have become widespread. Moreover, costs of onshore and offshore wind energy have declined by 39% and 29%, respectively, between 2010 and 2019 [1], making wind energy more affordable and helping reduce global energy poverty [2]. The technological maturity, combined with the economy of scale, gives wind energy a unique advantage over other renewable energy sources. As an affordable clean energy [3], it can play a synergetic role and help achieve several of the United Nations' sustainable development goals (SDGs), such as improving energy wealth, providing employment and economic growth opportunities, reducing inequality, promoting innovation [4], and fighting climate change [5,6].

Achieving transport and energy production decarbonization by 2050 will be crucial to comply with the terms of the Paris agreement [7], and reach net zero CO_2 emissions [8,9]. Although renewable technologies infrastructure still requires fossil fuels, life cycle greenhouse gas emissions are significantly lower for technologies powered by renewable resources than those powered by non-renewable ones [10]. Renewable energy corporations have been criticized for perpetuating social injustices [11] or using vast land extensions for energy production. However, when comparing normalized land use for both renewable and conventional energy sources, it has been found that some types of renewables, like PV, actually use the least amount of land [12]. Tröndle [13] showed that onshore wind has the highest land requirement if the spacing is considered, when compared to rooftop Photovoltaics (PV), utility-scale PV, and offshore wind, with the latter three being "no-regrets" options when the aim is to reduce the spatial extent of land-based renewables. Moreover, PV and wind power plants can be located in multi-use brownfields [14], and recent research has shown that land requirements of renewables can be reduced with little effect on costs [13].

Additional cost reductions can be achieved with hybrid systems and by addressing electricity generation and water desalination [15]. Studies on solar-wind independent systems are common, but not those integrating access to electricity with hydrogen storage and desalination. Although this technology would help provide electricity and potable water for communities in semi-arid coastal regions, the reliability of the system and its cost-benefit advantage, particularly at small scales, is unclear. Rajewski et al. [16] showed that wind turbines and crop co-location, such as corn and soybeans, were beneficial for the crops because turbines slow down the wind but increase turbulence. Therefore the wind interacts more with the crop, possibly increasing evaporation from the crop or moving carbon dioxide down into the crop. The turbines delay dew formation at night, which is beneficial to the crops because dew may cause fungi issues. Farmers can therefore get a stable income from the lease of the land, and as turbines take up a small proportion of the land, they can carry on with their farming activities. Moreover, because of the effects of the turbines on the microclimate around the crops, their crops will be healthier with present turbines than without.

From a socio-economic and rural sustainability perspective, a recent study by Mills [17] showed that wind energy development might help reverse the rural population loss observed since agriculture's industrialization. The economic impact of leasing the land to a wind farm is easy to measure. The income from land leasing is reinvested into agricultural activities by the farmers, but the social impact is more nuanced. An important finding of the study was that a farmer with a wind farm lease is significantly more likely to have a succession plan in place as well. In other words, the supplemental income provided by the wind turbines helps convince the younger generation that it is worth staying on the farm.

In relation to the impacts of adopting utility-scale wind energy in the fight against climate change, the immediate consequence of renewable energy production is the reduction of CO_2. However, the impacts go beyond just the reducting CO_2 emissions, with studies showing that large-scale wind farms can increase rainfall and change vegetation growth patterns in arid lands [18]. Energy-intensive industries such as steel and iron are ideal clients for utility-scale wind. They have proactively researched and implemented green energy generation models to reduce their greenhouse gas emissions [19], without jeopardizing operations and securing the jobs provided by industry. The impacts of climate change can be reduced significantly thanks to the transition of these industries to clean energy sources.

As the Danish experience of the 1970s demonstrated, common citizens and small to medium-sized businesses can also contribute to the energy transition by organizing into energy communities. These energy communities play crucial active roles in the energy markets: they contribute two to eight times more to the local economy than non-local competitors, while efficiently decarbonizing the economy. A report by consultants CE Delft, based on the European union (EU), showed that energy communities could produce up to half of the EU's clean energy by 2050 [20]. Moreover, energy communities advance new forms of justice and democracy in practice [21]. However, it is unclear how they can gain a foothold on the prevailing structures of the renewable energy economic system [22].

This review paper is motivated by Mexico's lag in implementing onshore and offshore wind energy projects. By analyzing global and national installed capacities and their annual growth in the past years, we show that in the case of Mexico, such lag can be explained by the current Mexican economic and political context. Mexico's current policy discourages private investment in Renewable Energy projects, as the government argues that private projects perpetuate social injustice. To rebut this, we discuss an example of a community energy project that provides a solution to energy poverty and addresses the social injustices wind energy developers have otherwise caused in some parts of the country. Community energy projects based on wind energy, like any other wind energy project, require a characterization of the wind resources that is as accurate as possible at a local scale, i.e., the microscale. This improved accuracy should be reflected in what we commonly refer to as wind energy atlases. However, not all wind atlases incorporate the microscale effects, particularly those generated from weather models. Several wind atlases are available for Mexico; here, we show that the Global Wind Atlas produced by the Danish Technical University (DTU), which considers meso-microscale coupling for wind speed predictions, can be used to preliminary investigate wind energy potential. Wind faces other challenges, including the effect of future climate change scenarios, grid planning, and vulnerability and risk associated with tropical storms. Wind energy can combat climate change, but the degree to which it can achieve this depends on a number of factors, e.g., future generation scenarios; technical, ecological, and economic restrictions; the degree of development of the transmission lines; and the effects of hydro-meteorological extremes on wind farm siting and choice of technology. Other issues and solutions regarding the sustainable development of wind energy, e.g., territorial planning [23] and economic feasibility of wind energy projects for different site and technology choices based on the local wind climate [24,25], should be addressed too. We recognize the importance of these issues, as can be inferred by some of the examples we will use, but they are site and project-dependent. Here we will focus mostly, on problems and possible solutions with implications at a countrywide scale.

This work is organized as follows. In Section 2, the World's current status in installed capacity (IC) is discussed, and the evolution of IC in Mexico in the last few years is presented and discussed in relation to the energy policies implemented by the previous and the current federal administration. We selected some wind farm samples to show the spread of important wind energy resources throughout the Mexican territory. In Section 3, Mexico's lag with respect to global trends is explained within the context of the current government's political and economical approach. In Section 4, we present the case of an energy community in North Uist, an Island of the Outer Hebrides (in Scotland, UK), where a wind turbine project was implemented for community consumption and energy export. This has been included to show a current community energy success story using wind turbines and consider this a possible avenue in other countries, such as Mexico. In

Section 5, we present different wind energy resource evaluation methods and highlight the advantages of models that integrate microscale effects into mesoscale wind energy resource assessments. Sections 6–8 focus on the challenges posed to wind energy development by future climate change scenarios, grid planning, and the vulnerability and risk indexes associated with tropical storms. Finally, in Section 9, long-term perspectives and concluding remarks are provided. It is worth noting that although the study focuses on Mexico, it can be replicated for any other country or region of the World.

2. Status of Installed Capacity and Changes in Energy Policies

Global renewable energy status reports show that the global IC in the wind energy sector increased between 52 and 64 GW annually from 2014 to 2019 [26–28]. In 2020 and 2021, it increased by 95 GW and 102 GW, respectively, thus reaching a total of 845 GW by 2021. In 2020, 35 GW [27], and in 2021 almost 19 GW [28], of the total IC corresponded to offshore wind farms. Figure 1 shows global installed capacity between 2002 and 2021 [28,29].

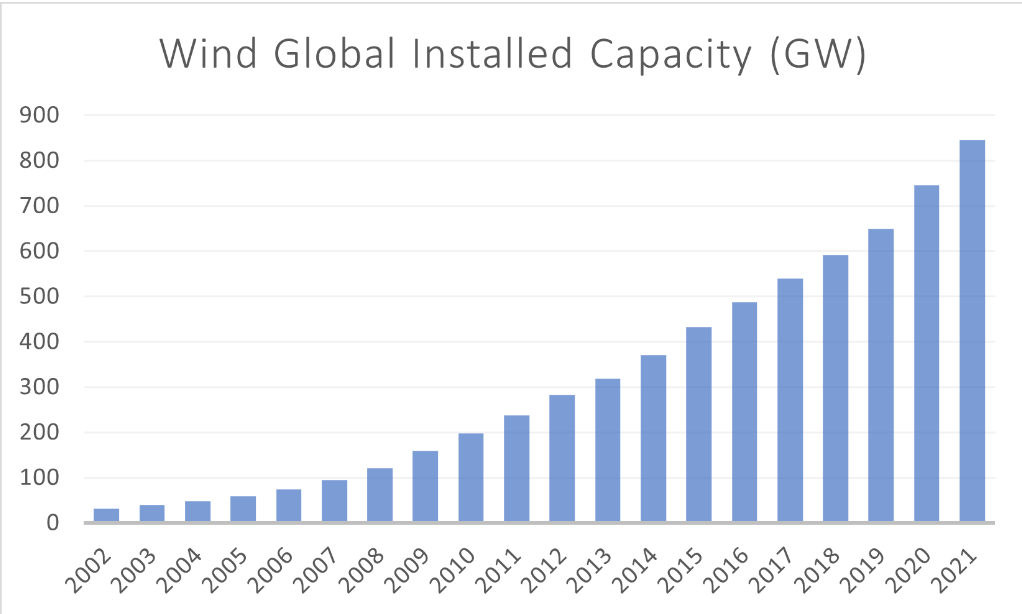

Figure 1. Global wind installed capacity from 2002 to 2021. Data taken from [28,29] (accessed on 1 March 2023).

