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The assessment of renewable energy in Poland on the background of the world renewable energy sector

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ABSTRACT

The issues of the article are associated with the development of the renewable energy source (RES) sector in the world and in Poland. The subject is undoubtedly connected with the problem of the energy transformation taking place in most countries nowadays. Energy transformation processes are mainly associated with an increase in the share of energy production from RES and increased awareness of energy use by end consumers. This means that the systematic development of the RES sector is a necessary condition for linking the effective course of energy transition processes with simultaneous socio-economic development.

The main objective of this study is to present the status of the RES sector in Poland against the background of worldwide development tendencies. The implementation of the objective made it possible to indicate key trends in the production and use of energy from individual RES and to assess to what extent Poland follows global trends. Poland is one of the European countries where hard coal and lignite constitute the main source of energy. On the other hand Poland, as a Member State of the EU, is obliged to implement the energy strategy within the framework of the European Green Deal, where all Member States are to become climate neutral.

1. Introduction

The 1990s saw an unprecedented increase in globalization processes [1]. Already at the beginning of the 21st century, most of the world's markets formed a relatively homogeneous socio-economic system, interconnected by a network of complex interdependencies. The systematic development of globalization processes was accompanied by dynamic economic growth, which in most economies of the world, contributed to an increase in the level of social development and changes in consumption patterns. Systematic economic development has contributed to a significant increase in energy demand. Unfortunately, within 20 years the existing resources of energy from non-renewable sources are slowly running out. In addition, obtaining energy from non-renewable sources is becoming increasingly expensive and has a negative impact on the environment. In the face of such changes, more and more economies are looking for renewable energy solutions [2]. It can be said that most countries are currently undergoing an energy transition based not only on the systematic development of the RES sector but also on concomitant changes in the labor market and consumption patterns of final consumers. Depending on the geographical location and climate in the region, selected RES sources are predisposed. However, the energy transition should proceed in each country in such a way as to eventually achieve an optimal energy mix, based as much as possible on RES [3].

The subject of the article is the evaluation of the RES sector in Poland against the background of the development of this sector in the world. The subject is related to the problem of the energy transition, which in Poland has been institutionally strengthened due to the EU membership and the necessity to implement the strategy, defined in legal acts, related to the transition processes. This strategy is defined within the framework of the European Green Deal, whereas as a result of the energy transformation the Member States of the Community are to have climate-neutral economies with zero gas emissions [4]. Poland is at the beginning of the energy transition towards low- and zero-emission

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technologies. The energy transition continues with numerous problems on its way, which include, first of all, the opposition of the coal lobby, as well as the still limited knowledge of the public about RES technologies. The favourability of politicians and the public towards RES technologies is growing every year, but the transition will still take at least two decades. Further education of the public through conferences, demonstrations or financial incentives to help finance RES installations is very important [5].

Poland is one of the European countries that is currently strongly dependent on primary energy sources, such as hard coal and lignite. This means that the RES sector development is extremely important for the continuation of Poland's socio-economic development as well as for the implementation of the European Green Deal [6]. The RES sector development for Poland and other Eastern European countries is also important from a geopolitical point of view. As far as renewable energy sources are concerned, it should be emphasised that due to high agricultural culture, Poland has a significant waste biomass potential [7]. Biomass can be burned and subjected to methane fermentation throughout biogas production. Biomass and biogas should be burned in cogeneration to produce electricity and heat. In addition to biomethane upgrading, biogas can also be used in the gas grid as fuel in self-driving vehicles. Favourable conditions in Poland also make it possible to build wind farms. Northern Poland, with its entire belt bordering the Baltic Sea, seems to be particularly attractive in terms of wind energy production. Also, the photovoltaic sector is developing very dynamically. Due to affordable costs of purchase of the installation, households also produce this type of energy. In Poland, excess energy from wind and photovoltaics (PV) can be used to produce "green" hydrogen through electrolysis, which is another energy transition step. This means that Poland, like most countries in the world, is going through the next steps of the energy transition in its own way, but using global patterns and available technologies [8].

