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Article

The European Union toward a green economy: Current situation and perspective in the use of renewables for electricity generation

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Abstract: The European Union (EU) is making significant progress in its energy transition strategy, positioning itself as a global leader. The use of renewable energy sources for electricity generation is increasing yearly. In 2012, the share of renewable electricity in gross electricity consumption in the EU was 24.1%. This figure rose to 38% in 2020, overtaking fossil-fired generation for the first time, which fell to 37%. In 2021, the EU produced 4032.5 TWh using all energy sources. Renewable energies generated 1670.4 TWh or 41.4% of the total. Conventional and nuclear energy sources produced the remaining 58.6%. In the coming years, conventional energy sources are expected to generate less electricity than renewable and nuclear energy sources. In the coming years, solar and wind energy will remain the two main renewable energy sources for electricity generation in the EU. The EU's energy transition is a concern and a key apprehension for the European Commission (EC), which strives to ensure sustainable, secure, and reasonable energy prices in the coming years. In February 2015, the EC set out its energy strategy, focusing on five key areas: Energy security, solidarity, and trust; a fully integrated European energy market; Energy efficiency contributing to moderation of demand; decarbonizing the economy; research, innovation, and competitiveness.

Keywords: renewable energy; fossil fuels; electricity generation; European Union; green economy; energy transition

1. Introduction

The EU comprises 27 continental European countries. These countries are Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden (see **Figure 1**) with a population exceeding 500 million. The EU is undergoing a historical energy transition driven by increasingly strong decarbonization policies and quick low-carbon technology developments. The Paris Agreement marked a major step forward in global efforts to address global warming. For the first time, developed and developing countries committed to act in order to limit global average temperature increase to well below 2 °C and to pursue efforts to further limit this to 1.5 °C above pre-industrial levels [1].

One of the European Commission's (EC) main concerns is the EU's energy problems associated with the transition to ensure sustainable and secure energy at reasonable prices. In February 2015, the EC set out its energy strategy to ensure the EU can deal with an energy crisis in the coming years. The strategy focuses on five key areas: Energy security, solidarity, and trust; a fully integrated European energy market; Energy efficiency contributing to moderation of demand; decarbonizing the economy; and research, innovation, and competitiveness. In 2016, the EC presented a package of legislative proposals called 'Clean Energy for all Europeans' to translate the strategy adopted into reality. The EC's proposals were discussed within the Council and at the European Parliament, and negotiations started in 2017. By May 2019, all legislation in the package was adopted [2].

Figure 1. Member state of the European Union.
Source: ai.inspiredpencil.com.

On 18 May 2022, the EU explained, as part of the REPower EU Plan, how it would support energy transition to ensure sustainable, secure, and affordable energy [3].

This article describes the current participation and perspective of the different renewable energy sources within the EU's energy mix and, based on the information offered, suggests their future participation in a green economy.

2. Research method

A review of the published literature was conducted to prepare this paper, which provides the reader with the most relevant updated data and information on the EU energy transition from a society based on burning fossil fuels for electricity generation to a green economy using different renewable energy sources for the same purpose.

The methodology used to prepare the manuscript is the "Historical-Logical Method." This method allows the author to describe the facts through their logical development.

3. Discussion

3.1. Key elements of the 2030 European Commission on energy policy

According to IMEDIA [4], the cornerstones of the 2030 EU's energy and climate policy are the target of a 40% reduction in emissions compared to 1990 levels in each Member State, a binding EU-wide target for using renewable energy for power production, transforming its current energy system into a more competitive, secure, and sustainable energy system; a new power policy considering energy efficiency as a key factor in achieving all the objectives of the new policy; and a set of key indicators to assess ongoing progress and provide a factual basis for possible policy responses.

The 2030 EC Energy Policy suggests a new policy based on national plans to ensure a competitive, secure, and sustainable energy supply, drawing from the guidelines provided by the EC.

3.2. Primary energy production in the European Union

Primary energy production within the EU in 2022 accounted for 23,566 petajoules (PJ), 5.9% lower than in 2021. Primary production increased for solid fossil fuels but decreased for oil, natural gas, and renewables from 2021 to 2022. In the case of renewables, this is an exception in its long-term increasing trend. Renewable energies accounted for the highest share in primary energy production in the EU in 2021 (43.2%), followed by nuclear energy (27.6%), solid fossil fuels (16.4%), natural gas (6.2%), oil and petroleum products (3.3%), and non-renewable waste (2.4%). Over the past decade (2012–2022), the trend in primary energy production was generally negative for solid fossil fuels, oil, natural gas, and nuclear energy. Natural gas production saw the sharpest decline (−64.9%), followed by solid fossil fuels and oil and petroleum products (with a drop of 38.7% and 38%, respectively). The production of renewable energies followed a clear positive trend over the same period, with a 32.6% increase, similar to waste (non-renewable), which saw a 22.3% increase [5].

3.3. Final energy consumption in the European Union

Final energy consumption in the EU in 2022 was 37,771 PJ, 3.9% less than in 2021. Final energy consumption slowly increased from 1994 until it reached its highest value of 41,447 Mtoe in 2006. By 2022, it had decreased from its peak level by 8.9% [5]. It is important to note that the final energy consumption was 1.6 times the EU's primary energy production. **Figure 2** shows the EU's final power consumption by sector in 2022.

In 2022, the services sector was the one that consumed more energy within the EU. The household sector was the one that consumed less energy within the EU in that year.

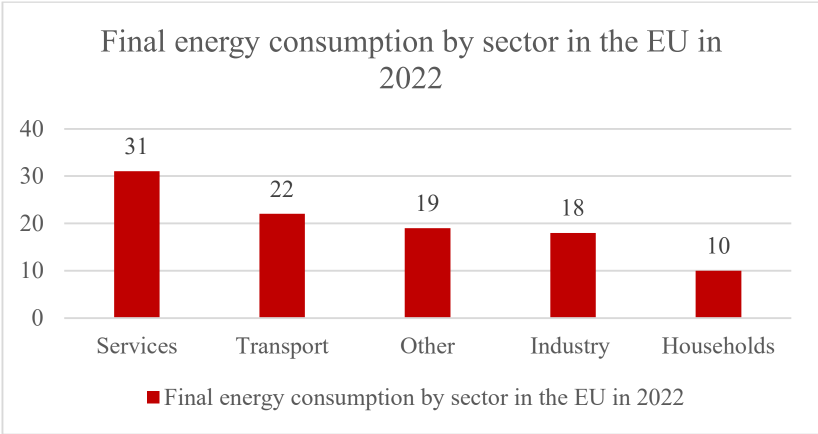

Figure 2. Final power consumption by sector in the EU in 2022 [5].

3.4. The role of fossil fuels in the European Union

The decrease in fossil fuel utilization in many EU Member States economic sectors is significant. The largest reduction was reported in coal and lignite electricity production, which was replaced mainly by electricity generated from natural gas. However, natural gas has also lost ground inside the EU due to the increased use of renewable energy and its higher prices.

Replacing coal and oil with alternative clean energy has significantly reduced greenhouse gas emissions in sectors closely linked to the EU's electricity consumption. This substitution plays an essential role in the energy transition process in the EU, from a system based on using conventional energy sources for electricity production to another based on clean energy sources.

One important aspect must be carefully studied before a decision is adopted to replace fossil fuels with other energy sources during the energy transition towards a green economy in the EU. This aspect is unpredictability. Renewable energies are unpredictable because they depend on the weather, so there is no guarantee that they will generate at any given time the level of electricity that will satisfy the required needs (Unlike coal, oil, or gas, electricity cannot be stored easily. It must thus be generated and delivered at the precise moment it is needed, something that most renewable energy sources cannot ensure. The demand load curve is the most important element to be considered when addressing power generation. A load curve shows the variation of load (in kW or MW) over time (in hours). The load curve can be plotted for 24 h a day; it is then called a daily load curve; if one year is considered, it is called an annual load curve. The load curve is important because the electricity capacity demanded by consumers (industry, residential, and commercial) varies over time. Typically, industrial activities are the highest during the day, commercial activities are high during the day and the early evening hours, and residential activities are high mainly in the evening when everybody is at home and turns on the lights, watches television, and uses other electric devices [6]). To guarantee this, for the time being, nuclear energy or natural gas power plants must be ready to supply the electricity needed when renewable energy cannot.

3.5. Energy mix in the European Union

The energy available in the EU comes from energy produced inside the EU or imported energy. Therefore, to get a good overview of the total energy available in the EU, both types of energy should be considered. In 2021, the EU produced around 44% of its energy needs, while 56% was imported. In other words, the EU's consumption depends heavily on power imported.

In 2021, the energy mix in the EU was the following:

- Crude oil and petroleum products (34.2%);
- Natural gas (23.3%);
- Renewable energy (17.2%);
- Nuclear energy (13.8%);
- Solid fossil fuels (12%);
- Other (0.2%) [7].

Crude oil and petroleum products are the most consumed energy sources in the EU, accounting for 34.2% of the total energy produced in the country, followed by natural gas, 23.3%, and renewables, 17.2%. In 2023, the EU energy mix capacity was structured in the following manner:

- Renewables: Wind (34.1%), hydro (23.8%), solar (40%), bioenergy (5.4%), and geothermal (0.1%);
- Fossil fuel: Coal (12.8%), oil (1.7%), and natural gas (21.1%);
- Nuclear: 24.6%;
- Others: 0.7% [8–10].

However, energy production is very different from one EU member to another. For example, renewable energy was the exclusive source of primary power production in Malta and represented the main power source in several EU Member States, with shares of over 95% in Latvia, Portugal, and Cyprus [7]. The nuclear share was particularly high in France (62.6%), Slovakia (59.2%), Hungary (47%), Belgium (46.4%), and Slovenia (42.8%) [9]. Solid fuels were the main source of energy produced in Poland (72%), Estonia (56%) and Czechia (45%). Natural gas had the largest share in the Netherlands (58%) and Ireland (42%), while the share of crude oil was the largest in Denmark (35%) [7].

3.6. The European Green Deal

The EC has been fully committed to transforming the EU into a clean, resource-efficient, and competitive economy, in line with the goals of the Paris Agreement. To achieve the goal mentioned above, the European Green Deal was adopted. Its objective is to ensure zero emissions by 2050, making Europe the first climate-neutral continent in the world. In 2021, the EU approved its first European Climate Law. Its objective is to allow Europe to become climate-neutral by 2050 and to establish a target of 55% less emissions by 2030 compared to 1990. As required under the Climate Law mentioned above, the EC recommended, in February 2024, an additional intermediate target of 90% less emissions by 2040 [11].

