International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2022 | Issue 51 | Volume 14 | Number 2 | Pages 347-352

STATE OF WIND ENERGY IN THE WORLD: EVOLUTION, IMPACTS AND PERSPECTIVES

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Abstract- Electrical energy is a vital sector for humanity, which is why its production is constantly increasing. However, it produces CO_2 emissions which are among the factors causing global warming. Aware of this problem and in order to reach the objective of zero greenhouse gas emissions by 2050, multiple countries have decided to switch to renewable energies, in particular, wind energy which is considered the least polluting source of electrical energy. The objective of this paper is to give a quantitative and qualitative study of the development of wind energy in the world, examining its evolution during the last decade, its distribution by regions and leading countries and its share in the global electricity mix while giving an assessment of the most powerful wind farms in the world. The focus is on its impact on electric energy autonomy, job creation and reduction of carbon dioxide emissions, as well as its prospects towards 2050.

1. INTRODUCTION

The electrical energy installed worldwide is growing year after year in order to satisfy the demand which is constantly increasing due to the growth of the population and the technological progress in all fields, which require in most cases, an electrical power supply [1, 2]. Considering the limit of fossil resources and their polluting effect on the planet, the world has set itself the goal of boosting the part of renewable energies to attain the goal of zero greenhouse gas emissions within 2050 (2060 for China) [3-5].

Wind energy has a high potential, competitive prices, easy to maintain and especially one of the least polluting renewable sources [6, 7]. The objective of this paper is to make a quantitative and qualitative study, and a synthesis of the evolution of the world wind energy, to show its contribution in the energy autonomy, its environmental impact and its role in the reduction of CO_2 emissions, in order to reach zero emissions by 2050, as well as its economic impact.

In the literature, many authors have been interested in wind energy, but each one has treated it according to his own field of interest and according to his own vision. The [8] provides a literature review of methods for estimating the world's wind energy resource explains the difficulty of estimation and critiques the methods cited.

The [3] reviews the successful policies of the wind energy industry in selected countries from the five continents to address the problems of greenhouse gas emission reduction and electric power shortage and studies the particular case of Malaysia. It concludes that among the most successful energy policies practiced are the establishment of the price law and the adoption of quota system. The [9] gives a concise analysis of trends in wind power and electricity demand between 1990 and 2014 for the world's major regions and by 2014 gross national income per capita levels, while comparing energy growth rates with electricity growth rates by country, and comparing electricity growth rates across regions. The authors [4] gives forecasts and prospects for global wind capacity by 2050, the potential for reducing CO_2 emissions at the global and regional level and conclude that the electrification of the global energy system is necessary. The [10] reviews the technological aspects of the latest developments in wind energy systems and discusses predictions for the design of these systems.

The [11] provides a review of wind research on three axes: design of wind turbines, development and exploitation of onshore and offshore wind farms. The [12] calculates the world wind potential taking into account the windspeed and hub height data of the turbines. The paper also discusses the practical obstacles to be overcome to fully realize the estimated potential.

The [13] reviews scientific developments aimed at improving the use of renewable energies, increasing their share of the overall electricity mix and reducing greenhouse gas emissions. The [14] presents a methodology for a geospatial information system to determine overall onshore potential wind energy based on topographic features and environmental constraints. The [15] provides an analysis of the state, potential and policies of wind energy production, discusses the problems encountered while formulating some recommendations in this field.

2. STATE OF ELECTRICAL ENERGY IN THE WORLD

2.1. Electricity Demand in the World

World's demand for electricity continues to grow due to the increase in the world's population, exceeding in 2020 the 7.8 billion [16], the strong global economic growth, technological advances in industry, transportation and other areas requiring electrical energy for their operation [17, 18]. This increase is mainly driven by China and India, followed by the USA and Europe. As shown in Figure 1, it increased from 19850.3 TWh in 2010 to 22461.8 TWh in 2015 to reach 24776.73 TWh in 2020, i.e., an average annual growth rate of 2.24% [9, 16]. It should be noted that 772 million of the world's population, including 600 million in Africa, do not yet have access to electricity [16].