Wind farms are operating in more than 90 countries; in 30 of them, more than 1 GW of IC has already been achieved. It is worth mentioning that by 2017, several European and some Latin American countries produced more than 10% of their energy from wind. Denmark and Uruguay, in particular, produced almost 60% and 40%, respectively, of their electricity from wind. The case of Denmark is noteworthy; since the 1970s, a number of wind farm projects have been developed by local energy cooperatives. This significantly increased the contribution of wind energy to the country's energy matrix and improved the level of acceptability of wind turbines as a source of energy among the Danish population.

Figure 2 shows the wind power generation (TWh) for all IEA member states from 2010 to 2021 [30], and Mexico's wind power generation (GWh) for the same years [31]. While IEA members' global wind power generation grew steadily between 2010 and 2021, we notice growth fluctuations in wind power generation for Mexico over that same period, with a growth deceleration from 2018 onwards.

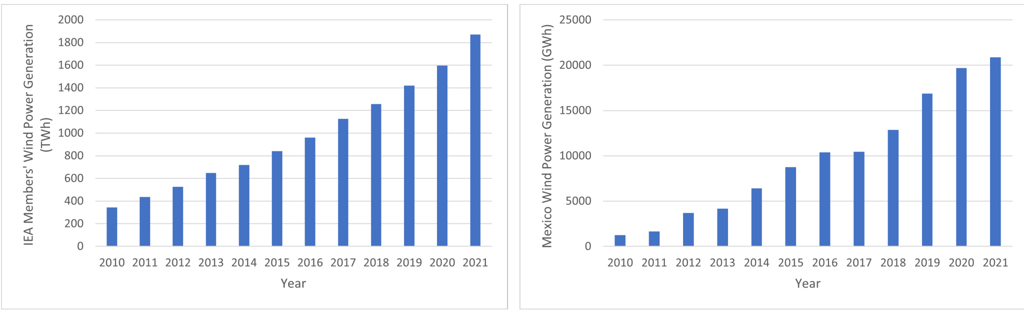

Figure 2. IEA members' total wind power generation in TWh (**left**), and Mexico's wind power generation in GWh (**right**), from 2010 to 2021. Figures generated with data from [30,31], respectively.

In 2018, 95% of new energy installations were exploiting renewable energy resources [32]. Furthermore, in 2018, the EU generated 362 TWh from wind energy farms, which increased to 458 TWh in 2020, corresponding to an increase of 25% in 2018 [33]. Wind energy covered 13.7% of the EU's energy demand in 2018, and 16% by 2020. It is expected that from now until 2025, some European countries will lead the wind energy development market, with the following IC (in GW): UK, 18; Germany, 16; France, 12; Sweden, 7; The Netherlands, 6 [33]. In 2020, Finland installed wind energy plants with the largest wind turbines on land, with an average rated power of 4.5 MW, while the smallest turbines, with an average rated power of 2.2 MW, were installed in the UK [33].

Offshore wind turbines are increasing continuously in rated power. While the largest turbine in 2017 had a rated power of 8 MW, some prototypes now reach 16 MW [34]. On the other hand, offshore wind turbines, such as the Heliade-X, have increased their capacity factors to up to 64%, compared to 25% to 42% that offshore wind turbines could achieve in the 1970s and 1980s [33]. From an economic point of view, each percentage increase in capacity factor represents a return on investment of approximately seven million dollars [35]. Thus, an increase to 60–64% in capacity factor represents an increase in the return on investment of 100 to 300 million dollars per turbine. Finally, wind turbines with hubs at higher heights and with longer blades might operate under conditions where wind speeds are less variable and under low turbulence, making energy production more predictable [35]. These facts illustrate some of the benefits of the economy of scale. Unfortunately, Mexico is far behind in wind development and deployment, with only onshore wind farms in operation and no clear offshore wind farm plans.

We now focus on historical and current onshore wind energy development in Mexico. In 2017, wind energy plants in Mexico produced 10 TWh, corresponding to 3.44% of the global annual energy production (AEP) from wind for that year. With 45 wind farms distributed throughout the national territory, only 3% of the total annual energy produced by the country was wind generated [36]. Table 1 shows some of the major wind energy plants currently in operation in Mexico. Compared to the largest wind farm in the world, Hornsea 2, off the Yorkshire coast, with 1.3 GW of IC, the largest wind farms in Mexico have installed capacities three times smaller. This helps put into perspective the degree of development of wind energy, or lack of it, in Mexico.

In 2017 the total installed capacity (IC) in Mexico was 75 GW, with only 29.5% of that based on renewable energy sources. This total IC had increased to 83 GW by 2020 [36,37], or a 10% growth in three years. The wind energy IC was 4 GW in 2017 and 6 GW in 2019, representing an increase of 50% in only two years. However, we must highlight that this growth took place mostly in 2018, under a regulatory policy framework promoting renewable energy projects. During 2020 and 2021, regulatory changes were introduced that hampered investments in the renewable energy sector. In fact, between 2019 and 2020, the wind energy sector only grew by 0.76 GW in IC [38]. Despite the regulatory measures introduced by the federal government, some states with the highest wind energy potential, such as Tamaulipas, have carried on planning a significant growth in IC, from 1.5 GW in 2020 to 1.9 GW by 2025 [38].

Table 1. Operating wind power plants (source: obtrenmx.org, accessed on 10 March 2022).

Plant Name	MW	Region	Owner	Prod. Scheme
Eólica del Sur	132.0	Oax	PGGM Inv.	Self-Supply
Alarde Tizimin	75.6	Yuc	Alarde Soc. de En.	Generation
Enel Palo Alto	129.0	Jal	Enel	Self-Supply
EDP Coahuila	199.5	Coah	EDP	Self-Supply
Acciona El Cortijo	183.0	Tamps	Acciona SA	Generation
Dominica En. Limp.	200.0	SLP	Enel SpA	Self-Supply
Enel Vien. del Altipl.	100.0	Zac	Enel SpA	Self-Supply
Sierra Juárez	155.0	BC	Sempra Energy	Export
Zuma Reynosa III	424.0	Tamps	Actis LLP	Generation
El Mezquite	250.0	NL	Cubico Ltd	Unknown

Plant Name Abbreviations: En. Limp.—Energía Limpia (Clean Energy); Vien. del Altipl.—Viento del Altiplano (Highland Wind). Region Abbreviations: Oax—Oaxaca; Yuc—Yucatan; Jal— Jalisco; Coah—Coahuila; Tamps—amaulipas; SLP—San Luis Potosí; Zac—Zacatecas; BC—Baja California; NL—Nuevo León. Owner Abbreviations: Inv.—Investments; Soc. de En.—Sociedad de Energía (Energy Society); EDP—Energías de Portugal (Portugal Energías). Prod.— Production.

In Mexico, only 10% of the total energy consumed was provided by renewable energy sources in 2020 [27]. Without considering hydraulic dams, renewables contributed 12.8% of the country's IC in 2017. This had increased to 18.4% by 2020. The IC of solar photovoltaic grew from 214 MW in 2017 to 5149 MW in 2020, being by far the renewable energy source with the largest annual growth rate, and positioning Mexico among the four most important photovoltaic energy developers in Latin America [27]. There was also a large increase in thermal solar energy projects in the industrial sector, positioning Mexico as the global development leader. Mexico also became the leader in Latin America in new geothermal developments, and sixth worldwide, with an IC of 9.9 GW at the end of 2020 [27].