The main aim of this paper is to present the status of the RES sector in Poland against the background of the situation in the RES sector worldwide. The achievement of the objective will allow illustrating global trends in the application of modern technologies for energy production from individual renewable sources. Should be noted that, due to physical and socio-economic conditions, Poland has its own pattern of the RES sector development. However, the analysis conducted in this sector over time will allow its level of development to be assessed, taking the RES sector development in the world as a benchmark. Additionally, the extent to which Poland follows global trends in the use of selected energy sources will be assessed.

The authors were the first to compare RES both in the world and in Poland. Poland may show an example from other countries on how to carry out the energy transformation towards clean energy technologies. The authors believe that Poland should develop an energy mix based on RES – only then is it possible to move away from fossil fuels. It is very important for the Polish economy in the context of the war in Ukraine – the RES will ensure Poland's energy security. Further development of the RES will make it possible to become independent from the import of fossil fuels from Russia.

Based on the review of the literature, the authors presented the development of RES in the world and in Poland in the sections "Literature overview" and "Global tendencies in the development of the RES sector". On the other hand, the results for individual energy sources and the entire RES sector are described in the sections "Key sources of energy for the renewable energy sector", "Electromobility", "Discussion" and "Conclusions".

2. Literature overview

So far, there are some publications on RES in the world, but out-of-the-date information. More information on the RES can be found on a country-by-country basis.

The authors in the paper [9] and in the paper [10] present how RES are currently being used, scientific developments to improve their use, their future prospects, and their deployment. Biomass, geothermal energy, hydropower, marine energy, solar energy, wind energy are described in turn. However, the above-mentioned data are already 10 years old, and this is "a long time" in RES. Our paper presents data for the years 2020/2021.

Owusu and Asmadu-Sarkodie [11] believe that a return to the RES will help mitigate climate change. RES slowly develops a sustainable development so as to meet the energy needs of future generations. The presented, not very extensive, data for the RES sector is years earlier than 2016.

A very good position on RES is a report published by the U.S. Department of Energy [12]. It broadly presents the development of US RES against the background of the world until 2017 (so far there are no more recent reports available). The report also further describes energy storage, hydrogen, fuel cells, plug-in electric vehicles, renewable and alternative fuels, and clean energy investments.

More recent data on RES can be found in the article [13]. However, only: "dry data" is presented there: tables and graphs, and no detailed descriptions are available. There is also no information about electromobility.

In the literature, you can find publications about RES in some countries. For example, it is proposed that the Ethiopian government should try to encourage international and domestic entrepreneurs to invest in the RES sector [14]. Moreover, the possibility of obtaining a foreign capital contribution should be seriously considered in order to cover the high initial costs of the development of RES infrastructure. The main findings and these recommendations are potentially valuable not only to researchers and policymakers in Ethiopia but also to other developing countries.

Kim [15] argues that in 2017, the global RES capacity reached a total of 2,195 GW, and PV and wind power contributed to the majority of global RES growth. However, there are still many challenges in implementing RES in power plants and buildings. In Korea, the RES policy started in the 1980s but was not a high priority in national energy policies. However, in 2017, the government committed to phasing out nuclear power plants and suggested renewables as an alternative domestic energy source for the future. The authors [16] showed that the energy demand in Africa will increase significantly due to progressing industrialisation and demographics. Most of Sub-Saharan Africa's energy supply comes from RES, while countries such as Nigeria, Algeria, South Africa, Morocco, and Egypt are still heavily dependent on fossil fuels. The researchers concluded that a circular economy approach could enable greater use of RES and a gradual transition to it.

Four scenarios were presented for the sectors of energy, heating, transport, and desalination in Chile [17]. The results revealed that a transition to a 100% RES system by 2050 is technically feasible. Chile can contribute to global sustainable energy transition and transition to a global fossil fuel economy through a clean extraction of key raw materials and the production of fuels and chemicals based on RES.