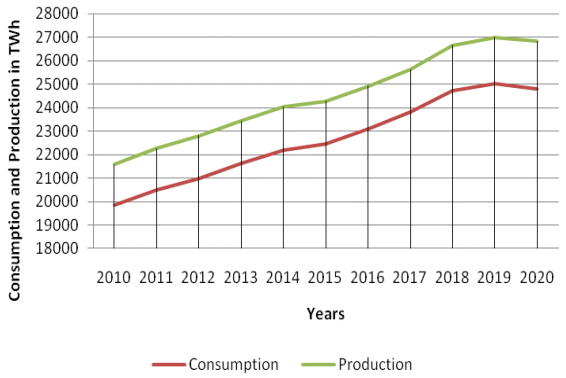

Figure 1. Consumption and production in the world in TWh [9, 16]

2.2. Electricity Generation in the World

This section describes the evolution of world electricity production from 2010 to 2020 as well as its distribution by source and by region in 2020. We stopped at 2020 because it is the last year for which data is available. Figure 1 shows the evolution of the world electricity production which went from 21570.7 TWh in 2010 to 24270.5 TWh in 2015 to reach 26823.2 TWh in 2020 i.e., an average annual growth rate of 2.2% [16]. We notice in Figure 1 that global electricity production and consumption have declined in 2020 compared to 2019. This is due to the decline in economic activity due to the Covid-19 pandemic.

As shown in Figure 2, in 2020, fossil fuels contributed to 61% of the global electricity production of which coal is the main source with a share of 35%, followed by natural gas with a share of 23% [16]. Renewable energies contributed to 28% of the world's electricity production with a clear dominance of hydropower. In fact, as shown in Figure 3, the electrical power produced by hydropower reached approximately 4297 TWh, compared to 1591 TWh of wind power and 856 TWh of solar power, representing respectively 58%, 21% and 12% of the total electrical production by renewable energy.

The dominant regions for power generation are Asia, led by China and India, followed by North America and Europe. Asia produces 12919.3 TWh, which represents 48% of global production, compared to 20% for North America and 14% for Europe [19].

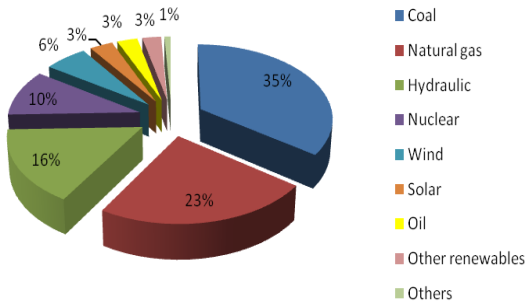

Figure 2. Distribution of world electricity production by source in 2020 in percent [16, 19]

2.3. Electrical Installed Power in the World

As shown in Figure 4, the world's installed electric power capacity increased from about 5088.8 GW in 2010 to 6265.2 GW in 2015 to reach 7320.3 GW in 2019, i.e., an average annual growth rate of 4.1%. Looking at Figure 5, we can see that fossil sources are still predominant compared to renewable, although their share in the overall electric power has decreased from 67% in 2010 to 59% in 2019. The share of nuclear power has dropped from 7% to 5% in the same period, as several countries, mainly Germany, have decided to shut down some nuclear power plants and stop investing in nuclear power [16, 20].

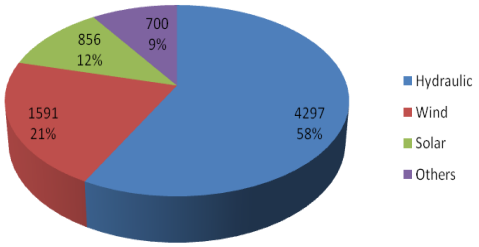

Figure 3. Distribution of global renewable energy production by source in 2020 in percent [16, 19]