However, the European Green Deal is about setting targets and creating the right enabling environment. First, it is about putting people at the core of the transition to Europe's green economy. That is why the EC has been ensuring that the clean transition is fair by supporting those more vulnerable and most affected by the effects of climate change. For this reason, the EC will create the following funds:

- Just Transition Fund: The EC has supported workers and regions to develop new skills and thrive in the EU green economy through this fund.
- Social Climate Fund: Partly funded via the EU Emissions Trading System (While market mechanisms—such as the EU Emissions Trading System (EU ETS)—that set price signals for market actors are important in changing investment and behavioral patterns, they have significant regressive distributional effects, disproportionally affecting low-income households [12]), it will provide EU Member States with dedicated funding to support vulnerable groups thanks to investments in energy efficiency, renovation of buildings, and clean heating.
- Solidarity Fund: This fund and the Civil Protection Mechanism have brought support where needed most, including farming communities, after climate-related disasters such as wildfires, storms, and floods [11].

Second, to achieve the EU climate-neutrality goal, its Member States need a power system that is cleaner, more efficient, and no longer dependent on conventional energy sources. Therefore, the EC must ensure that capital flows in the right direction and that people and businesses can access the financial resources needed to make green investments [11].

Third, the EU has mobilized private and public funding to support the deployment of low-carbon energy sources and increase buildings' energy efficiency. An estimated €275 billion will be needed to support clean investments and €118 billion until 2027 for the clean energy transition [11].

Fourth, the EU has ensured that the European economy and industries are ready to reap the benefits of the energy transition while acting to maintain a level playing field with their economic competitors. For this reason, in February 2023, the EU adopted the Green Deal Industrial Plan, which includes the Critical Raw Materials Act and The Net-Zero Industry Act to create a predictable and simplified regulatory environment in their respective fields of action and enable the scaling up of manufacturing capacity for the net-zero technologies and products that the EU economy needs [11].

One of the main objectives of the European Green Deal is to increase the use of renewables for electricity production. The transition to a climate-neutral energy system in 2050, largely based on renewable energy sources, can be seen as a technological rupture vis a vis the still largely fossil fuel-based energy and economic system in place. It is a source of challenges and opportunities for economic actors in the EU and globally. Research and innovation will be crucial in the transformation through individual technology development or systemic innovation. The key to success in the long term is to develop a wide portfolio of cost-effective and efficient carbon-free alternatives in combination with solutions for an integrated energy system built on digitalization and sector integration. Understanding this complex transition of the energy system and its components requires a sound methodology to capture the dynamics within different fields and their interplay. Given the 2050 time horizon for reaching climate neutrality, the interaction between technology development and energy system design becomes crucial. While many technologies required for the energy transition are known in principle, costs may change rapidly, as seen for renewable energy during the last decade. Research and innovation will define the speed at which decarbonization can occur and at which costs [13].

The current role and perspectives of the different energy sources within the energy transition of the EU to a green economy are explained in the following sections.

3.7. The current situation and perspectives on the use of renewable energies for electricity production

The EU promotes using renewable energy for electricity generation to decarbonize the power sector by 2050 because using conventional energy sources for electricity generation is the largest source of greenhouse gas emissions in its Member States. Three-quarters of the EU's greenhouse gas emissions are due to electricity production, heat, and transport. Accelerating the implementation of projects on renewable energies is indispensable to drastically reduce greenhouse gas emissions and achieve the EU's goal of climate neutrality by 2050.

More than 20% of the power consumed in the EU comes from renewable energy sources, more than double that in 2004. The possibility of increasing the EU target in 2030 is currently being reviewed, as are the objectives for buildings, heating and cooling, and industry. In September 2022, the EU Parliament demanded that the renewable energy target be raised to 45% by 2030 from the 32% already approved. **Figure 3** shows the contribution of renewable energies to the EU energy mix.

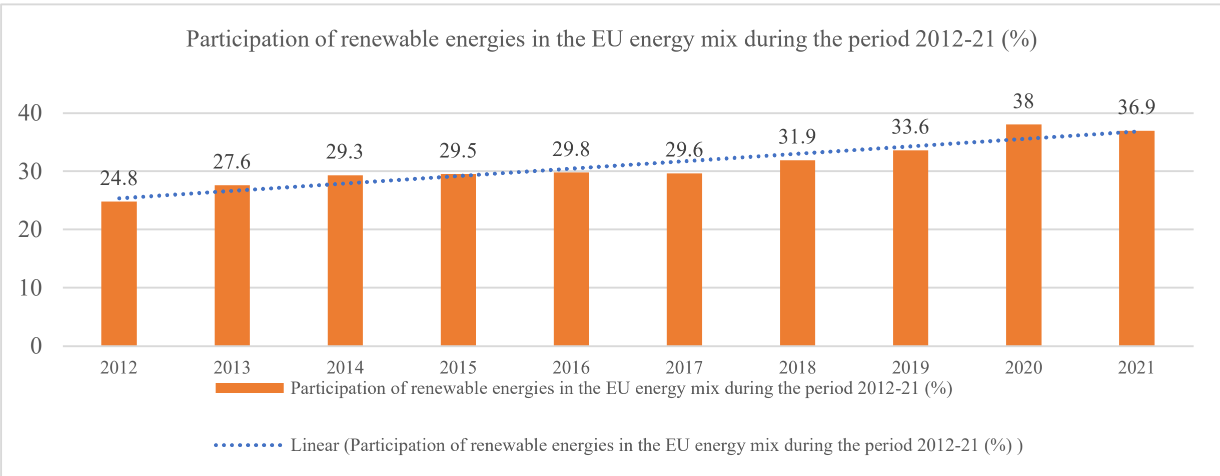

Figure 3. Participation of renewable energies in the EU energy mix during 2012–2021 [14].

Figure 3 shows that renewable energy participation in electricity production in the EU grew from 24.8% in 2012 to 36.9% in 2021, an increase of 12.1%. **Figure 4** shows the capacity of renewable energy plants installed in the EU from 2014 to 2023.

According to **Figure 4**, the capacity of renewable power plants installed in the EU grew 81.9%, from 352,565 MW in 2014 to 641,478 MW in 2023. Considering measures adopted by the EU to decarbonize its energy sector, the capacities of renewables in the EU are expected to grow to 42.5% in 2030.

It is important to note that by the end of 2023, renewable energies accounted for 43% of global installed power capacity. However, as countries move closer to a world where renewable energy accounts for half the total capacity installed, many new renewable power plants still need to be constructed. These new capacities will push renewables as the most significant source of electricity generation—including in the context of grid flexibility and adaptation to variable renewable power.

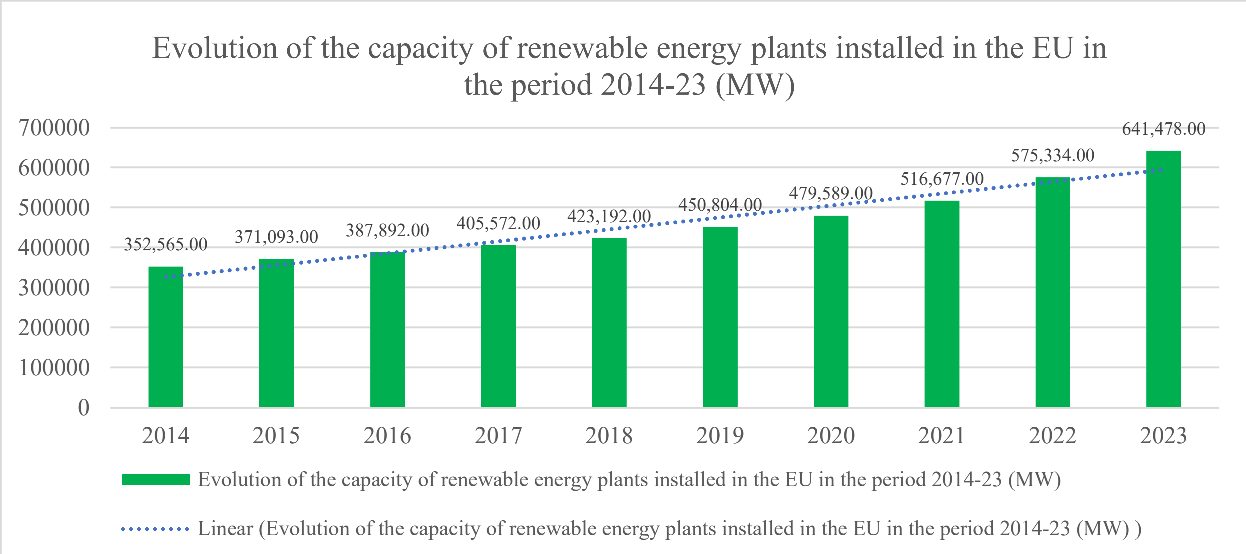

Figure 4. Evolution of the capacity of renewable energy plants installed in the EU in 2014–2023 [10].

Figure 5 shows the electricity generation using renewables in the EU during 2013–2021.

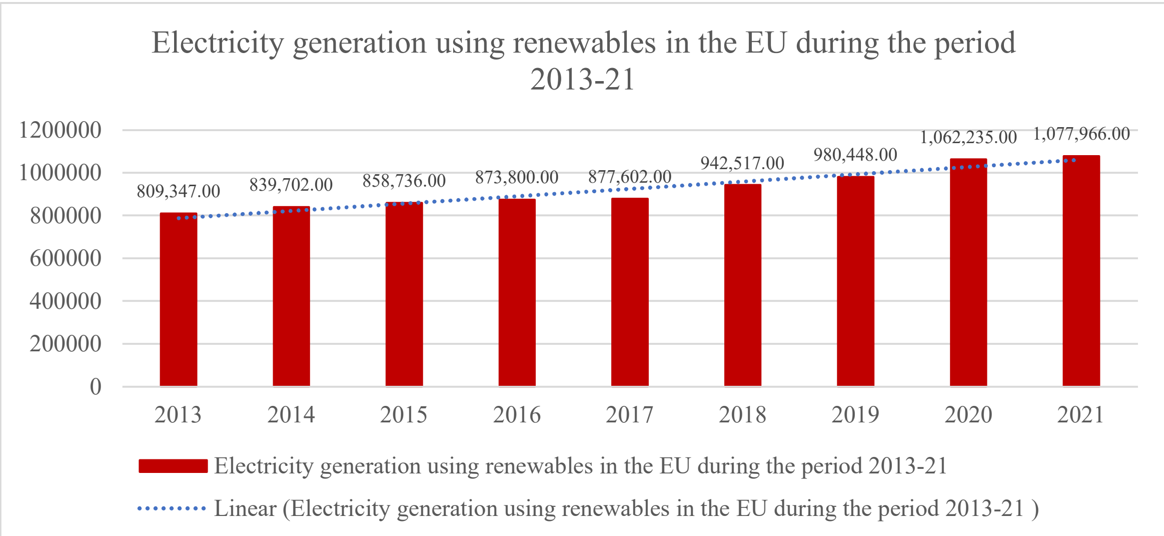

Figure 5. Evolution of electricity generation using renewables in the EU during 2013–2021 [14].