Hydropower is the RES with the highest installed capacity in Mexico (11,603 MW), while geothermal energy capacity (958 MW) puts Mexico in 4th place in the world in terms of the use of this energy [18]. Solar energy exhibits high potential due to the ideal location of Mexico – in the so-called solar belt. Wind energy potential is concentrated in five different zones, mainly in the state of Oaxaca. Mexico has set itself a target that by 2024, 35% of its energy needs will come from RES.

A small hydropower plant (SHP) is one of the technological options for generating and delivering electricity to the grid and rural applications with nearly zero emissions in Malaysia [19]. A review of the available work shows that the estimated Malaysian hydropower resource is 29,000 MW, 500 MW of which comes from a small hydropower plant.

Bielska et al. [20] introduced the importance of RES in Poland's energy mix. The article also presents the advantages and disadvantages of types of RES, obstacles to the progress of RES in Poland, and proposed measures to increase the share of RES in the overall energy mix. The presented data has already become obsolete, as it is from 2016 to 2018.

The article [21] describes and analyzes the development of wind energy in 2012–2013 in Poland. It includes the construction of new turbines and wind farms as well as prospects for offshore wind farms. The article indicates the current biggest barriers to further development of wind energy and its future trends. This article is "out of date". The "Distance Act" [] has been in force since 2016, which practically inhibited the development of wind energy in Poland.

Igliński and his team undertook to describe the RES for some voivodeships in Poland: Kujawsko-Pomorskie [22], Zachodniopomorskie Voivodeship [23], Łódzkie Voivodeship [24], Warmińsko-Mazurskie Voivodeship [25], Pomerania Voivodeship [26], Mazowieckie Voivodeship [27] and Greater Poland Voivodeship [28]. In the above-mentioned articles, the RES potential was calculated, which allowed to state that it is possible to achieve 100% RES in a given voivodship; SWOT and PEST analysis was also performed.

3. Global tendencies in the development of the RES sector

The end of the 20th century brought changes in the structure of the use of individual energy sources in the world, especially in Europe [29]. Environmental considerations and the depletion of fossil energy resources have increased the use of renewable energy. The diversification of energy sources results from searching for efficient, cheaper manufacturing technologies whose impact on the environment is lower than those used so far. The change in the structure of energy resource use, from conventional to renewable and locally available, is dictated, on the one hand, by the desire to minimise environmental pollution, and on the other hand, by the inevitable depletion of fossil fuels. This caused the beginning of the dynamic development of the renewable energy sector, which can be treated as the beginning of energy transformation processes in the world. These processes should be understood as a systemic transition of countries to an energy mix based on energy from RES. It is thanks to the systematic development of the RES sector that innovative renewable energy technologies are introduced and disseminated. The institutional and legal framework related to energy production and consumption is also in development [30].

Undoubtedly, the development of the renewable energy sector and the ongoing energy transformation processes are part of the concept of sustainable development, where the RES sector is an important element for the sustainable development of the world. Much responsibility for this development rests with international organisations and national governments. With this in mind, numerous joint actions and international conventions are underway to minimise the negative economic, social and environmental effects caused by the activity of this sector. The International Energy Agency, taking part in the development of the power sector and operating within the OECD, defines sustainable energy as an energy sector with a long-term, global vision of development, which ensures competitiveness and economic efficiency, social responsibility and environmental protection. The European Union will also formulate a long-term energy strategy as part of the European Green Deal. It should be emphasised that in the case of the European Union, the energy transformation is of an institutional and legal nature, where all Member States must adapt their laws so that their economies become zero-emission by 2050 [31].

The European Green Deal constitutes a new strategy for the economic development of the European Union (EU). Its most important goal is to restructure the economy to reduce greenhouse gas emissions in Europe to a net-zero level by 2050 at the latest. Some greenhouse gases may still end up in the atmosphere, but this needs to be counterbalanced by absorption through ecosystems or technical devices. The goal of achieving climate neutrality has been supported by the Parliament and the European Council and is reflected in the European Climate Law. To achieve the goal of climate neutrality, the EU's climate goals have been set for 2030. Currently, EU law obliges EU countries to jointly reduce greenhouse gas emissions by 40% compared to 1990, increase the share of renewable energy to 32% and reduce energy demand by 32.5% compared to forecasts. The first step towards climate neutrality under the Green Deal is to increase the EU's commitment to reduce emissions to 50 or 55%. The decision approving such a reduction will also involve increasing the remaining goals: the share of RES and limiting the growth rate of energy demand, as well as introducing stricter regulations on emissions from the sectors of industry, transport, and agriculture, and a radical reduction in energy consumption in buildings [32].