3. Wind Energy Development in the Current Economic Context

From January 2020 to date, a global pandemic has slowed all the world's economies, dislocated industries and logistical and commercial production chains while simultaneously demonstrating the interdependence between countries and the importance of the energy sector on the economy. This economical crisis has been exacerbated by climate change impacts that are more noticeable and extreme than before. In this economic, energetic and environmental crisis, developing renewable energy sources, such as wind, plays a critical role.

Mobility and economic activities were significantly reduced during the pandemic, which caused a large reduction in energy demand. Consequently, we saw a negative price of crude oil in April 2020. The pandemic caused a contraction of the gross domestic product of −8.5% [39], an inflation rise of 7.45% [40], and a lower tax return on oil exports. On the other hand, the war in Ukraine has also contributed to oil price increases and inflation in 2022. Mexico has always exported oil and used oil revenue as a lever for economic growth. However, basing the country's development on fossil fuel exploitation is incompatible with climate change mitigation strategies. Energy is one of the strategic productive factors for all economies and having energy availability at affordable costs favors economic growth. However, if this energy comes from fossil fuels, GHG emissions will be generated, remaining in the atmosphere and causing global warming.

Renewable energy resources play a critical role in reducing GHG emissions and are compatible with green economic growth. The International Energy Agency estimates that over the next 30 years, radical changes will occur in the global energy sector toward a growth path with neutral emissions (net zero). In line with this perspective, daily oil production could go from 90 million barrels in 2020 to 22 million daily in 2050. These changes in the energy sector would be accompanied by an expansion of new electrical capacity, going from 261 GW in 2020 to 1000 GW in 2030, of which an additional 600 GW will be from photovoltaic solar power and 400 GW from wind power [41].

The investments and costs of renewable energies will be an essential variable to achieve a path of economic growth compatible with sustainable development goals. The capital invested in renewable energy projects was just over 1 trillion dollars (2019 USD) during the period 2016–2020 and is expected to increase to 4 trillion dollars by 2030 and until 2050 [41]. During the last decade, a downward cost trend has been observed in the renewable energy sector, being an economically viable option even without any subsidy. Indeed, the weighted average leveled costs decreased in 2020 in solar thermal (16%), photovoltaic (7%) and wind energy both onshore (13%) and offshore (9%) compared to the year 2019, making them economically viable options [42]. The energy technologies that will allow a future with economic growth and neutral emissions already exist, their costs have decreased in recent years, and they should be installed in the country.

4. Community Wind Energy: The Case of North Uist, an Outer Hebrides Island

The North Uist project is a community-led, utility-scale wind energy development that demonstrates that well-organized communities can achieve their energy autonomy and turn into prosumers, both to produce energy for their homes and businesses or trade energy for other goods [43]. The project started operating in August 2019, and two ENERCON 0.9 MW community turbines generated 6129 MWh per year until September 2020, close to the forecasted yield of 6370 MWh per year. enough to cover the needs of the 1600 residents with an average household electricity consumption of 3831 kWh [44]. This project was chosen because of its success as a community project, and because it paves the way for similar projects of rural communities in other countries, particularly in Mexico.

The feasibility analysis of North Uist Wind was based on future community demands of energy, using clean energy technologies at the commercial readiness level, for the benefit of the local community and the environment [43]. The feasibility study included three types of energy: marine renewable energy, wind energy, and bioenergy. The Uist Wind partners analyzed the impacts and consequences of different projects at different scales: small-scale projects that can reduce the costs of energy consumption and at the same time reduce greenhouse gas emissions and large-scale projects that can become a sustained source of income for the community. The impacts focused on benefits and employment opportunities within reach of the community based on the renewable energy resources available on the island. This preliminary study, which includes from the start a socio-economic analysis, allows for prioritizing and planning different community-led projects, beginning with those with the best return on investment from the economic, ecological, and social perspectives.

The first issue considered in the planning and prioritization process concerned the population. The population density, settlement size in terms of the number of residents and a number of households, and settlement spread were critical in the analysis. These considerations help determine the optimal IC according to the distance from the grid and the nearest human settlements' size.

The second issue considered from the start was the presence of extensive industrial states in given areas. In coastal regions such as North Uist, industrial states include ports, warehouses, food processing plants, commercial fisheries, government offices, tourists, sports or retirement centers, or schools, to name but a few. The energy and heating needs of such users may be substantial. In locations with extreme environments or poorly insulated buildings such as North Uist, an eight-bedroom hotel may require between 25 and 35 thousand liters of fuel oil per year and have a demand for 30–45 kW in either heating or air conditioning, equivalent to 272–408 MWh per year [43].

The third issue concerns energy poverty and is directly linked to SDG7, i.e., universal access to clean and affordable energy. The feasibility analysis included a population census where the percentage of the population who live in energy poverty, i.e., those who used more than 10% of their net income to cover their energy needs, was determined [43]. In Mexico, alternative definitions of energy poverty based on relative social well-being have been proposed [45]. Still, the definition based on net income is non-ambiguous and thus more transparent to the need for action. Either way, renewable energy projects' ultimate aim should empower the communities through democratic access to energy, energy services, and energy poverty abatement.

The fourth and final issue concerns possible development restrictions for conserving endangered species and natural protected areas. Which government and community authorities are in charge of managing these areas? How restrictive are the laws in relation to the development of renewable energy projects in these areas? Highly-restrictive areas need to be mapped out and identified as no-tolerance regions. Such is the case for areas of importance for the conservation of birds, or AICAs [23], for example. In marine areas, regions of no-tolerance include those for critically endangered marine species, such as the *Vaquita Marina* porpoise in the Gulf of California [46].

If there are only isolated settlements in a region, distributed small-scale renewable energy networks may be considered without any (or very few) negative environmental impacts. In this case, residential-scale turbines could be installed on rooftops or other locations with known wind speed classes and adapted to local conditions. Adopting this strategy would still solve energy poverty and GHG emission issues, albeit on a smaller scale. It should be noted that an isolated utility-scale turbine does not pose a significant threat to wildlife, even when installed in an AICA. If the turbine is still deemed unsafe for some endangered species after a thorough analysis, mitigation strategies must be put in place, or the turbine installed elsewhere.

Achieving project development milestones depends on flawless planning, thorough environmental and social impact studies, and focused community consultations. The fact that a project is community-based should be advantageous since the staff promoting it are part of the community and therefore know the region and the community's needs. However, there will always be a need to dialogue and negotiate with associations and local authorities to carry out the planning correctly and improve the chances of success. Table 2 summarizes some possible impacts that McLean and Robertson [43] considered, indicating who would be the possible stakeholders and responsible authorities in the case of Mexico.

Table 2. Potential impacts of onshore and offshore wind energy parks, based on the analysis by McLean and Robertson [43].

Problem	Description of Approach	Actors Involved
Landscape problems (sound or visual)	The local managing authorities (LMA) evaluate the project proposal for potential impacts and determine the methodology used to quantify the impact, whether they are acceptable, and if not if mitigation strategies can be implemented. LMAs in charge of historical heritage will provide information on cultural and historical areas that can be affected.	LMAs, INAH, other historical, archaeological, or cultural associations.
Ecological and geophysical studies	Geophysical issues include effects on the hydrological cycle, on fracture or subsidence of soils, the risk of hurricanes or other extreme events on wind power plants, and the environmental impacts of offshore turbines for sea projects, among others. Ecological issues include effects on flora and fauna, especially on birds and bats.	LMAs, CONANP, HEIs and NRCs, CONABIO, SEMARNAT, recognized national associations of geophysicists (e.g., the UGM) or ecologists.
Radar and aviation	The movement of the turbine blades can interfere with RADAR signals. Large turbines can interfere with aeronautical operations, particularly near airports or military bases.	SEMAR, MOD, DGAC, AAC

Table 2. *Cont.*

Problem	Description of Approach	Actors Involved
Television and communications	Wind farms can interfere with high frequencies (microwaves) or telemetry (transfer of satellite information) transmission lines. Wind farms can also interfere with terrestrial television transmitters, or with relay links. The costs of mitigation measures that counter these effects must be in the budget so the project can move forward.	Telephone companies, telecommunication offices, television transmitters.

LMA: local managing authorities. INAH: National Institute of History and Anthropology. CONANP: National Commission of Natural Protected Areas. HEI: Higher education institutions. NRC: Non-research centers. CONABIO: National Commission for the Knowledge and Use of Biodiversity. SEMARNAT: Environment and Natural Resources Secretariat. UGM: Mexican Geophysical Union. SEMAR. Marine Secretariat. MOD: Ministry of Defence. DGAC: General Directorate of Civil Aviation. AAC: Civil aviation authorities.