According to **Figure 5**, the electricity generated by all renewable energy sources in the EU during 2013–2021 increased by 33.2%, growing from 809,347 GWh in 2013 to 1,077,966 GWh in 2021. The countries with the highest electricity generation in 2021 within the EU are Germany with 230,800 GWh, Spain with 125,747 GWh, France with 122,377 GWh, and Italy with 116,352 GWh.

Finally, it is important to stress that 2023 saw the largest increase in renewable energy capacity to date—with the addition of 473 GW of renewables—expanding the stock of renewable power by 13.9%, reaching 86% of global power additions. That increase was due to significant solar and wind power growth. Solar power accounted for nearly three-quarters of new additions, with a record 346 GW, while one-quarter or 116 GW was due to wind energy additions [10].

3.7.1. Hydropower in the European Union

There are three hydropower generation types. These are run-of-river, hydro storage, and pumped storage. The electricity generation in all these three types of hydropower plants follows the same principle, as water is used to turn one or multiple turbines. One can calculate the power output of a hydroelectric turbine with the following formula:

$$P = \eta \times p \times q \times g \times h$$

where P is the power output, η the efficiency of the turbine (generally between 0.8 and 0.95), ρ the density (approximately 1000 kg/m^3 for water), q the site-specific water flow in m^3 per second, g is the gravity (9.81 m/s^2), and h stands for the hydraulic head, that is, the falling height in meters [6].

In hydropower plants, water located in a reservoir and retained by the dam accesses a turbine through high-pressure forced pipes in which the water acquires a great speed that will later be transformed into energy. The water reaches its maximum speed in the turbine room thanks to rotational movement. These turbines transfer the energy obtained through the force of the water to an electric generator that will be in charge of transforming it into electrical energy. In hydropower plants, the difference in the two elevations that conform plant is called the "head" (see **Figure 6**).

Figure 6. Hydropower plant.

Source: Free photo on Pixabay.

Hydroelectric power plants are usually located on dams that dam up rivers, thus raising the water level behind the dam and creating as much head as possible.

In most communities, the demand for electric power is different at different times of the day. Pumped-storage hydroelectric plants are sometimes built to balance the load on generators. These plants have two water reservoirs located at different elevations. They are designed to lift water to a reservoir at a higher elevation when the electricity demand is low. During peak power demand, water flows from the highest-placed reservoir through the turbine to generate electrical power.

Hydropower installed capacity

The installed capacity of hydropower plants in the EU has been growing in recent years. In 2023, France was the country with the highest installed capacity with 25,881 MW or 16.9% of the total, followed by Italy with 22,887 MW or 15% of the total, Spain with 20,140 MW or 13.2% of the total, Sweden with 16,399 MW or 10.7%, and

Austria with 14,708 MW or 9.6%. Outside the EU, but within Europe, the country with the largest capacity in hydroelectric plants installed is Norway, with 34,401 MW [10]. **Figure 7** shows the growth of the capacity of hydroelectric plants in the EU from 2014 to 2023.

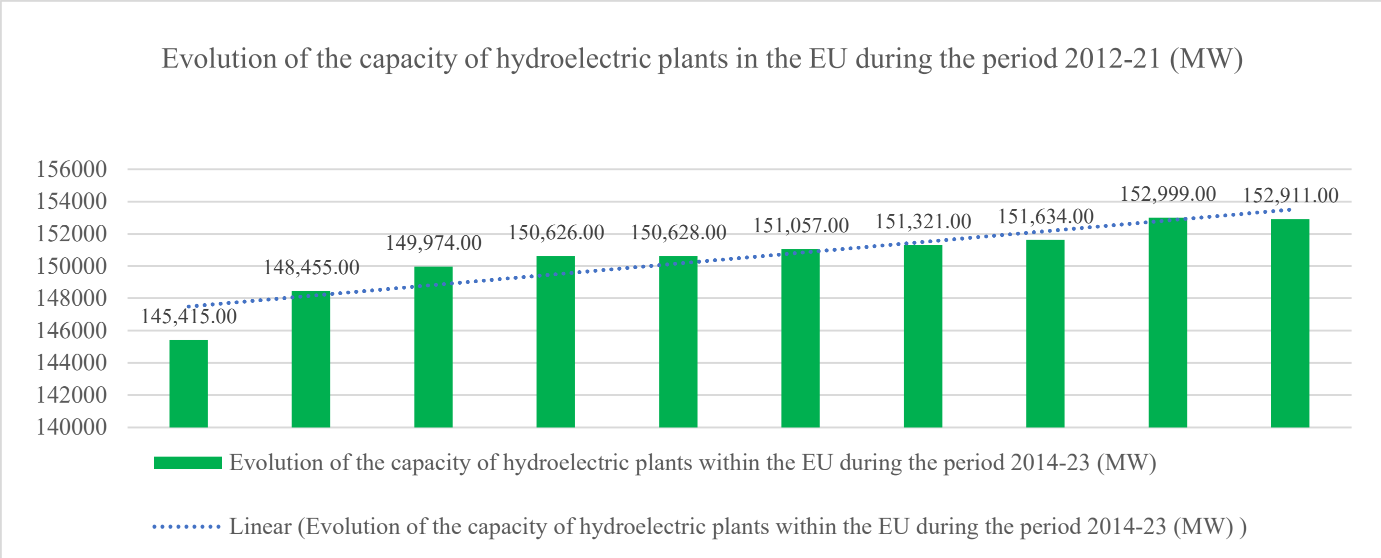

Figure 7. Evolution of the capacity of hydroelectric plants within the EU during 2014–2023 [10].

According to **Figure 7**, the capacity of hydroelectric plants within the EU grew by 5.2% during the 2014–2023 period, growing from 145,415 MW in 2014 to 151,911 MW in 2023. Considering the plans approved by the EU to decarbonize the energy mix of its Member States by 2050, it is projected that hydropower capacities will continue growing over the coming years, even though the growth potential is not very broad as a result of strong opposition from public opinion of many of EU's Member States. Most of the population in several EU Member States are against increasing the hydroelectric capacities installed to avoid further environmental damage.

Hydropower electricity generation

The EU's electricity production from hydroelectric plants reached 375,804 GWh in 2021, representing 8.5% of the world's total (4,400,679 GWh). In 2021, the regions that surpassed the EU in terms of generating electricity through hydroelectric plants were Asia, with 1,917,754 GWh or 43.6% of the world's total; North America, with 692,113 GWh or 15,7%, and South America, with 632,279 GWh or 14.4% [14].

Figure 8 shows the evolution of electricity generation through hydroelectric plants from 2013 to 2021.

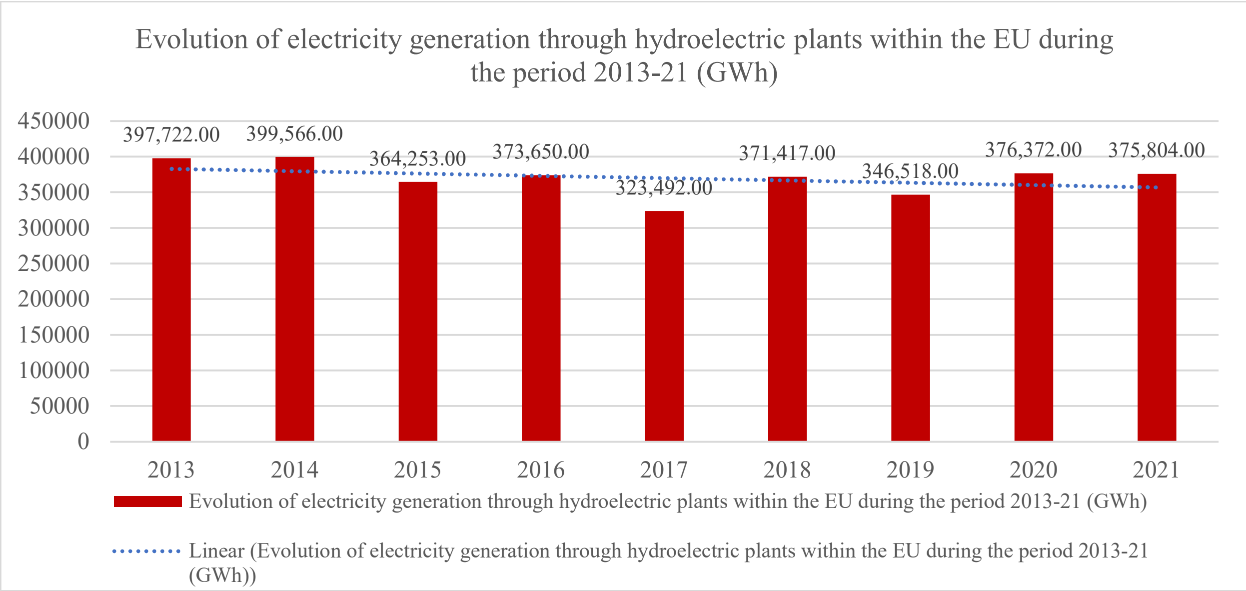

Figure 8. Evolution of electricity production through hydroelectric plants during 2013–2021 [14].

According to **Figure 8**, electricity production through hydroelectric power plants in the EU decreased by 5.5% during the period under consideration due to the drought that affected several countries in 2011, 2012, 2015, 2016, 2017, and 2019.

It is important to single out that the increase in electricity production using hydroelectric plants in the EU will be limited in the coming years, not only due to the droughts that climate change may cause in the region but also due to the strong opposition that exists in many EU Member States to increasing already installed hydropower capacities due to the reason mentioned above.

In summary, the following can be stated: in 2022, renewables accounted for 23% of total energy consumption in the EU. The share of renewables in electricity consumption was even higher at 41.2%. Wind power produced 37.5% of total electricity generated from renewable sources (a significant increase from 4.9% of all renewables in 2000). The share of wind power in total electricity production was 16% (14% onshore and 2% offshore) [15].

3.7.2. Wind energy in the European Union

Wind energy is a relevant part of the "green" or "ecological energies" that are more environmentally friendly. That is why constructing wind farms worldwide, particularly in the EU, has become an important component of the EU energy mix in recent decades. These wind farms are usually built on the seacoast, as well as on plains and large plains where the wind is constant and considerable.

Undoubtedly, wind power is an important element in the current energy mix of many EU Member States and is likely to play an important role in electricity generation during the coming decades [16].

Wind farms installed capacity

Figure 9 shows that the capacity of wind farms installed in the EU during 2014–2023 has grown yearly.