2.4. Electrical Capacity in Renewable Energy

Figure 6 illustrates the development of global installed renewable energy capacity between 2010 and 2020. This capacity has increased very significantly from 1189 GW in 2010 to 2766 GW in 2020, which translates into an average annual growth rate of 4.3%. The share of renewable, excluding pumped hydro, has registered a very significant increase between 2010 and 2019, rising from 23% to 34% of the overall installed electricity capacity [16, 19]. As shown in Figure 7, the installed capacity of renewable energies tends to continue its growth, but without being able to overtake fossil energies. When we compare Figure 8 at Figure 9, we can see that the share of wind and solar in the overall capacity of renewable energy has grown very significantly between 2010 and 2020. Indeed, the share of solar has increased from 3% to 26% and that of wind has increased from 15% to 27%. These are very significant rates showing the significant growth of the integration of solar and wind in the global energy mix at the expense of hydro whose share has decreased from 74% in 2010 to only 42% in 2020 [16, 19, 20].

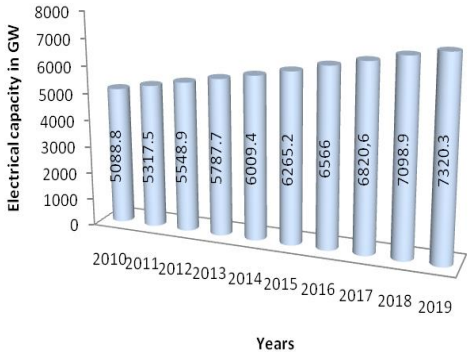

Figure 4. Evolution of the world installed electrical capacity from 2010 to 2019 in GW [16, 20]

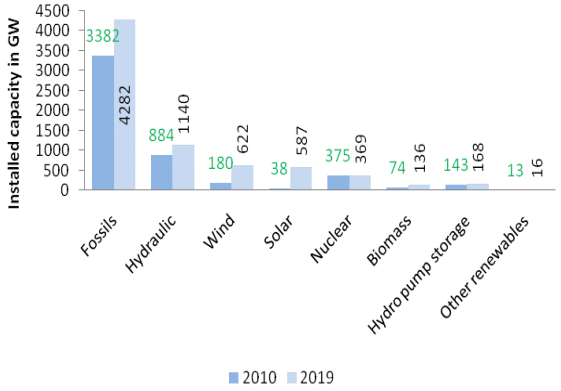

Figure 5. Comparison of global installed electrical capacity between 2010 and 2019 [16, 20]

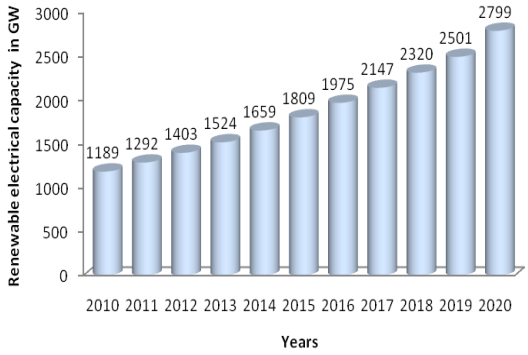

Figure 6. Evolution of the global electrical capacity in renewable energies in GW [19]

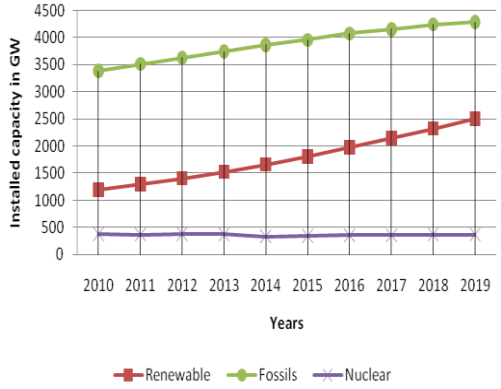

Figure 7. Electrical capacity in renewable, fossil and nuclear energies in GW [16, 20]