5. Wind Energy Resource Evaluation for Mexico

Wind energy resource analysis and pre-feasibility studies are based on the yearly (or longer) distribution of wind speed, U, and wind direction, θ, the wind power density (WPD), and the AEP. Wind speed and direction are normally displayed as time series at selected locations and heights or as interactive maps, as in the Global Wind Atlas (GWA): https://globalwindatlas.info (accessed on 29 December 2022). The GWA was produced from wind data generated by the Weather Research and Forecasting (WRF) numerical weather prediction (NWP) model, with initial and boundary conditions provided by the ERA5 reanalysis. This model was used to simulate the atmospheric flow at 62 vertical layers on a global domain with a 3 km $\times$ 3 km horizontal grid spacing covering all the land surface and up to 200 km into the ocean. The topographic information and the output generated with an NWP (in particular, the velocities) can be used to generalize the wind field. This generalized wind field can be interpreted as the wind that would prevail without the influence of local topographic features. This generalized wind field is again reduced/downscaled in temporal and spatial scales to grids with much finer horizontal spacing (in the order of tens of meters), using the microscale models in the WAsP software developed by DTU (see https://www.wasp.dk/, accessed on 3 March 2023), and in combination with high-resolution topographic data at local scales. The data shown on the GWA website is integrated into a horizontal grid with a spacing of 250 m $\times$ 250 m. This procedure (generalization and downscaling) is known as the European Wind Atlas method [47]. Dörenkämper et al. [48] followed a similar procedure for producing the New European Wind Atlas (NEWA). The GWA also shows the yearly-averaged wind speed maps at 50, 100, and 200 m, representing past, present and future hub heights.

Wind energy resource analysis tools are provided on the GWA website. Figure 3 shows the annual WPD at 100 m above ground level (all heights are hereafter above ground level) for Mexico. A location with a WPD larger than 1000 W m^{-2} is considered to have great wind resource potential. Such WPD values are found in some Mexican sites, as illustrated in Table 3.

Table 3. Locations around Mexico with great (larger than 1000 W m^{-2}) wind resource potential, as measured with their yearly wind power density (WPD) at 100 m above ground. Based on the Global Wind Atlas (https://globalwindatlas.info/en, accessed on accessed on 29 December 2022).

Location	Short Name	WPD (W m^{-2})	Latitude	Longitude
La Rumorosa	BC	2486	32.54	−116.03
Tamaulipas	Tam	2451	24.641	−99.076
Eastern BC Peninsula	BC	2019	29.7	−114.52
Chihuahua	So-Chi	1681	31.08	−107.69
Sonora	So-Chi	1665	30.67	−109.803
Isthmus of Tehuantepec	IST	1492	16.329	−94.78

The regions mentioned in Table 3 appear in Figure 3. The geographical coordinates show approximate locations within each of the mentioned Mexican states. They should not be used for wind farm planning purposes unless supported by a microscale wind energy analysis and on-site measurements.

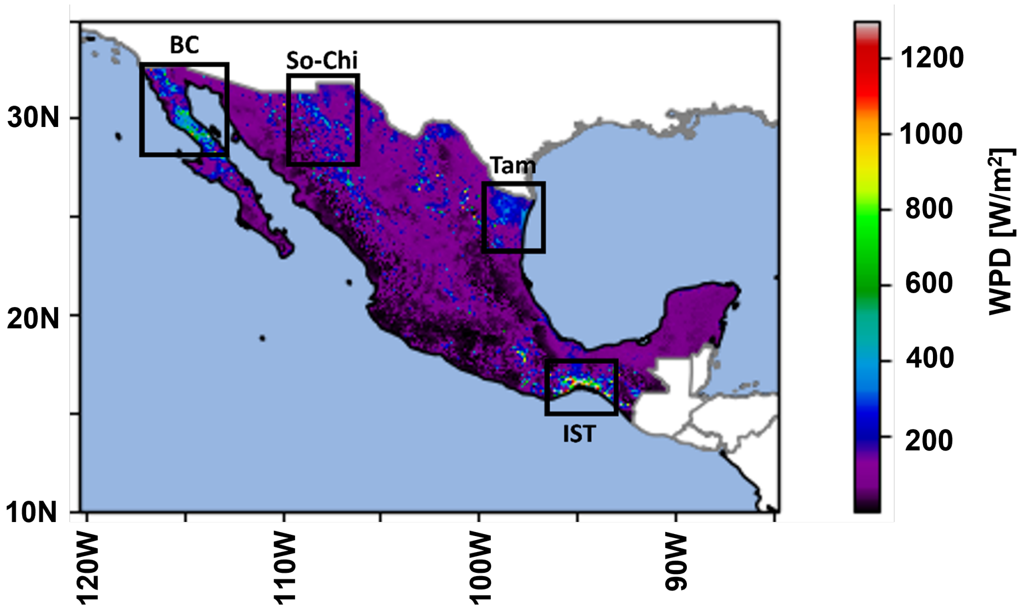

Figure 3. Annual wind power density (WPD) at 100 m based on the GWA 3.0 data available at https://globalwindatlas.info/ (accessed on 29 December 2022). The rectangles show regions with high wind power density (see text for details).

Wind speed predictions may vary significantly depending on the wind data sources. In order to illustrate this, we used three different sources: the GWA 3.0 previously presented; the WINDToolkit, a database with current wind predictions and future scenarios developed by the U.S. National Renewable Energy Laboratory (NREL) with a horizontal grid spacing of 2000 m (see https://www.nrel.gov/grid/wind-toolkit.html, accessed on 1 June 2020); and a yearly-averaged WPD map developed by VESTAS with a horizontal grid spacing of 3000 m (see https://maps.nrel.gov/gst-mexico, accessed on 1 June 2020). While the wind energy maps generated in the GWA 3.0 are produced using WRF and WAsP, those using the NREL and VESTAS data are produced with the WRF model only and therefore do not consider microscale effects on the wind, which are crucial for accurate predictions of local winds.

Figure 4 shows the maximum relative difference between the VESTAS and the WINDToolkit wind speed predictions relative to the GWA. The blanked-out areas are regions where the difference is larger than 50%, and include, for example, the central part of the Isthmus of Tehuantepec, the Pacific Coast from Jalisco to Oaxaca, as well as some areas in the Coast of Tamaulipas. This is a substantial area of the country, and most importantly, these are areas generally known for having good wind energy resources [24]. Note that values larger than 30% can also be observed throughout the country near the coast and inland. It is also noteworthy that there is no correlation between large percentage differences between atlas products (Figure 4) and WPD (see Figure 3): regions with either low or high WPD can present high percentage differences between atlas products. Therefore, all wind energy assessments, especially those based on NWP models that do not consider microscale effects, must be interpreted cautiously.

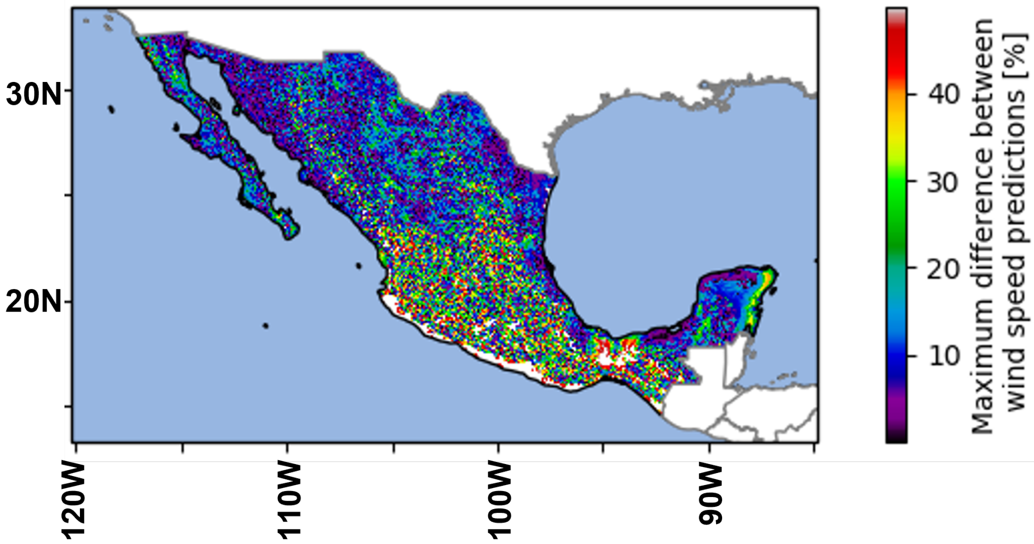

Figure 4. Maximum relative difference between wind speed estimated by the WINDToolkit and VESTAS in relation to that of the GWA, shown in Figure 3.