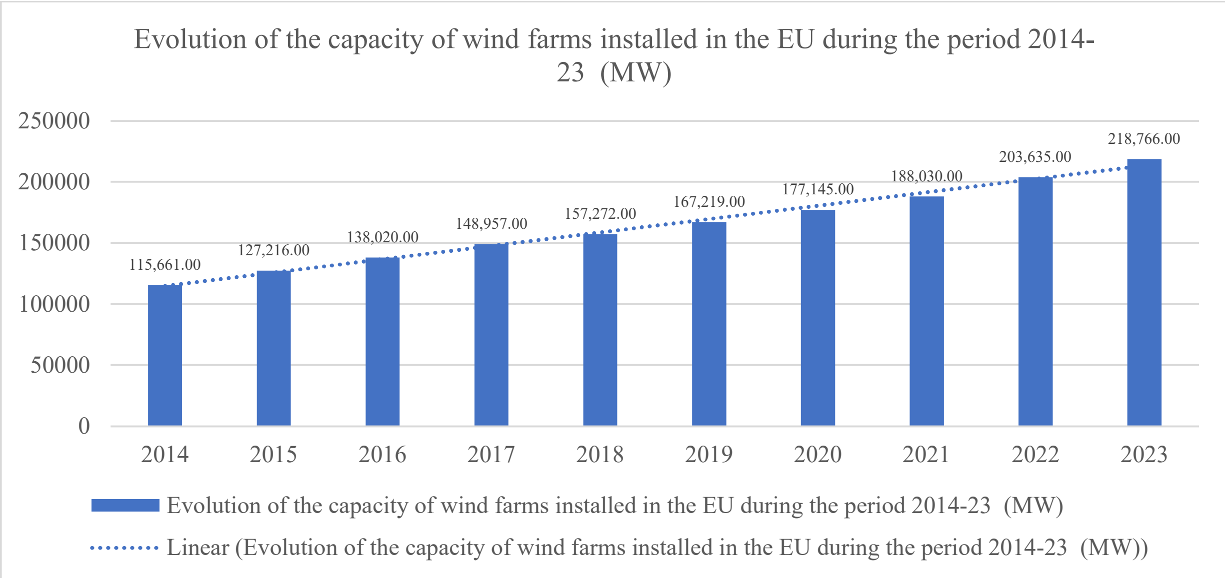

Figure 9. Evolution of the capacity of wind farms installed in the EU during 2014–2023 [10].

Based on **Figure 9**, it can be stated that the capacity of the wind farms installed in the EU grew by 89.1% during 2014–2023, growing from 115,661 MW in 2014 to 218,766 MW in 2023. The EU wind farms capacity in 2023 represents 21.5% of the world's total (1,017,199 MW), behind Asia with 508,452 MW or 50%. China has the largest installed wind capacity, with 441,895 MW or 43.4% of the world's total (86.9% of the region's total). Germany has the EU's largest installed wind farm capacities, with 69,459 MW or 31.8% of the region's total, followed by Spain, with 31,028 MW or 14.2%. The capacity of wind farms in the EU is projected to continue growing every year until 2030, helping to decarbonize the region's energy mix by 2050.

Wind farm electricity generation

Figure 10 shows the evolution of electricity production from wind farms established in the EU from 2013 to 2021.

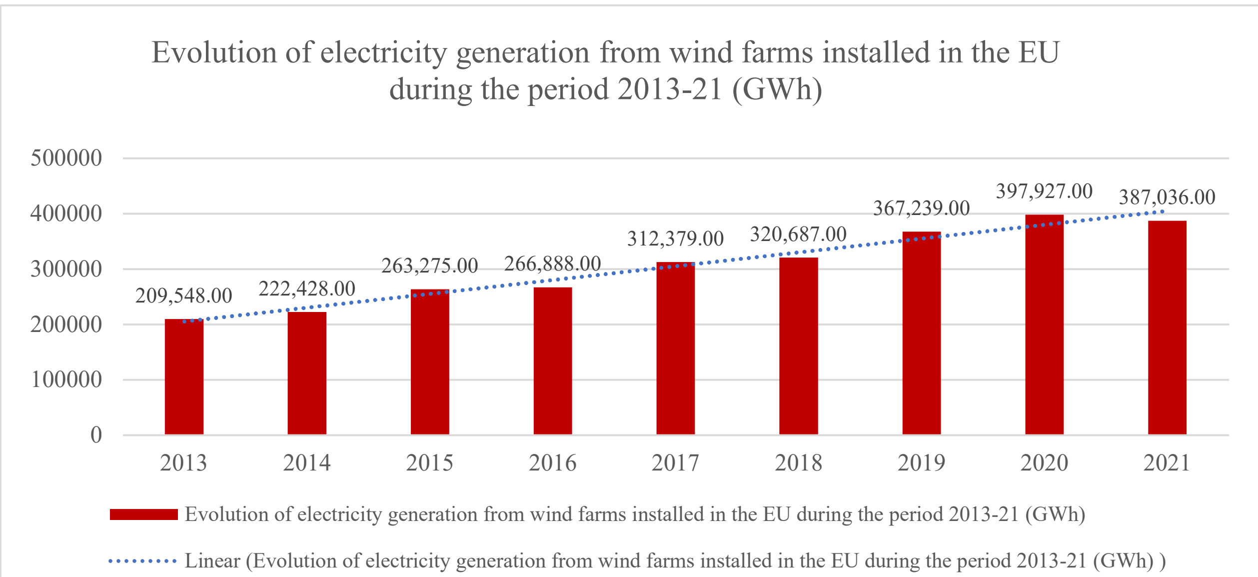

Figure 10. Electricity generation from wind farms in the EU during 2013–2021 [14].

Based on **Figure 10**, it can be affirmed that the electricity generation through the wind farms installed in the EU grew by 84.7% during the period under consideration, growing from 209,548 GWh in 2013 to 387,026 GWh in 2021, being surpassed only by the Asian region with 747,548 GWh or 35% of the world's total. The EU countries with the highest electricity generation using wind energy were Germany with 114,647 GWh or 6.2% of the world total, Spain with 62,061 GWh or 3.4%, and France with 36,831 GWh or 2%. It is important to highlight that from 2013 to 2020, electricity generated by wind farms in the EU grew yearly. However, this trend stopped in 2021, when the electricity generation by wind farms decreased by 2.8%, but is expected to continue growing until 2030.

Wind energy is crucial to the EU's climate targets and energy security needs. Here are some key points about wind farms in the EU.

- In 2023, the total installed wind power capacity in the EU reached 218,766 MW. Most of this capacity was onshore, accounting for 92% of the total.
- The EU aims for at least 42.5% renewable energy consumption by 2030. To achieve that goal, wind farm capacity must grow to over 500 GW by 2030, overcoming several challenges. For example, the EU wind sector faces important challenges such as insufficient demand, complex permit processes, supply risks, and a shortage of skilled workers, delaying the construction of more wind farms within the EU. Other challenges should also be overcome, such as public acceptance, environmental impact, and co-existence with other activities (e.g., fisheries).

Finally, it is important to note that investment in new wind power technologies like floating wind and hybrid projects (combining wind solar, hydrogen, or battery energy production) is essential to achieving the abovementioned goal. Wind farms are vital to the EU's renewable energy strategy, contributing significantly to electricity generation and the transition toward cleaner energy sources [15].

Onshore wind farms

Wind farms installed in the EU are of two types: a) onshore and b) offshore. The evolution of the capacity of onshore wind farms within the EU grew by 79.3% during 2014–2023, growing from 112,178 MW in 2013 to 201,144 MW in 2023 (see **Figures 11** and **12**). This capacity represents 21.3% of the world's total (944,536 MW), only surpassed by Asia with 468,200 MW or 49.6%. The EU countries with the highest onshore installed wind farm capacities in 2023 were Germany, with 61,052 MW or 30.4% of the EU's total, and Spain, with 31,021 MW or 15.4% [10].

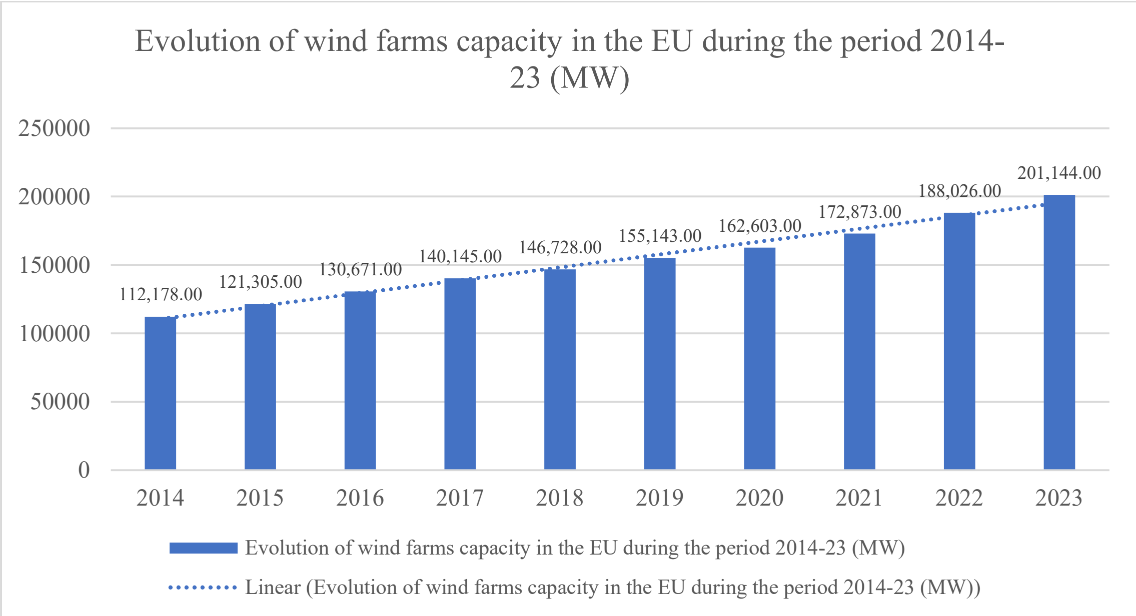

Figure 11. Evolution of the capacity of onshore wind farms within the EU during 2014–2023 [10].

Figure 12. Onshore wind farms.

Source: freepik.es.Free Pixabay photos.