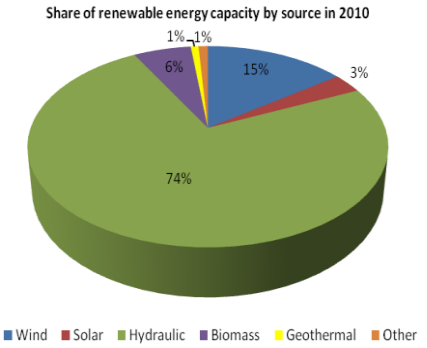

Figure 8. Percentage of renewable capacity by source in 2010 [19]

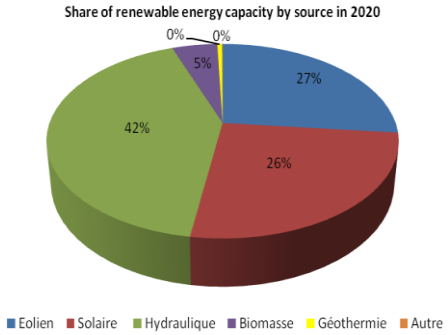

Figure 9. Share of renewable capacity by source in percent in 2020 [19]

3. WIND ENERGY IN THE WORLD

3.1. World Wind Potential

The estimation of the wind potential varies according to data and parameters taken into account by the Geographic Information System of the Wind Atlas. It also varies according to turbine technology, such as power rating, rotor diameter and hub height, as well as geographic, environmental, technical, safety, social and other restrictions. This is why it is not easy to give a precise number of the global wind energy potential.

In 1993, [21, 22] gave a first evaluation of the world's wind potential at about 56 TW, with a capacity factor of 35%. The study was based on turbines of 0.75 MW power and 50 m rotor diameter. In 2005, it was estimated at 72 TW, with a capacity factor of 48% and an average wind speed above 6.9 m/s [22, 23]. In 2009, the onshore wind potential was estimated at 96 TW and the offshore wind potential at 148 TW, based on turbines of power 2 to 4 MW [24]. In 2013, the global wind power potential was estimated at 400 TW [8, 25].

In a report published by the International Energy Agency in 2019, offshore wind power potential alone is estimated to be around 420,000 TWh per year, while the potential of onshore wind energy is estimated at 100,000 TWh in 2020 per year [26]. Taking into account that the world electricity production in 2020 was 26823 TWh, it is clear that the wind power production alone could meet the electrical needs of the planet. Table 1 gives an indication of the wind energy potential of the main countries that have invested in this field [14, 26, 27].

Table 1. Wind potential of leading countries in GW [14, 26, 27]

Countries	China	USA	Germany	India	Spain
Offshore potential	2982	5259	203	174	219
Onshore potential	2400 -3000	10459	1200	302	330

3.2. Evolution of the World Wind Capacity

Wind capacity has increased rapidly over the past decade because it is clean, competitively priced and has a very large untapped potential that far exceeds global electricity demand. As shown in Figure 10, global installed wind capacity has increased from 180 GW in 2010, to 416 GW in 2015 to reach 736 GW in 2020, an average annual growth rate of 15.12% [16, 19, 27].

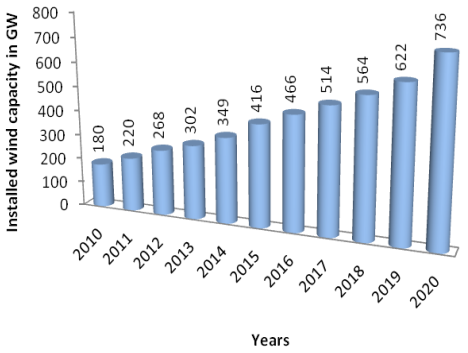

Figure 10. Evolution of global installed wind capacity from 2010 to 2020 in GW [16, 19, 27]

As shown in Figure 11, the continent with the most investment in wind power at the end of 2020 is Asia with 341.9 GW, followed by Europe with 216.6 GW and North America with 139.4 GW [16, 19, 27].

As shown in Figure 12, the leading country in wind power is China with 282 GW representing about 38% of the world's capacity, followed by the USA at 117.7 GW, Germany with 62.2 GW and India with 38.6 GW of wind power capacity [16, 19, 27]. However, it should be noted that Denmark is the main country that has invested in wind power. It has the highest wind capacity per capita, where China's is 200 W. /capita despite being the country with the highest wind capacity of all countries. The penetration rate of wind energy in Denmark is 48%, the highest in the world.