These maps show regions where the probability of finding a site with commercially-exploitable wind resources is high. However, it is essential to quantify the wind resources with in situ wind speed measurements taken for at least one year and at heights close to the proposed hub heights, to have robust and reliable wind climatologies that are useful for the wind energy sector, and to assess the accuracy of the numerical models at those heights. If installing meteorological towers with sensors at different heights from the ground to hub height or higher is impossible, wind lidars can be used [49]. Wind lidar measurements have been performed in Mexico since 2017, and high-quality meteorological towers were installed as part of the Mexican Wind Atlas (MWA) project. The MWA project involved the installation of 10 towers, with cup anemometers and wind vanes measuring both wind speed and direction at 20 m intervals, between 20 m and 80 m.

In summary, a wind energy atlas is not a simple map of mean wind speed and direction at a given height for a given region on the Earth. The wind field needs to be validated against observations, wind speed and direction need to be provided at several heights, and a broad database that allows for more detailed computations needs to be made available [50]. Moreover, the numerical simulations must include a microscale evaluation of the wind energy resource. Numerical datasets based on mesoscale models that omit such evaluation, like the VESTAS and NREL datasets used here, have mean relative differences in wind speed relative to a meso-microscale coupled model that can be over 50%, with differences above 30% in a significant percentage of the land surface.

6. Possible Generation Solutions: Contrasts and Limitations

To evaluate possible wind energy generation scenarios, we used the atlas of regions with optimal wind energy resources (AZEL). The AZEL was developed with input from a team of experts who identified access to transmission lines as the most important limiting factor. Distance to the national grid is crucial for a project to be commercially viable. Based on this, four different scenarios were proposed. The data for the four scenarios, SCE1 to SCE4, was downloaded from https://dgel.energia.gob.mx/azel/ (accessed on 4 February 2021). The SCEs satisfy the following characteristics: SCE1 includes all regions with commercially-viable energy resources; SCE2 includes the commercially-viable regions that are at an average distance of 20 km from the transmission lines; SCE3 includes only the regions at an average distance of 10 km or less from the transmission lines; and SCE4 includes the regions at an average distance of more than 20 km from the transmission lines.

Table 4 shows the installable wind energy capacity (IWEC) in GW, the expected annual energy production (EAEP) in 10^3 GWh/year, and the preventable CO_2 emissions (PCO_2E) in 10^3 Mton/year. The IWEC takes into consideration social, environmental, and techno-economic exclusion zones, for all four scenarios. The EAEP and the PCO_2E are computed based on the IWEC and other technical information obtained during the IWEC analysis. SCE1 gives a maximum estimation of these three indicators, subject to the AZEL assumptions, based on the commercially-viable sites. Here we see that the maximum IWEC is 583.2 GW. Considering that up to December 2018, the IC was 5.14 GW [36,51], we have not even reached 1% of the installable wind energy capacity offered by the land part of the Mexican territory. Indeed, the AZEL data does not include the offshore wind energy potential, which is only available from other publications [24,52].

Table 4. Installable wind energy capacity (IWEC), expected annual energy production (EAEP) and preventable CO_2 emissions (PCO_2E) under the four AZEL scenarios. The information was obtained from the AZEL website (last accessed in 2021).

Indicator	Units	SCE1	SCE2	SCE3	SCE4
IWEC	GW	583.20	290.25	158.30	297.44
EAEP	10^3 GWh/year	1486.71	740.33	402.85	750.19
PCO_2E	10^3 Mton/year	674.97	336.11	182.89	340.58

The AZEL recognizes the crucial importance of access to transmission lines as one of the main limitations of renewable energy developments. Based on proximity to transmission lines alone, the IWEC drops to 290.25 GW, to less than 50% of the total IWEC. This, however, does not provide information on the available voltage of the transmission line, which is also a critical parameter to consider. SCE4 shows the IWEC that could be exploited by isolated turbines connected to a local grid, possibly as a distributed renewable energy system providing energy to the homes and businesses within small human settlements or for agricultural activities. At 297.44 GW of IWEC, this is a very important energy resource. By exploiting this, one could avoid up to 674.97 Mton/year of CO_2 emissions, equivalent to the emissions of almost 70% of the country's population in 2019 [53].

Figure 5 shows the regions included in SCE1, the scenario with all commercially-viable regions. The AZEL has not included, for example, any areas along the Pacific Coast except for the Isthmus of Tehuantepec, and some small regions in the Baja California Peninsula. Therefore, the AZEL is not reporting all the available wind energy resources, as identified with the GWA wind energy resource assessment presented in Section 5. This implies that the AZEL scenarios are underestimating the country's installable capacity, in part due to the limitations of the numerical models on which the scenarios were based. Moreover, the only restriction considered in the AZEL is the site's proximity to transmission lines. Several additional restrictions may be considered, such as land use, exclusions based on topographical characteristics, exposure to natural hazards, AICAs, RAMSAR sites, or others.

Finally, offshore wind capacity has not been considered in the country's future development plans, at least not in the official documents published by the Mexican Ministry of Energy (SENER). However, some studies have attempted to characterize offshore wind energy potential in Mexican waters [24]; the effect of climate change on offshore wind energy resources [52]; and offshore wind energy development under marine planning restrictions in the Gulf of California [23].

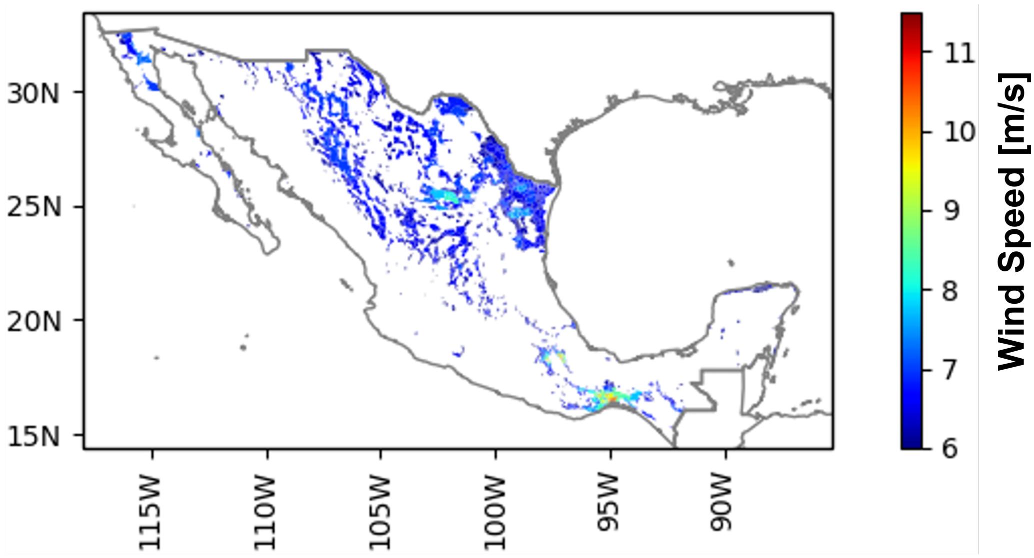

Figure 5. Wind speed over some areas of Mexico, covered by the scenario SCE1 of the AZEL (the data was downloaded from https://dgel.energia.gob.mx/azel/, accessed on 4 February 2021).

7. Long-Distance vs. Distributed Transmission Lines: Challenges and Solutions for Sustainable Growth

Although Mexico has regions with high potential for wind harvesting, the lack of reliable, near-zero leak, high-voltage transmission and distribution lines has been one of the factors hampering the most the growth of this sector [54]. Decisions made in relation to the development of the transmission lines will also determine which regions will implement wind farm developments first. Therefore, it is crucial to plan the national grid's growth adequately. Here we describe the status of the Mexican transmission grid in 2018 and the plans put in place to solve the challenges posed by the grid to renewable energy project developments. It is worth noting that community wind energy project development may also require stronger distributed systems as a solution for the energy transition. We will comment more on this at the end of the section.

The Mexican national transmission network (NTN) consists of four isolated systems: the national interconnected system (SIN); the Baja California Sur (BCS) system; the Baja California (BC) system; and the Mulegé (SEM) system. The SIN is divided further into seven control regions. The BCS, BC, and SEM systems are all located in the Baja California Peninsula; the plan was to connect these three systems to the SIN by 2023 [36]. 94.6% of the gross annual energy consumption (GAEC) in 2017 was concentrated in the SIN, which in that year amounted to a GAEC of 309.73 GW% larger than in 2016, and above the 2007–2017 average annual growth rate of 2.6% [36]. One of the most important limitations for implementing utility-scale renewable energy systems has been transmission line weaknesses [54]. Wind farms are no exception, hence the need to expand and modernize the grid and implement energy storage and smart control systems. For instance, the energy generated in Baja California can only be consumed locally or exported to the United States because none of the transmission line subsystems in the BC peninsula is connected to the SIN.