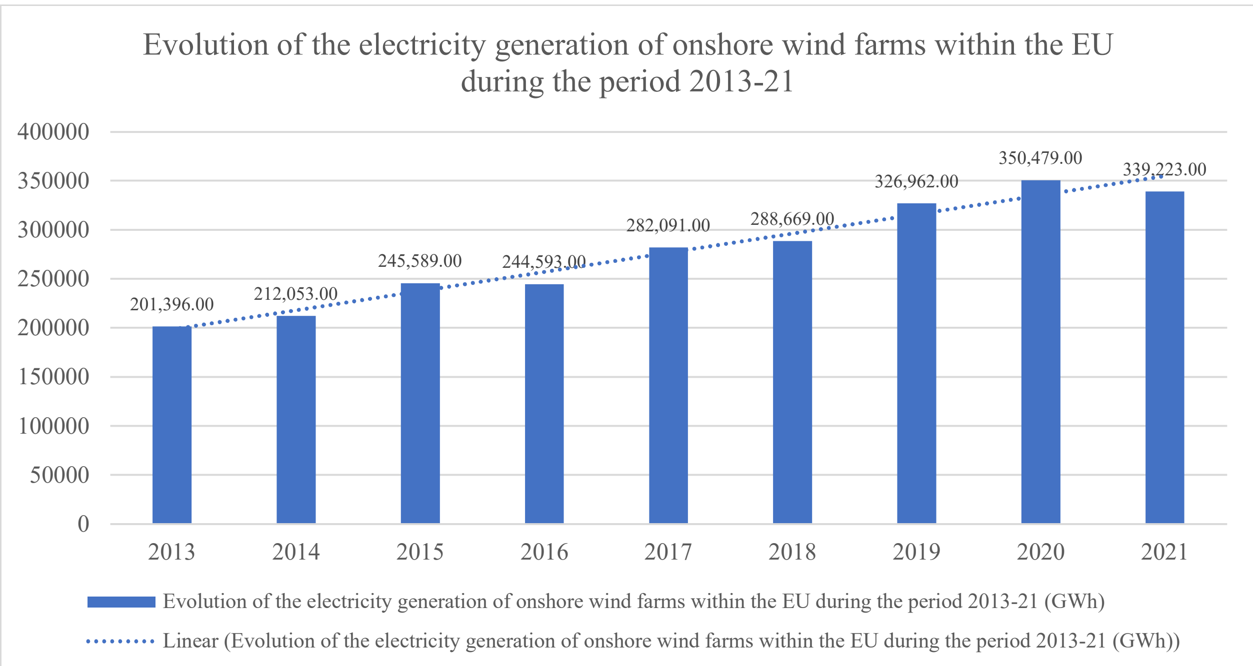

Figure 13. Electricity generation from onshore wind farms installed in the EU during 2013–2021 [14].

Electricity generation from onshore wind farms installed in the EU grew by 68.5% during the 2013–2021 period, growing from 201,396 GWh in 2013 to 339,223 GWh in 2021 (see **Figure 13**). This generation level represented 20% of the world's total (1,700,650 GWh), only surpassed by Asia with 693,397 GWh or 40.8%. China generated most of its electricity through onshore wind farms, with 603,994 GWh or 87% of the region's total [14].

In summary, onshore wind farms play today and will continue to play in the future a crucial role in electricity generation within the EU in its transition toward a green economy. Wind energy is central to accelerating the use of renewables in order to achieve the green transition outlined in the European Green Deal and the REPower EU Plan. The EU aims to have at least 42.5% renewable energy consumption by 2030, which will require installed capacity to grow to over 500 GW.

However, despite its importance, the wind energy sector faces the following challenges:

- Slow, insufficient, and uncertain demand;
- Slow and complex permit application processes;
- High supply risks linked to raw materials;
- High inflation and commodity prices;
- More pressure from international competitors;
- Limited availability of a skilled workforce.

It is expected that regulatory responses, including streamlined permit procedures and support for cross-border projects, aim to address these issues. Successful wind energy deployment must consider public acceptance, which tends to be higher for offshore wind, biodiversity impact, and co-existence with other economic activities like fisheries. Europe continues to invest in wind energy. In 2023, wind energy generated 466 TWh of electricity, covering 19% of electricity demand. New onshore wind farms had capacity factors ranging from 30% to 45%, while offshore wind farms achieved around 50% capacity factors [15].

Undoubtedly, onshore wind farms are vital to the EU's renewable energy strategy, contributing significantly to electricity generation and the transition toward cleaner energy sources for electricity generation.

Offshore wind farms

The first offshore wind farm was installed in Denmark in 1991. Additionally, floating offshore wind turbines are being explored for sites farther out to sea, where winds are stronger and more consistent. Undoubtedly, European companies have valuable experience as pioneers in offshore wind.

The EU capacity installed for offshore wind farms (see **Figure 14**) reached 17,621 MW in 2023. **Figure 14** shows the evolution of the offshore wind farm capacity in the EU during 2014–2023.

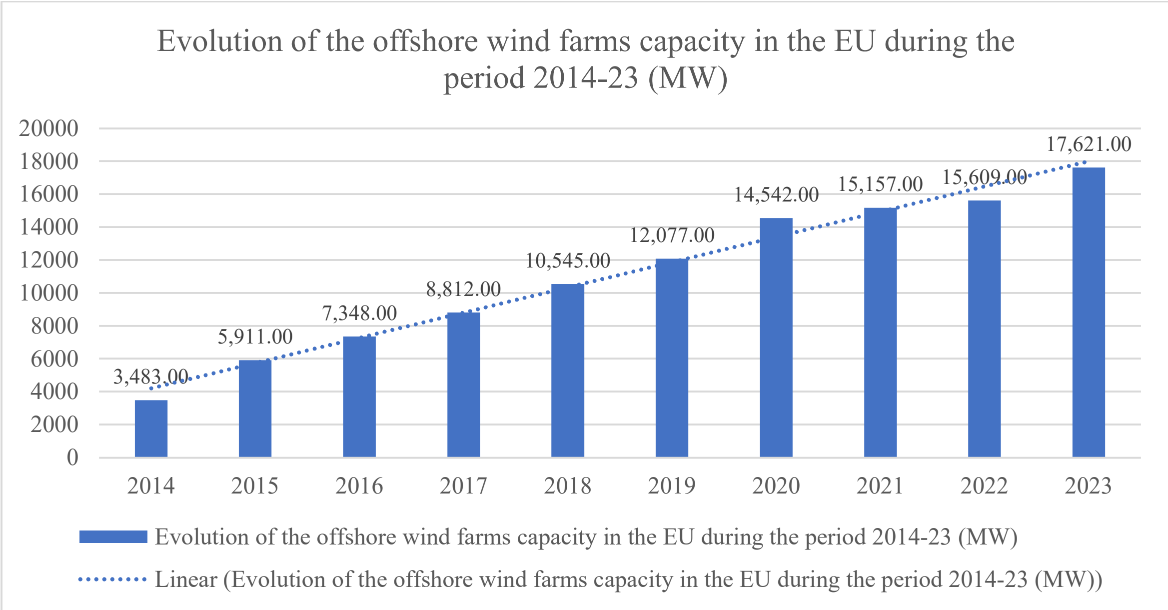

Figure 14. Evolution of the capacity installed of offshore wind farms in the EU during 2014–2023 [10].

Based on **Figure 14**, it can be stated that the capacity installed of offshore wind farms in the EU during 2014–2023 increased 5.1-fold, growing from 3483 MW in 2014 to 17,621 MW in 2023. The country with the largest installed offshore wind capacity in the EU in 2023 was Germany, with 8407 MW or 11.6% of the world's total (72,663 MW). The electricity generated by offshore wind farms installed in the EU in 2021 amounted to 47,804 GWh or 33.5% of the world's total (137,614 GWh). The EU country with the highest electricity generation in 2021 was Germany, with 24,375 GWh or 33.5% of the world's total [14].

In summary, offshore wind farms (see **Figure 15**) have played and will continue to play a vital role in electricity generation within the EU. Without a doubt, Europe is a global leader in offshore wind energy capacity installed, with 17.6 GW in 2023. These farms consist of wind turbines located at sea, harnessing abundant and consistent wind resources. Under the European Green Deal, the EU aims to achieve climate neutrality by 2050. Offshore wind is a critical component to achieving this goal. The EC's strategy targets 60 GW of offshore wind by 2030 and 300 GW by 2050, contributing significantly to clean energy production. Some of the EU's main challenges in increasing the use of wind energy for electricity generation in its Member States are complex permitting processes, supply chain risks, and skilled workforce availability. The EU's strategy addresses broader issues such as sea-space access, regional cooperation, and industrial dimensions. Offshore wind farms are crucial for achieving renewable energy targets and reducing EU dependency on conventional energy sources [15].

Figure 15. Offshore wind farm.

Courtesy: Pixabay free photos.

Figure 16 shows the evolution of electricity generation by offshore wind farms in the EU from 2013 to 2021.

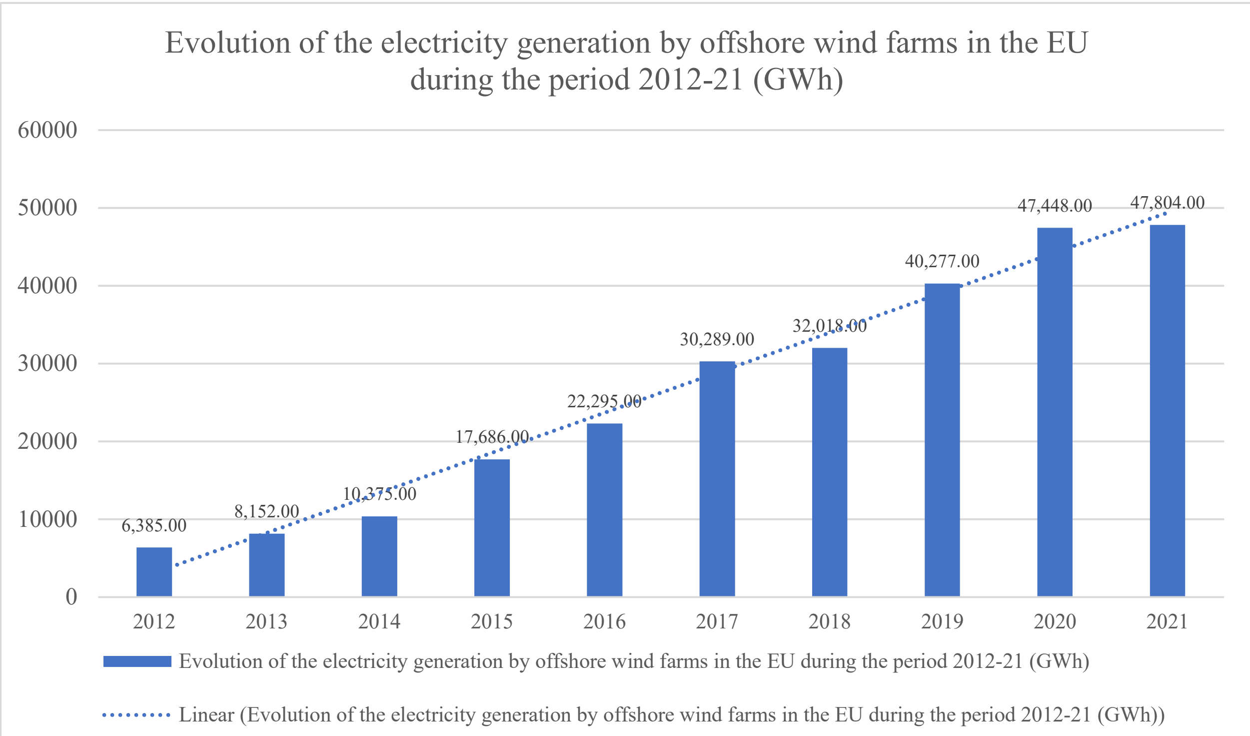

Figure 16. Evolution of the electricity generation of offshore wind farms in the EU during 2012–2021 [14].