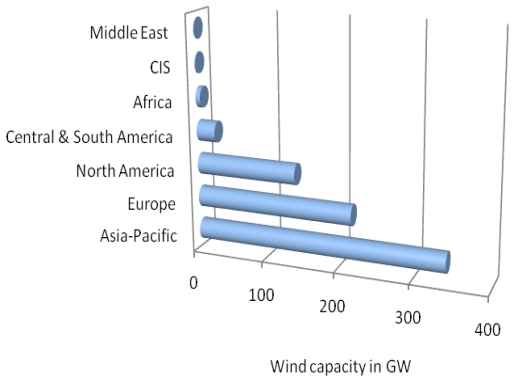

Figure 11. Wind capacities by region in 2020 in GW [16, 19, 27]

3.3. World's Most Powerful Wind Farms

As shown in Table 2, the Chinese wind farm, called "Gansu" or "Jiuquan Wind Power Base" is the world's largest installed capacity with 7960 GW of power. It is followed by the "Alta Wind Energy Center" (AWEC) in the USA, with 1550 MW of installed capacity, and the "Muppandal" wind farm in India, with 1500 MW. The most powerful offshore wind farm is "Hornsea" in England with 1200 MW of power [9, 16, 19, 27, 28, 29].

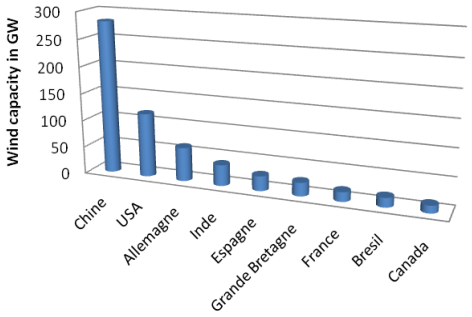

Figure 12. Global wind capacity by leading countries in 2020 in GW [16, 19, 27]

Table 2. World's most powerful wind farms [3, 9-10, 16-17, 19-20, 27-29]

Park name	Location	Estimated Year of commissioning	Installed capacity (MW)	Number of turbines	Unit power of turbines	Type
Gansu	China	2010-2021	10000	7000	0.75-0.85-1.5	Onshore
AWEC	USA	2011-2014	1550	600	1.5-3	Onshore
Muppandal	India	1986	1500	3000	0.2-1.65	Onshore
Hornsea	England	2019	1200	174	7	Offshore
Jaisalmer	India	2010-2012	1064	-	0.35-2.25	Onshore
Los Vientos	USA	2012-2016	912	426	2-2.3	Onshore
Shepherds Flat	USA	2012	845	338	2.5	Onshore
Roscoe	USA	2009	781.5	627	1-1.5-2.3	Onshore
Borssele 1- 2	Holland	2020	752	94	8	Offshore
Horse Hollow	USA	2005-2006	735.5	421	1.5-2.3	Onshore
Borssele 3- 4	Holland	2021	731.5	77	9.5	Offshore
Capricorn Ridge	USA	2007, 2008	662	407	1.5- 2.3	Onshore
Walney Extension	England	2018	659	87	7-8	Offshore
London Array	England	2013	630	175	3.6	Offshore
Fantanele-Cogealac	Romania	2012	600	240	2.5	Onshore
Fowler Ridge	USA	2008-2010	750	355	1.5-1.65-2.5	Onshore
Gemini	Holland	2017	600	150	4	Offshore
Sweetwater	USA	2003-2007	585.3	392	1-1.5-2.3	Onshore
Brahmanvel	India	2006-2012	528	451	0.6-1.25-3	Onshore
Buffalo Gap	USA	2006-2008	523.3	296	1.5-1.8-2.3	Onshore

3.4. Impacts of Wind Energy Integration

3.4.1. Impacts on Security of Electricity Supply

The integration of wind energy in the electricity grids has allowed producing in 2020 about 6% of the global electricity production and allows approaching the progressive energy autonomy of these countries and contributes to the world populations to have more access to electricity and to meet their electrical needs.