The federal electricity commission (CFE) currently is the main developer of the NTN. The criteria for NTN developments up to 2018 included the size and location of the energy demand poles, the geographical location of electricity generation plants, and the planned renewable energy farm developments [55]. It is important to highlight that the region with the largest transmission capacity is the Northeastern region, where 25% of the country's capacity is located [55]. This region is connected to the Central region through the states of Queretaro and Veracruz. The interconnection capacity between the central region is also large with the states of Oaxaca and Chiapas. These two states are in the eastern control region. It is believed that the BC subsystem might be able to connect to the SIN by 2023, allowing developments in the BC peninsula to cover part of the demand in the SIN in Northwest Sonora, and vice versa [55].

Figure 6 compares transmission line limits between 2018 and those planned for 2024 by the previous government administration. In some locations, the planned expansions would have doubled the limits. In others, the planned lines consisted of completely new installations, such as the submarine cable connecting the mainland to the middle part of the BC Peninsula, connecting the SIN with the SEM and the BCS grids, the connection of the SIN to the BC system along the Mexico-US border, and the cable connecting Chihuahua and Tamaulipas to the center of the country. These new grid connections would boost the development of renewable energy projects in those regions and provide both energy and employment opportunities. Unfortunately, it is uncertain which grid expansions will go ahead by 2024, mostly for political reasons. An analysis of the new transmission line development plans, published in the latest SENER documents [37], highlighted that the current administration is proposing no substantial advances in maintenance or new developments of the NTN in relation to 2018.

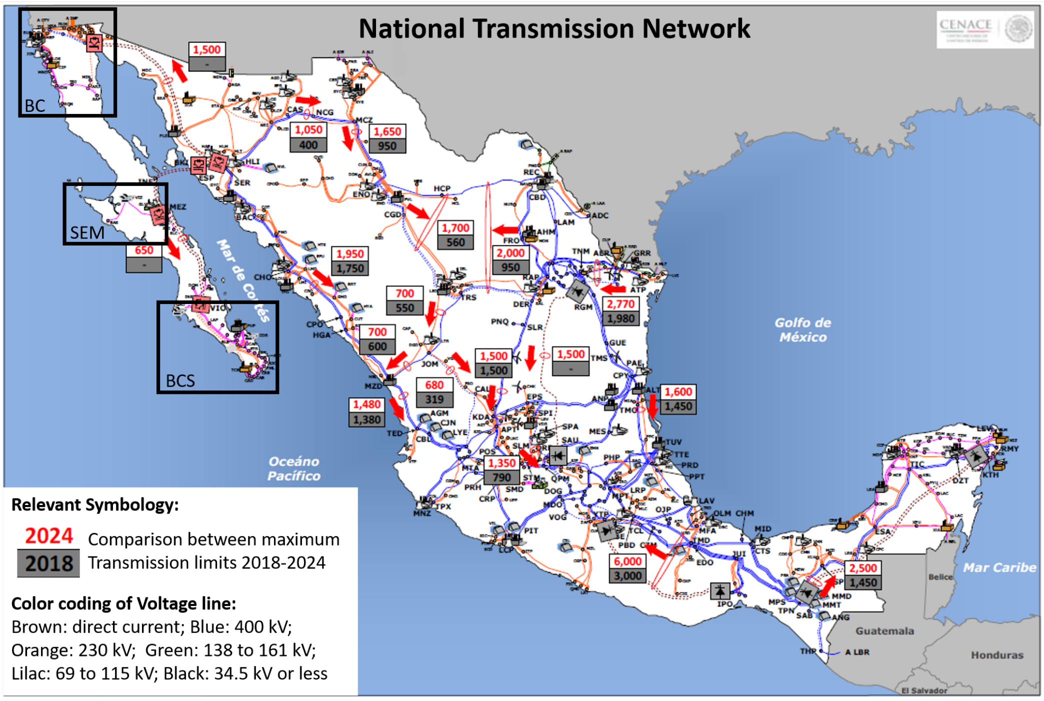

Figure 6. Comparison between the transmission limit for 2018 and that expected in 2024. The NTN consists of four subgrids: the national interconnected system on the mainland; and the Baja California (BC), the Mulegé (SEM), and the Baja California Sur (BCS) grids on the Baja California Peninsula, based on transmission line development plans proposed by the Mexican ministry of energy in 2018 [55].

The current national transmission network (NTN) limitations have important economic consequences. For example, the energy produced in the BC grid can only be consumed locally or exported to the US. Moreover, the Baja California Peninsula is fragmented into three energy islands, the BC, the SEM and the BCS grids. Most lines are 138–161 kV lines, with low transmission limits and high energy losses (see Figure 6). The region with the most transmission capacity is the Northeastern region, with almost 25% of the country's total transmission capacity [55]. The North East is well connected to the central region along the Gulf of Mexico. The states of Oaxaca and Chiapas, on the South, also have high transmission capacity. New NTN developments usually consider the demands for transmission, which depends in turn on the location of current electricity plants and those under planning [55]. CFE historically has been the main developer of the national grid. CFE is not planning new renewable energy projects in the near future, so we can only speculate that CFE will focus on strengthening the existing grid infrastructure, not on installing new grid connections. This means that independent prosumers in isolated regions will need to generate energy, consume it or store it on-site, off the grid.

The weaknesses in the NTN that we have highlighted for the BC Peninsula subgrids and the SIN should be resolved to improve the national connectivity and strengthen the transmission capacity of the whole network. According to the PRODESEN 2018–2032 [36], Mexico needs an additional IC of 67 GW to satisfy the national energy demand between 2018 and 2032, equivalent to an investment of 1.7 billion MXN (almost 50,000 million USD), or 7.8% of Mexico's Gross Domestic Product (GDP) in 2018. Renewable energy projects in isolated regions with high wind speeds will be limited without resolving the grid limitations. Furthermore, we run the risk that all utility-scale wind farm projects are developed in Class I sites already connected to the grid, as has happened in Oaxaca. This is risky, first because the grid will quickly become saturated, and second, because of all the ecological and socio-economical problems that this can generate [56].

A country-wide balanced and equitable development of the wind energy sector should be pursued. Spreading wind farm development throughout the country is feasible because current wind turbines may be installed in locations with different wind classes: Class I, or 10 m/s yearly-averaged wind speeds at hub height; Class II, or 8.5 m/s; Class III, or 7.5 m/s; and Class IV, or 6 m/s, according to the IEC-61400 standards [57]. However, other important parameters may affect wind turbine performance and AEP; and this is reflected in part in the capacity factor of each individual wind farm. Those parameters may include complex topographies or vegetation cover, the turbulent structure at the site, and the effects of wind gusts with return periods of 50 years [57,58], for example. However, as the diversity of the IEC-61400 standard demonstrates, wind turbine technologies are very mature, and therefore several regions in Mexico are good candidates for wind farm developments, even in complex terrain [59].

8. Hydrometeorological Extremes and Their Impacts on Wind Farm Siting

Wind turbines are vulnerable to hydrometeorological extremes, and in most cases, they cannot operate above a cut-off speed of 25 m/s. Any region on the Earth located roughly between the tropics of Capricorn and Cancer (currently the parallels at 23.43655° S and 23.43655° N, respectively) is subject to tropical storms, cyclones and hurricanes. Tropical storms may be defined as mild hydrometeorological perturbations (with wind speeds below 33 m/s or 120 km/h), while tropical cyclones and hurricanes are high wind speed perturbations. Cyclones, like typhoons, are extreme events observed in the Pacific and the Indian Ocean, and hurricanes occur in the Atlantic. Tropical cyclones consist of events where the wind speeds can reach 83 m/s (https://public.wmo.int/es/ciclones-tropicales, accessed on 16 March 2023). Thus, all commercial wind turbines cannot operate even under mild storm conditions. Once the wind speeds reach the turbine cut-off speed, turbine protection mechanisms are activated. In all cases, a lock stops the blades from turning in response to the wind. Some new technologies have been developed that not only stop the blades from turning but lower the whole wind energy conversion system to the ground, like the 30 kW turbine developed and tested at the Regional Centre for Wind Energy Technology site, in Oaxaca [60]; the pilot turbine deployed in 2019 is shown in Figure 7. If the wind speeds are too strong, the turbines are taken down until the extreme conditions end. They are checked for potential damage before being lifted into operational position.