Based on **Figure 16**, it can be affirmed that the electricity generation of offshore wind farms in the EU during 2012–2021 increased 7.5-fold, growing from 6.385 GWh in 2012 to 47,804 GWh in 2021. The country with the largest offshore wind electricity generation in the EU in 2021 was Germany, with 24,375 GWh, or 17.7% of the world's total (137,614 GWh).

In summary, the following can be stated: Offshore wind farms play a critical role in the EU's energy transition to a clean economy. Offshore wind energy is abundant, domestically sourced, and increasingly affordable. It contributes significantly to reducing dependency on imported fossil fuels for electricity generation. The global average levelized energy cost for offshore wind farms has declined by 48% between

2010 and 2020, decreasing from 0.14€ to 0.071€/kWh. For this reason, offshore wind is a decisive element in the EU green transition, paving the way for a modern, resource-efficient, and competitive economy, and has become one of the most important pillars of the EU's climate ambitions, according to the European Union [17].

Challenges faced by the wind power sector include insufficient demand, complex permitting processes, supply chain risks, inflation, and a limited skilled workforce. The EU has adopted a group of regulatory measures to overcome these challenges. Among these regulations are the revised Renewable Energy Directive streamlines permit application procedures; the TEN-E framework supports cross-border projects; and the newly announced wind power package aims to strengthen the EU wind industry and develop offshore wind farms further.

The EU aims to add around 30 GW of wind power annually to meet its 2030 targets. Offshore wind farms will be critical to achieving this goal and are essential for achieving renewable energy targets, enhancing energy security, and driving the EU's transition to a greener economy.

3.7.3. Solar energy in the European Union

Another important component of the EU energy mix is solar energy. Solar energy is often used to refer to electrical or thermal energy obtained using solar radiation, the main energy source on Earth. There are three types of solar energy: Solar photovoltaic (Solar PV) (see **Figure 17**), Concentrated solar power (CSP) (see **Figure 18**), and Passive solar energy [18].

Figure 17. Solar PV park.

Source: Pixabay photos gratis.

Figure 18. Concentrated solar power park.

Source: Pinterest.

The total capacity of the solar parks installed in the EU in 2023 amounted to

257,057 MW, representing 18.1% of the world's total (1,418,969 MW) [9]. The EU has been supporting, for several years now, the construction of solar parks in its Member States to reduce electricity generation using coal and oil thermal power plants and strengthen the role of renewable energies in the EU energy mix. The capacity of solar parks installed in the EU from 2014 to 2023 is shown in **Figure 19**.

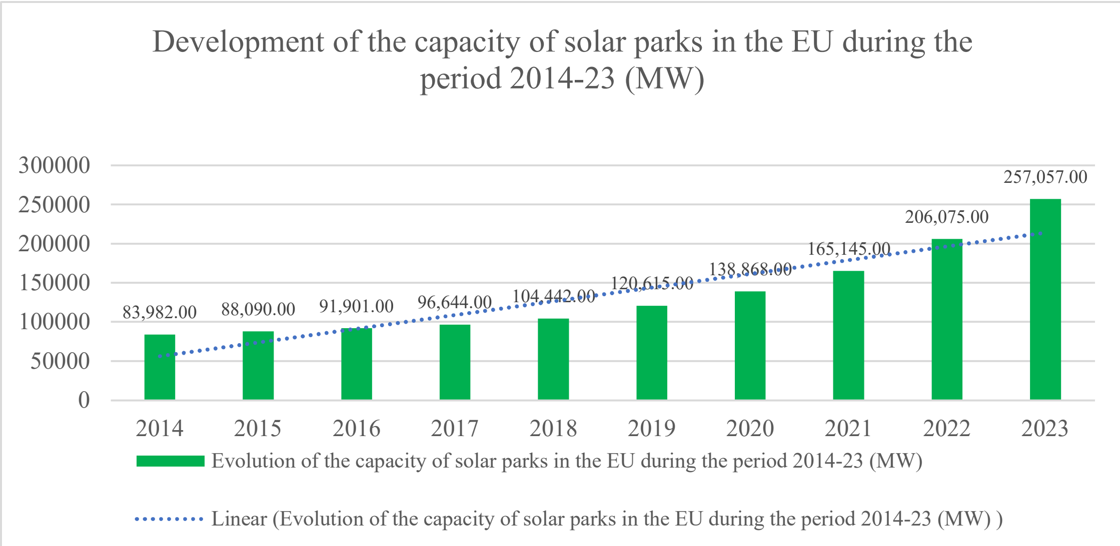

Figure 19. Development of the capacity of solar parks in the EU from 2014 to 2023 [10].

As seen in **Figure 19**, the capacity of solar parks within the EU grew by about 3.1-fold during the period considered, growing from 83,982 MW in 2014 to 257,057 MW in 2023. Throughout 2014–2023, the capacity of solar parks grew steadily but significantly since 2020. This tendency is projected to continue until 2030, helping the decarbonization of the regional energy mix. The countries with the greatest capacities of solar parks installed in the EU in 2023 were Germany, with 81,739 MW or 31.8% of the total for the region, followed by Spain, with 31,016 MW or 12.1%, and Italy, with 29,795 MW or 11.6% (The United Kingdom, which has not been a member of the EU since January 2021, had an installed capacity of solar parks of 15,657 MW in 2024, representing 5.4% of the region's total (288,122 MW) [10].).

Solar Park electricity generation

The evolution of electricity production in the EU by solar parks installed in the region is shown in **Figure 20**.

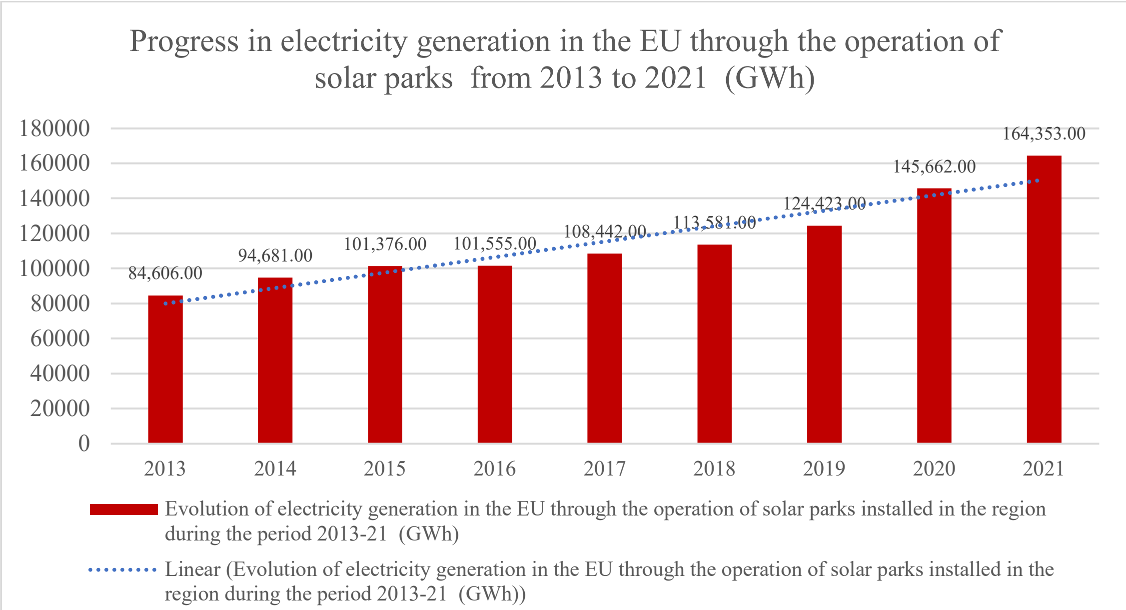

Figure 20. Evolution in electricity generation in the EU by solar parks installed in the region during 2013–2021 [14].

According to **Figure 20**, the electricity generated by the solar parks installed in the EU grew 94.3% during the period under consideration, growing from 84,606 GWh in 2013 to 164,353 GWh in 2021. In all these years, there was a systematic growth in electricity generation through solar parks installed in the EU, a trend that is expected to continue at least until 2030.

Solar photovoltaic capacity

Solar photovoltaic is the renewable energy source most used in the EU for electricity generation. Its installed capacity reached 254,736 MW in 2023, representing 18% of the world's total (1,412,093 MW) [10], generating 159,165 GWh in 2021, or 15.6% of the total electricity generated worldwide (1,020,297 GWh) in that year [19]. **Figure 21** shows the growth of the capacity of solar PV parks in the EU from 2014 to 23.

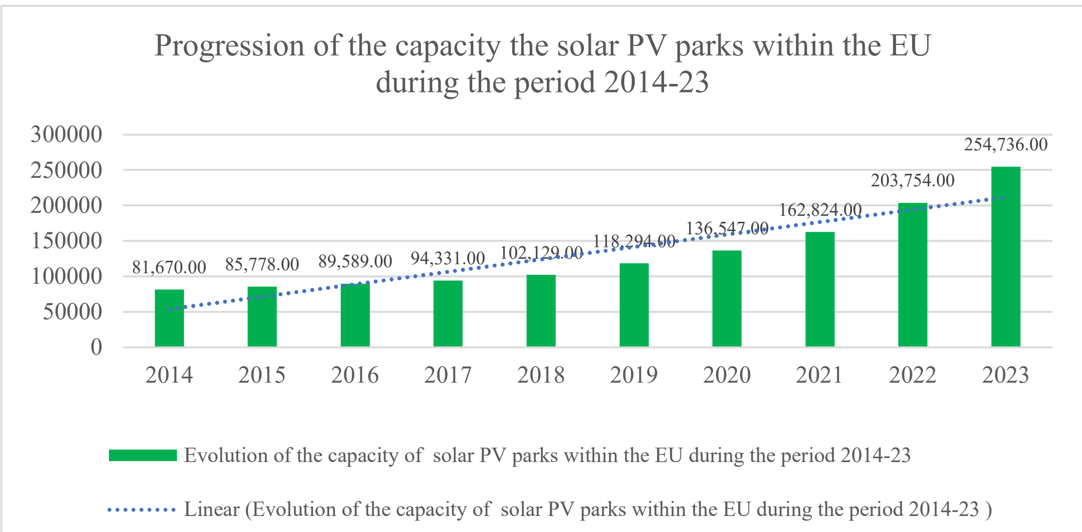

Figure 21. Progression of the capacity of solar PV parks installed in the EU during 2014–2023 [10].