3.4.2. Environmental impacts

The CO_2 emissions from onshore wind parcs varies from 11 to 12.7 gCO_2e/KWh, and that of an offshore wind farm between 12 and 14 gCO_2e, while coal emits on average 820 gCO_2e/KWh. With a global installed wind power capacity of 736 GW, wind power reduces CO_2 emissions by approximately 1.1 billion tons [16, 27, 30].

3.4.3. Social Impacts

According to the IEA and IRENA, the renewable energy sector, especially wind power, creates 2 to 5 times more jobs than the fossil fuel sector. As shown in Figure 13, the number of direct jobs created by wind energy has increased from 0.63 million jobs in 2010 to 1.254 million in 2020, not including indirect jobs. Moreover, these jobs are better rewarded compared to other electric power sectors [10, 19, 26, 27].

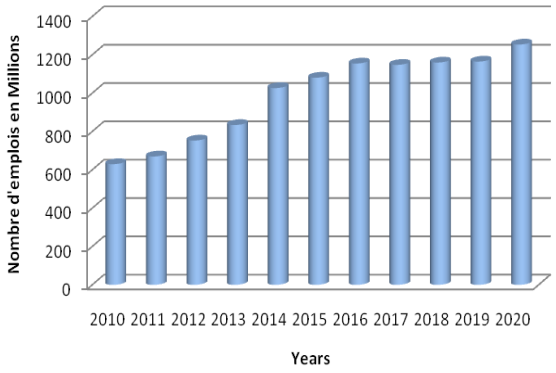

Figure 13. Number of jobs created by the wind energy sector by year in Millions [10, 19, 26-27]

3.5. Perspectives

From 2010 to 2020, annual additions in global wind energy installations have varied at an average of 55.17 GW/year and with a clear improvement in 2020 by adding 111GW in 2020 [19]. Despite this significant increase, the analyses of GWEC and IRENA, the main operators in this field, consider that these additions remain insufficient and if the aim is to attain zero GHG emissions in 2050, it must reach 180 GW per year from 2021 to 2025. On the other hand, the IEA estimated that new wind installations should reach 160 GW per year from 2021 to 2025, and 280 GW per year from 2026 to 2030 [27].

Based on the policies adopted by the leading countries, their forecasts of installation or expansion of wind farms and given the expiry of the incentive systems granted by China and the USA to the wind sector, it is expected that new wind power installations will not reach this number, but will be, from 2020 to 2025, around 94 GW per year, that is to say 469 GW in total, of which 399 GW onshore and 70 GW offshore. The global wind capacity would then exceed 1 TW [4, 27].

4. CONCLUSIONS

In this paper, we propose a synthesis and a quantitative and qualitative study of the development of wind energy in the world. We review its potential, evolution, impacts and prospects. Although fossil fuels are still predominant, renewable energies are clearly on the rise, are experiencing greater annual growth and will eventually overtake them. The potential for wind power, both onshore and especially offshore, far exceeds the world's electricity demand and is capable becoming a substitute to fossil fuels.

Wind energy has become one of the cleanest, most competitive and most abundant sources of renewable energy. It can substantially increase the autonomy of electrical energy of countries, the creation of new jobs and the protection of the environment by reducing CO2 emissions. In fact, during the last 10 years, global wind capacity has quadrupled, the number of jobs created has almost doubled to reach 1.254 million jobs and CO2 emissions have been reduced by about 1.1 billion tons.

However, wind power production still represents only 6% of the world's electricity production and there are large disparities between the different countries in this area. To remedy this, it is necessary, on the one hand, to strengthen international cooperation through technical and financial support from rich countries to countries with limited means, and on the other hand, to encourage governments relying on fossil fuels to diversify their sources of electrical energy by investing in renewable energies and by gradually introducing restrictions on the use of fossil fuels.

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