Energy downtime probability plots can be deduced from the turbine specifications and the probability of occurrence of an extreme event.

The vulnerability index due to a tropical storm ($VITS$) is defined as [61]

$$VITS = \sum_{i=1}^{7} I_i \, P(I_i), \tag{1}$$

where I_i with $i = 1, 2, \ldots, 7$ is the intensity of the tropical storm, and $P(I_i)$ is the annual probability of exceedance of storms with intensity I_i. I_1 is the intensity of a tropical depression, I_2 the intensity of a tropical storm, and intensities I_3 to I_7 the intensities of hurricanes of categories 1 to 5. The trajectories of the tropical storms between 1949 and 2015 were extracted from the National Hurricane Centre database [62], which have been counted inside and up to 10 km from the border of each of Mexico's counties using the natural (Jenks) break strategy with classes based on hurricane intensity [63,64]. The $VITS$ is then mapped in ways that acknowledge the similarities and differences between regions in terms of their vulnerability to tropical storms. Figure 8 is the $VITS$ computed in [61] for the storms recorded in the period 1949–2015.

Figure 7. 30 kW collapsible turbine trials at the Regional Centre for Wind Energy Technology site in Oaxaca in 2019. Taken from Hernández-Arriaga [60].

Figure 8 illustrates the $VITS$ for all of Mexico, showing regions in Tamaulipas (Tam), the northern part of Veracruz (Ver), Campeche (Cam), Quintana Roo (QR), Jalisco (Jal), Sinaloa (Sin), BC and BCS, with very high $VITS$. Since the $VITS$ is a combination of intensity and probability of exceedance, the regions with high $VITS$ are regions more susceptible to damage by tropical storms. It is also worth noting that the $VITS$ does not consider the population density in the counties mentioned. For instance, BCS has high $VITS$, because, over the hurricane season, the probability is that a hurricane with a category of 3 or above will reach the southern half of the Baja California Peninsula. However, only the southern tip of the Peninsula is highly populated and therefore should be prioritized.

A Risk Index to Tropical Storms (RITS) is defined to correct for population density (D), as mentioned above, and take into consideration a measure of social vulnerability (SV) [65]:

$$RITS = [\ln(D) + 3](SV)(VITS). \tag{2}$$

So, the $RITS$ conditions the vulnerability index by considering the population density and the probability of loss of valuable assets. The value of the assets may be social, economic, or ecological. High $RITS$ regions cover less area than the high $VITS$ regions because the $RITS$ is a $VITS$ with additional restrictions. The $RITS$ is also determined using the method of Jenks natural break strategy [64], a data clustering method that identifies the optimal arrangement for data classification.

As Figure 9 shows, the areas with very high $RITS$ are contained within areas with very high $VITS$ (see Figure 8), as we expected. The areas of high $RITS$ are very well defined. They are located in the southern half of BCS, in some parts of Sinaloa and Jalisco, in southern Tamaulipas and northern Veracruz, and in the Caribbean and the northern parts of the Yucatan Peninsula. The $RITS$ and the $VITS$ complement each other as decision-making tools when it comes to identifying regions that may be better suited for wind farm development. On the one hand, regions with low $VITS$ should be preferred. On the other, if a wind farm is being planned in a high $VITS$ region, it is best to place it in an area of high $RITS$ to minimize construction risks and repair and maintenance costs.

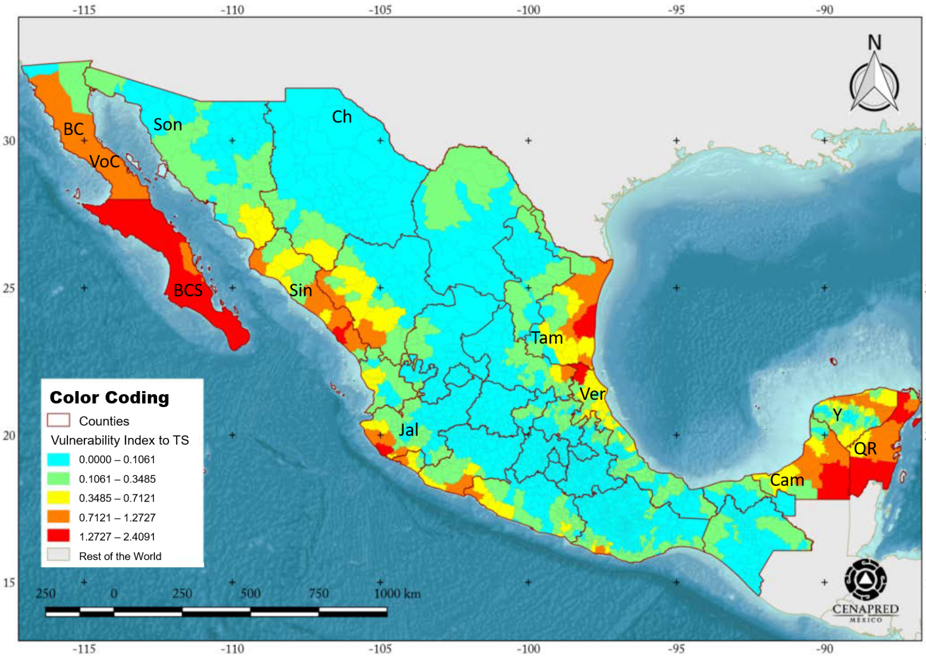

Figure 8. Vulnerability Index to Tropical Storms ($VITS$) based on hurricane trajectories in the period 1949–2015 from the Miami National Weather Centre, National Hurricane Center, and the natural (Jenks) break strategy. QR = Quintana Roo; Y = Yucatán; Cam = Campeche; Ver = Veracruz; Tam = Tamaulipas; Ch = Chihuahua; Son = Sonora; Sin = Sinaloa; BC = Baja California; VoC = Valley of Cirios (see Section 5); BCS = Baja California Sur. Figure reproduced with permission from Baeza-Ramírez and Jiménez-Espinosa [61].

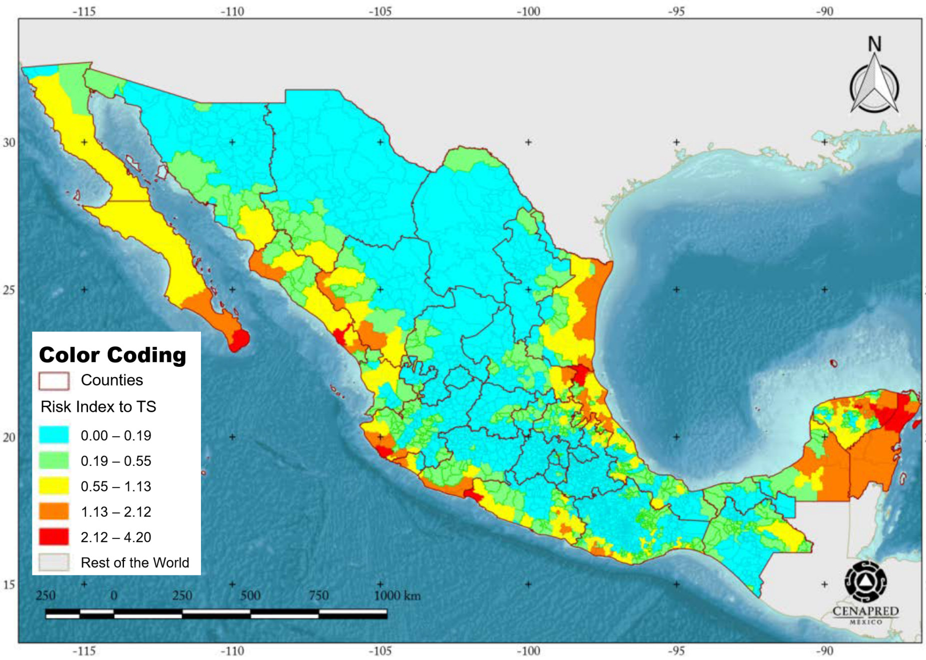

Figure 9. Risk index to tropical storms ($RITS$) for the period 1949–2015. The $RITS$ is defined as the product of the $VITS$ illustrated in Figure 8, by a social vulnerability SV, which is a measure of the value of the assets in the region, and by the factor $\ln(D) + 3$ where D is the population density. Figure reproduced with permission from Baeza-Ramírez and Jiménez-Espinosa [61].

In general, the coastal regions are the most vulnerable areas to tropical storms. It is worth noting, in particular, that all the states of QR, the eastern side of Campeche, and the southern half of BCS (see Figure 8) have high to very high $RITS$. Wind energy developments are also most at risk in these regions, especially at the coast and offshore.