Based on **Figure 21**, it can be stated that the capacity of solar PV parks installed within the EU grew 3.1-fold during 2014–2023, growing from 81,670 MW at the beginning of the period to 254,736 MW at the end of it. In all these years, the capacity of solar PV parks installed in the EU grew systematically, particularly after 2018. It is expected that this trend will continue until 2030. The countries with the largest solar PV park capacities already installed within the EU are Germany, with 81,737 MW or 5.8% of the world's total (1,412,093 MW), followed by Italy, with 29,789 MW or 2.1%, and Spain, with 28,712 MW or 2%.

Solar photovoltaic electricity generation

Figure 22 shows the electricity generated by solar PV parks installed in the EU from 2013 to 2021.

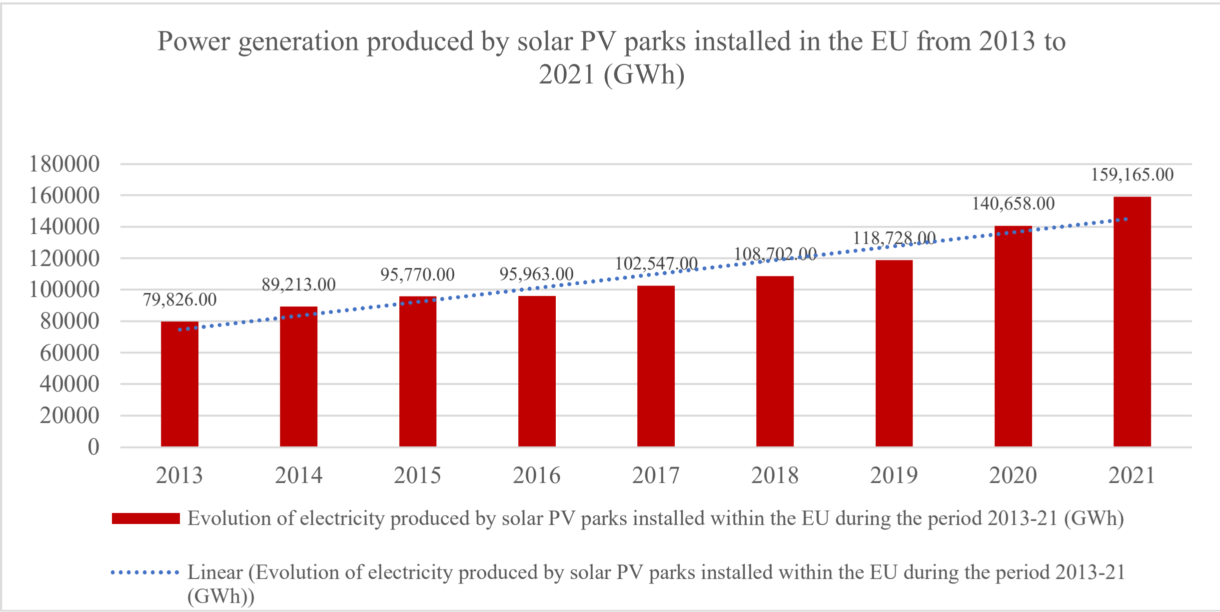

Figure 22. Electricity produced by solar PV parks installed in the EU during 2013–2021 [14].

According to **Figure 22**, electricity produced by solar PV parks installed in the EU grew 99.4% during 2013–2021, increasing from 79,826 GWh in 2013 to 159,165 GWh in 2021. The electricity produced by solar PV parks increased yearly within the abovementioned period. This trend is foreseen to stay without change during the coming years.

EU measures to increase the role of solar energy include installing solar panels on the rooftops of new buildings obligatory, simplifying permitting procedures for solar PV projects, improving the skills in the solar PV sector, and boosting the EU's capacity to manufacture photovoltaic panels. Several challenges still need to be addressed, including competition for land use for other purposes, technological issues, skills shortages, and the need to prevent a new energy dependency on non-EU solar panel producers. The ambitious plan includes doubling the current level of solar PV capacity by 2025 and to reach almost 600 GW by 2030. Achieving these goals will depend on continued commitment to solar PV deployment, success in addressing several challenges faced by the solar PV sector, and the ability to unlock the full potential of solar energy in the EU, for instance, by boosting domestic solar production and using new technologies [20].

Solar PV is crucial in the EU's transition to a green economy. Under the European Green Deal and the REPower EU Plan, solar PV is relevant for reducing the EU's dependence on imported conventional energy sources. It contributes to the clean energy transition and the goal of reducing reliance on energy imports from Russia and China, among others. Solar PV is currently one of the cheapest sources of electricity production, with costs having decreased by 82% over the past decade.

Concentrated solar power park capacity

The current capacity of the CSP parks installed within the EU is very small (2321 MW or 0.9% of the total) compared to the solar PV parks installed in the region (254,736 MW). In 2023, the countries with CSP park capacity installed in the EU were France (9 MW or 0.4%), Germany (2 MW, or 0.09%), Italy (6 MW or 0.3%), and Spain (2304 MW), the country with 99.3% of the total CSP capacity installed [10]. These CSP parks generated, in 2021, a total of 5188 GWh, a very small amount compared to the electricity produced during that year by other renewable energy sources, including solar PV. The EU countries with electricity generation using CSP parks reported in 2021 were Italy, with 12 GWh, or 0.2% of the total, and Spain, with 5176 GWh, or 99 [14].

3.7.4. Bioenergy in the European Union

Bioenergy is another of the main components of the EU energy mix, through which a stable power supply is ensured. According to FAO [21], bioenergy is energy from biomass, for example, wood, dung, or charcoal, excluding material embedded in geological formations and transformed into fossils. The IEA and the IPCC consider bioenergy a central element to achieving zero net growth and compliance with the Paris Agreement on Climate Change.

Bioenergy provides flexible power generation and the potential for negative emissions through carbon capture and storage. Biomethane is key to diversifying the EU gas supplies, while liquid and other gaseous bioenergy carriers are promising in the longer term.

According to Pelkmans and Georgiadou [22], the following are the main outcomes included in a report on the implementation of bioenergy in the EU in 2021:

- Renewable energy share in final energy consumption was 19%. Around 60% is from biomass;
- Solid biofuels represent almost 70%. Liquid biofuels, biogas, and renewable waste represent around 10%;
- Fossil fuels still dominate heat and transport energy in the EU. Bioenergy/biofuels are the main sources of renewable energy in these sectors. Fuel/heat consumption (excluding electric heating) in the EU is still more than 70% based on fossil fuels, with 15% directly using biomass for heat.

In 2010, bioenergy was the source of approximately 7.5% of the energy consumed in the EU. However, it is important to be aware that forest biomass and productive land are limited resources in the European region, and, therefore, all existing resources must be used to form the region's energy mix in the most efficient way possible before deciding to add new land for energy production.

Bioenergy plant capacity

According to EU Statistical Pocketbook 2022 [10], the most common bioenergy plants are the following:

- Solid biofuel and renewable waste plants (in all EU countries);
- Renewable municipal waste plants (in 19 EU countries);
- Bagasse plants, only in Portugal;
- Other solid biofuel plants (in 25 EU countries);
- Liquid biofuel plants (in 13 EU countries);
- Biogas plants (in all EU countries).

The capacities of bioenergy plants installed in the EU in 2023 amounted to 34,466 MW. Germany, with 9950 MW, or 6.6% of the world's total (150,261 MW), Sweden, with 4507 MW, or 3%, Italy, with 3434 MW, or 2.3%, and Finland, with 3059 MW, or 2%, were the EU countries with the largest bioenergy installed capacities in 2023 [10].

Figure 23 shows the development of bioenergy plant capacity installed in the EU from 2014 to 2023.

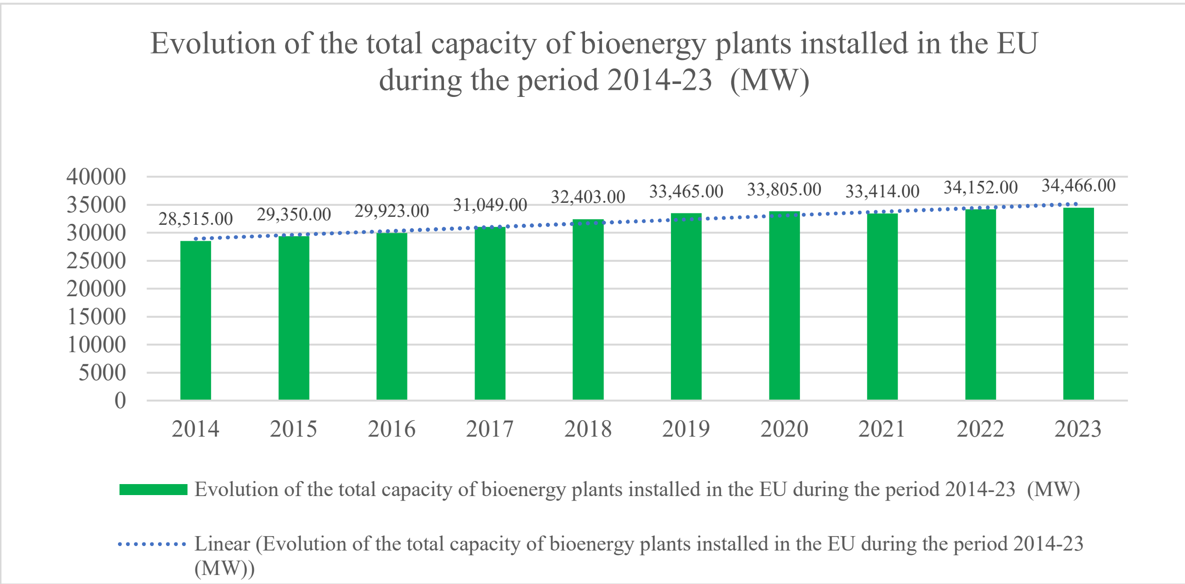

Figure 23. Evolution of the total capacity of bioenergy plants installed in the EU during 2014–2023 [10].

As shown in **Figure 23**, the bioenergy plant capacity installed in the EU grew by 20.9% during 2014–2023, growing from 28,515 MW in 2014 to 34,466 MW in 2023. The bioenergy plant capacities in the EU grew yearly in 2014–2023, and this trend is expected to continue without change until 2030.