The use of RES fits very well with the action plan for sustainable development, as it provides the means for achieving economic and social benefits with as little impact on the environment as possible. RES installations are local in nature and do not require the development of centralised technical infrastructure. Being small and dispersed technologies, they naturally fit into the policy, strategy and plans of regional and local development. The benefits of using renewable energy sources are both economic and non-economic. Among the economic benefits, the most important seems to be a strong impulse for local development, which is prompted by the use of RES. This impulse arises mainly from the creation of new jobs. It is also worth noting that these places are not created in large industrial centers, but in rural areas and are dispersed. The greatest number of jobs is created when biomass is used, which is caused by high labour inputs in the production, harvesting, and preparation of fuels [33]. Despite the COVID-19 pandemic, employment in the renewable energy sector is increasing (Fig. 1). In 2021, the largest number of people were employed in PV.

The energy transformation takes into account the processes of transformations in the power industry, heating, and transport, but also increases energy efficiency, progressive liberalization, innovation, and competitiveness, considered at the international level [33]. The main trends in the development of energy are:

- diversification of energy sources;
- spatial decentralisation of generation sources;
- implementations in the field of modern network solutions;
- energy storage.

The social aspect of generating energy from RES ensures the energy security of the country and its regions. Distributed energy sources make it possible to use them in the immediate vicinity, even in the event of a grid failure, and their total production may constitute a significant share in meeting the needs of the country's inhabitants. The spatial

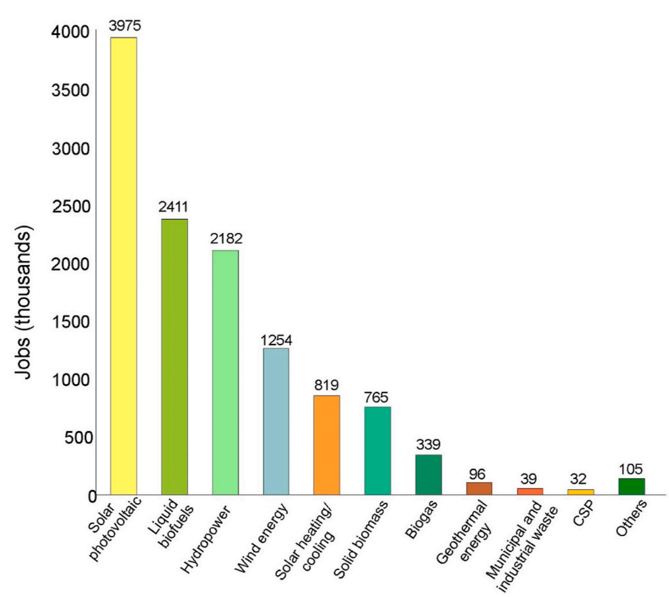

Fig. 1. Jobs in RES in the world (own study after [33]).

decentralisation of energy generation sources is a long-term process of the transformation of the energy sector, based on several large generation units, towards territorial and resource dispersion. This is a tendency that implements the plan to increase the number of generating sources in the energy system while reducing their installed capacity. The development of renewable energy technologies that have reached technological maturity in recent years is an aspect that favours decentralisation. Small power plants and combined heat and power plants, adapted to the needs of towns with a population of 5–15 thousand and with a moderately developed industry, are a frequently implemented model in Western Europe [34].