9. Long-Term Perspectives

Wind energy development requires improved technical and scientific methodologies, covering aspects of numerical modeling; in situ measurements; technological design, operation and maintenance; and environmental impacts mitigation strategies. Several projects or government programs on modeling and field monitoring campaigns should be planned and implemented to improve wind energy resource evaluations. For example, the sensitivity of the numerical weather forecast predictions to the modeling assumptions, in particular to the coupling with a microscale model as shown in Figure 2, indicates that the bottom boundary data should be improved, including better digital elevation models and better information on vegetation type and land use. Furthermore, while most models assume that the vegetation type does not change, it is a parameter that changes over time. These changes may include deforestation, reforestation, seasonal variations, or urbanization effects on regional wind speeds. Energy resource maps that assess the effects of vegetation and land use changes can allow better planning for urbanization and wind farm development projects. Topography, vegetation and land use resolution on wind energy resources has been recently studied in international projects, such as the "Multi-scale and model-chain Evaluation of Wind Atlases" (MEWA) project [66], the "Innovation for Global Wind Energy Exploitation on Land using Satellites" (InnoWind) project [67], and the "New European Wind Atlas" (NEWA) project [68]. In the future, these studies can be extended to analyze the effects of temporal changes in land use on wind resources.

Studies on the variability and effects of climate change on wind resources at decadal scales are scarce and should be explored more thoroughly. An analysis for Mexico showed the wind energy resources under the RCP8.5 scenario would decrease in Oaxaca [52]. For this reason, it is necessary to continue implementing numerical models that assess the effects of climate change, in particular for the RCP8.5 scenario. The IPCC recommendations imply that this is the scenario we must consider when evaluating impacts since only then will we provide information that is more appropriate to the reality of the climate crisis and its possible effects.

It is also imperative to continue measuring atmospheric variables with sensors at hub height, such as those carried out in the MWA project led by the National Institute of Electricity and Clean Energies [50]. In the MWA, ten monitoring towers were installed throughout the country. These measurements allow the study of local wind conditions and provide a reference for evaluating numerical models. These models help plan the wind farm layout, including the number of turbines and their geographical locations, to maximize energy production and minimize environmental impacts. More extensive project planning exercises also need to assess wind farms' interactions, since one plant may affect the flow field reaching the plants located downstream.

Despite being a mature technology with significant progress in its implementation at the commercial level, the dismantling and recycling of wind conversion systems, or at least of the parts, continues to be a big problem [69]. One reason is that few commercial wind plants are reaching the end of their life, and therefore there is little experience in decommissioning and recycling wind turbine parts. The other is that many plants that have already completed their life cycle continue to generate electricity. However, the recycling problem is beginning to be addressed, both by academia and industry. The blades are the part of the turbine that has received the most attention, although some manufacturers, including Vestas [70], have addressed the complete turbine's recycling problem. The magnitude of the recycling problem will depend mainly on the IC 30 to 40 years from now. The growth of IC depends, in turn, on the wind energy growth roadmap. The Organization for Economic Cooperation and Development and the International Energy Agency, for example, consider two possible growth scenarios [71]: the "2DC" scenario (2 °C)—with a Global IC of 1400 GW by 2030 and of 2300 GW by 2050; and the "HiRen" scenario (Renewables)—with a Global IC of 1600 GW by 2030 and of 2700 GW by 2050.

Life cycle analyses must consider the growth roadmaps to 2030 and 2050 to properly assess the type and volume of materials that need to be mined or manufactured. Recycling and reusing processes will help minimize waste during the decommissioning stage. The growth roadmaps are also critical when evaluating potential environmental impacts. Dismantling, recycling, or waste disposal must take into account some of the following, among other possible factors:

1. 5% of the IC installed by 2030 will need to be dismantled by 2050 [72].
2. Turbine size will change. Currently, turbines have, on average, 2 MW of IC, but the capacity is expected to increase to 10 MW by 2030 [73].
3. Changes in design and construction materials. For example, steel is easily recyclable, but it is challenging to handle and recycle fiberglass.
4. Take into account submarine cabling in the case of offshore wind farms [74].
5. Uncertainties and limitations in recovering and processing materials from offshore wind farms.
6. Type of vegetation and changes in land use should be included in the environmental impact studies, and the measures to reduce or correct these impacts should be accounted for in the budget [75].

Finally, it is essential to highlight that, to meet the sector's needs, it will be necessary to train thousands of specialists from different disciplines who focus only on the wind sector to achieve substantial advancements in research and technological development. The number of engineers and scientists explicitly training to become renewable energy professionals is extensive. However, this training is usually very general, limiting specific and highly advanced skill development in each renewable energy specialization sector that we must promote nationally.

10. Conclusions

A review of wind energy development in Mexico, focusing on the factors hampering it and on proposals for solutions, is presented. This analysis is relevant in the context of climate change mitigation strategies and the achievement of the UN's sustainable development goals. Indeed, wind and solar are currently the two most mature and easily scalable renewable energy technologies.

An analysis of the global and Mexico's installed capacity and wind generation for the past ten years shows that wind growth has reduced significantly since 2020 in Mexico. New government policies favoring fossil fuels over renewable energies are partially responsible for this growth deceleration. However, investments in renewable energies are essential to economic growth compatible with sustainable development goals.

Although the wind energy private sector in Mexico has been criticized for socially unfair land lease agreements with the land owners and for not addressing local energy poverty problems, community wind energy projects have shown that privately-owned projects, when led by local communities, can address energy poverty and achieve sustainable development goals. However, all energy projects would be more successful in attaining a return on investment and would do so faster if feasibility studies and environmental impact assessments were more robust. For example, most wind atlases are not precise enough, in part because they do not couple microscale and mesoscale models in their analysis. Indeed, the relative differences in wind power density estimates between mesoscale and micro-mesoscale models can be as large as 50% in some locations, demonstrating the importance of considering the microscale effects on wind energy characterization.

Four wind generation scenarios were examined. However, these scenarios only consider the regions with the highest annual wind power densities. Therefore, the installable wind energy capacity and the expected annual energy production may be significantly underestimated. Moreover, none of these scenarios takes into consideration Mexico's territorial waters. Proximity to high-voltage transmission lines is recognized as one of the most important limiting factors for renewable energy development. Thus, we analyze the Mexican NTN and its status in 2018, together with the development plans envisioned by the Mexican Ministry of Energy by 2024. However, the vision changed significantly during the current administration, and the weaknesses observed in the 2018 NTN are unlikely to be addressed in the near future, except for the high-voltage interconnection between the BC and the SIN grid networks, thanks to a solar energy megaproject currently being developed in Sonora.

Another crucial limitation of wind energy generation is the vulnerability and risk to extreme events. Because tropical storms are common in most of Mexico, we analyze the maps of vulnerability and risk index to tropical storms. Other vulnerability and risk index maps for other extreme events, such as snow storms, would be important at other latitudes and higher altitudes. Novel technology concepts are currently being proposed, built and tested to mitigate against damage by extreme events and low energy generation.

Improving micro-mesoscale models, providing in situ data for weather monitoring, and integrating models and in situ data with remotely sensed information, are discussed in long-term perspectives. Machine Learning methods combined with mesoscale models may help improve model performance and reduce computational costs. Decadal scale studies assessing climate change effects on wind speeds, wind power density atlases, and vulnerability and risk indexes are required. Furthermore, better generation scenarios would lead to better planning. Combining these scenarios with growth roadmaps would be critical for cost−benefit analyses, for more accurate estimates of carbon emission reductions, and potential environmental impacts, especially as turbines grow and decommissioning and material recycling practices improve. Finally, the need for a highly skilled workforce cannot be understated, with the industry growing faster than the number of specialized staff.

Author Contributions: conceptualization, V.M. and L.S.G.-H.; formal analysis, V.M., M.S.G. and A.N.H.; resources, A.P. and V.M.; data curation, M.S.G. and V.M.; writing–original draft preparation, V.M., A.P., A.N.H., D.A.P.-R., L.S.G.-H. and M.S.G.; writing—review and editing, V.M., A.P., A.N.H., D.A.P.-R., L.S.G.-H. and M.S.G. All authors have read and agreed to the published version of the manuscript.

Funding: This work was partly funded by the Danish Ministry of Foreign Affairs and administered by the DANIDA Fellowship Center, grant code 17-M01-DTU. See http://drp.dfcentre.com/project/multi-scale-and-model-chain-evaluation-wind-atlases (accessed on 16 March 2023).

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data reported in this manuscript is publicly available from the corresponding repositories.

Conflicts of Interest: The authors declare no conflict of interest.

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