Bioenergy plant for electricity generation

Figure 24 shows the electricity generation from bioenergy plants installed in the EU from 2013 to 2021.

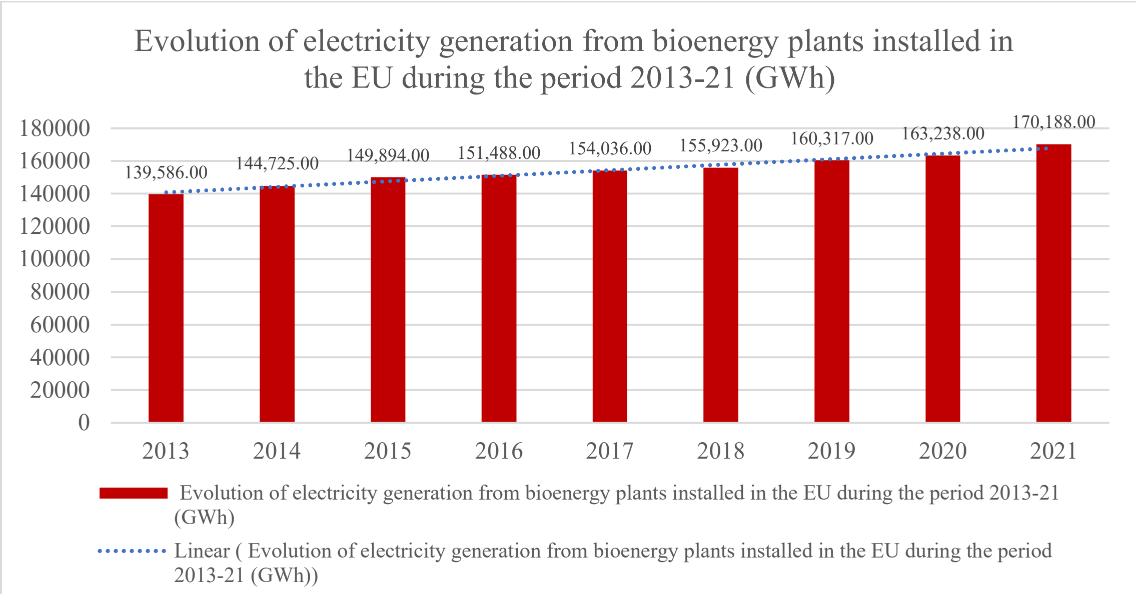

Figure 24. Evolution of electricity generation from bioenergy plants installed in the EU during 2013–2021 [14].

As shown in **Figure 24**, electricity generation through bioenergy plants installed in the EU grew by 21.9% during 2013–2021, growing from 139,586 GWh in 2013 to 170,188 GWh in 2021. The bioenergy plant capacity installed in the EU grew yearly during the period under consideration. This trend is expected to continue during the coming years, thus contributing to the decarbonization process of the EU energy sector approved by all its Member States.

Regarding the solid biofuels and renewable waste plants installed in EU countries, the information on their installed capacities in 2023 and their electricity generation in 2021 was, according to the EU Statistical Pocketbook 2022 [10] and IRENA Renewable Energy Statistics 2023 [14], as follows:

- In 2023, renewable municipal waste plants were installed in 19 EU countries. The installed capacity is 4018 MW, generating 19,577 GWh in 2021;
- Bagasse plants exist only in Portugal. The installed capacity is 2 MW, generating 15 GWh in 2021;
- Other solid biofuels are installed in 25 EU countries. The installed capacity is 16,652 MW, generating 91,475 GWh in 2021;
- Liquid biofuel plants are installed in 10 EU countries. The installed capacity is 2090 MW, generating a total of 4480 GWh in 2021;
- Biogas plants are installed in all EU countries. The installed capacity is 11,594 MW, generating 52,640 GWh in 2021.

3.7.5. Geothermal energy in the European Union

Geothermal energy is produced by harnessing the heat from inside the Earth. This heat is transmitted by convection and conduction through hot rock bodies or reservoirs (see **Figure 25**).

Figure 25. Geothermal power plant.

Courtesy: Pixabay free photos.

There are three geothermal power plants: a) Dry steam, b) Flash, and c) Binary. Dry steam, the oldest geothermal technology, extracts steam from fractures in the ground and uses it to directly drive a turbine. However, most future geothermal power plants will be Binary [23]. It is important to note that geothermal power is considered renewable energy that can provide reliable baseload power at a relatively low cost.

Where could it be built, considering the specific characteristics of the geothermal power plants? They are points on the map where a higher temperature can be found for natural reasons. These are the sites where a geothermal power plant can be built. There are four types of geothermal reservoirs:

- High-temperature reservoirs. There is a heat source where the fluid is stored at around 100 °C;
- Low-temperature reservoirs. Their temperature is between 100 °C and 60 °C;
- Very low-temperature reservoirs (above 15 °C);
- Hot rock reservoirs. These are rocks that are between five and eight km underground.

Geothermal energy is generated in more than 20 countries. In the EU, only eight countries (around 30% of the membership) use this energy source for electricity generation. The geothermal capacity installed in the EU in 2023 amounted to only 895 MW, almost all concentrated in Italy, with 772 MW or 86.3% of the region's total. The power generated by this type of power plant amounted, in 2022, to 6832 GWh, of which Italy generated 6022 GWh for 88.1% of the regional total. Other EU countries with geothermal power plants in operation in 2023 were Croatia (10 MW or 0.1%), France (16 MW or 0.2%), Germany (50 MW or 0.7%), and Portugal (29 MW or 0.4%). Outside the EU, but within Europe, the country with the second largest geothermal energy capacity installed is Iceland, with 756 MW in 2023. This country generated, in 2021, a total of 5802 GWh [10,14].

Geothermal energy accounts for over 1% of total power generation worldwide. However, in some countries like Iceland, the proportion is significantly higher due to the great potential that the country has due to its high volcanic and geological activity.

Above all, future geothermal power generation prospects are good because the exploration and exploitation costs are much lower than in previous years. The greatest difficulty lies in the extensive technical knowledge in the area and a significant initial investment in the exploration and construction of geothermal power plants. Undoubtedly, the geothermal power plant is one of the best options to preserve the planet and satisfy the needs and requirements of people and the EU industrial sector in those countries where this type of energy source exists.

4. Conclusion

From the war in Ukraine to worsening climate change, the EU is under intense pressure to accelerate its green transition and to identify the potential obstacles that may arise on the road to energy security [12]. The war in Ukraine and its consequences for world energy supplies and especially for the EU, "the sudden cut in the supply of fossil energy after Russia's invasion of Ukraine has led to an explosion of energy prices that has turned into a cost-of-living crisis. The energy and cost-of-living crisis can be seen as a stress test for both the European Green Deal and the European Social Model" [13]. High energy prices and the worsening effects of climate change, among others, are issues of special concern to the EU. The volatile global energy prices, limited energy suppliers, winter power shortages (Europe managed to get through the much-feared 2022/23 winter without energy shortages, power cuts and recession, showing a considerable level of resilience although at some considerable cost: between September 2021 and March 2023 EU Member States allocated 646 billion euros to shield consumers from rising energy costs [17]), and historic droughts affecting the production of agricultural products at a time when food prices were already rising are all interrelated issues. If the EU could replace conventional energy sources with sufficiently abundant renewables, it would lower energy prices, cut greenhouse gas emissions, cut energy dependency on external oil and energy supplies, and mitigate future risks of climate change and its impacts on food production.

In recent years, EU policies have set ambitious targets to accelerate the shift towards a green economy. In 2021, more than 22% of the gross final energy consumed in the EU came from renewable energies. The share of renewables in the energy mix varies considerably within the EU. In Sweden, it is around 60%; in Denmark, Estonia, Finland, and Latvia, more than 40%; and in Belgium, Hungary, Ireland, Luxembourg, Malta, and the Netherlands, between 10% and 15% [8,9].

According to Eurostat data, in 2020, in the EU, wind energy and hydropower accounted for 69% of the total electricity generated from renewable energy sources (36% and 33%, respectively), solar energy (14%), solid biofuels (8%), and other renewable energy sources (8%). Wind and hydropower energies are projected to continue to have the largest share in the EU energy matrix in 2050. By 2030, the EU should significantly increase the share of renewable energy in the global energy mix, following the SDG 7 goal target.

The energy system of the future must be resilient and adaptable to the inevitable impacts of climate change. Due to the increasing role of wind and solar power (The two most abundant forms of power on Earth are solar and wind. Both have been and will be becoming more cost-competitive compared to other energy carriers for electricity generation and thus are key factors in achieving climate reduction targets [1]), the EU energy system must be flexible enough to satisfy energy demand, even without wind or sunlight. That means the energy system should have baseload energy sources, such as nuclear, geothermal, and hydrogen, among other available energy sources, to stabilize the system and satisfy energy demand under any circumstance.

5. Recommendations

Based on the analysis of the present situation and the perspectives of greater participation of renewable energies within the EU energy mix for the generation of electricity, and taking into account the goal in the energy sector included in the objective of sustainable development (SD7), a set of recommendations for consideration by EU competent authorities have been prepared. These are the recommendations:

1) To speed up the transformation of a society based on using conventional energy sources for electricity generation to a society based on using renewable energy for the same purpose. However, this process must be carried out based on a well-prepared technical and economic plan, and where the replacement of thermal power plants by renewable energy plants warrants a stable supply of energy at a reasonable price during the whole process, ensuring universal access to energy sources, reliable, and up-to-date power services according to the SDG 7 goal target, and without any undue political interference.
2) Establish a special EU fund to support vulnerable households and small businesses during the energy transition.
3) The type of renewable energy to be installed must be selected, considering the advantages and disadvantages of each type of energy source, the geographic characteristics of the location selected, the level of electricity demand, the time of construction, energy efficiency, public opinion, and the investment to be made, among other elements.
4) During the decarbonization process, several baseload power plants that are the least polluting but can stabilize the system in case of interruption of the operation of the renewable energy plants due to weather problems, droughts, and cloudy days, among others, are necessary.
5) To promote and support the connection of the energy infrastructures between EU countries to diversify supply and address possible energy supply interruptions.
6) To promote using hydrogen as an important energy source to produce energy because it does not emit greenhouse gases.
7) To increase the participation of marine renewable energy within the EU energy mix in the future.
8) To enhance international cooperation to facilitate access to new renewable energy research and technology, energy efficiency, advanced and cleaner fossil-fuel technology, and support and promote investment in energy infrastructure.
9) Expand infrastructure and upgrade technology to provide modern and sustainable energy services for developing countries, particularly least-developing states, small islands, and land-locked developing countries.

Conflict of interest: The author declares no conflict of interest.

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