The implementation of modern network solutions means technical and technological improvements to the functioning of power grids. With them, it is possible to more precisely monitor, manage and balance energy demand and supply in a given region. In this sense, modern network solutions may constitute a new service provided by local energy operators, which will enable the appropriate coordination and complementarity of diversified and decentralised energy sources. In turn, this will make it possible to implement the entire value chain in the energy sector at a local level, thus leading to a partial energy autonomy of the region [34].

Energy storage is a solution to the problem of establishing the relationship between supply and demand. Currently, energy storage systems are the most dynamically developing field of energy in the research and implementation phase. Their main task is to ensure an adequate level of reserves in the energy system, which is done by using the entire spectrum of technological solutions. These include electrochemical (accumulators), chemical (hydrogen production), thermal (heat storage), mechanical (pumped storage plants, compressed air storage), biogas and biomethane storage, but also the complementarity of various forms of energy, i.e. heating, electricity, and transport. Solutions for electric motorisation and the development of the necessary infrastructure in the form of vehicle charging stations are spreading rapidly. The achievement of technological maturity by energy storage technologies will ensure a greater flexibility of the energy system, in particular in the context of uncontrollable electricity generation technologies such as photovoltaics or wind energy. In the near term, solutions for the storage of biogas and/or biomethane for peak energy use should become available. Currently, pumped storage hydropower plants, the energy balance of which is close to zero, play an important function of stabilising the network. Biogas plants with the option of storing the produced biogas could successfully fulfill the same function, while all the energy generated in them would be classified as renewable energy [34].

Installations producing energy based on RES are often destined for individual households. However, it is also possible to derive benefits not from meeting the needs of the household but from producing and selling energy. Then an application for a license granted by the Energy Regulatory Office in Poland can be filed. One of the solutions in this regard is to create communities dealing with energy production, which operate on the basis of cooperatives. Cooperative activity is conditioned by relevant regulations, with the energy sector being one of the many activities that can be performed by cooperatives. “Energy cooperatives” seem to be something new, but when it comes to the form of activity, it is well known and organised. Only the scope of activity is relatively new. So far, cooperatives have operated in the trade, food, processing and other industries. Nothing stands in the way of creating entities operating in the energy industry on the basis of the same regulations [35].

Another solution is to create an energy cluster. An energy cluster is a group that gathers, on the basis of a civil law agreement, consumers, energy producers, prosumers, energy sellers and suppliers of other energy services operating in an organised and coordinated manner in a coherent area, the purpose of which is to balance energy demand in the functional area of the cluster and to improve the competitiveness and innovation of its members. A cluster may include entities located in five communes or one poviat. Under a civil law agreement, legal and natural persons, research institutes, scientific units or local government units may be associated. Each cluster should have a coordinator to represent it. Clusters are a platform for the exchange of knowledge, experience and technology between entities from economy, science and public service sectors. Renewable energy producers, scientific units, local government units and members of local communities collaborating within energy clusters achieve tangible benefits from such exchange, learning from each other, promoting and jointly developing social and business initiatives, including investment projects [36].

4. Key sources of energy for the renewable energy sector

The key issues in the operation of the renewable energy sector include the effective use of solar energy, production of wind and water energy, use of biomass for energy purposes and the use of geothermal energy. When PV, solar heating and cooling systems are used, they serve millions of residential, office, industrial and public buildings. In 2020, these systems were sold in at least 134 countries for use in a wide range of applications including water heating, space heating and cooling, product drying and water desalination [37].

The use of silicon in the creation of solar cells has become a milestone in the history of photovoltaics (PV), leading to an efficiency increase of up to 6% of energy return. That achievement can be treated as the beginning of a sharp increase in interest in this technology. Scientific institutions around the world have started research to improve the existing solutions, achieving increasingly better cell efficiency [37]. Currently, PV is the fastest-growing industry in the world.

Meanwhile, wind energy is one of the most dynamically developing RES branches in the world. It is obtained by means of relatively simple technological solutions – wind turbines, which are part of wind power plants (power plants) where the kinetic energy of the wind is converted into mechanical or electrical energy. Electricity is generated in individual power plants or in groups of power plants known as wind farms [38]. The current wind energy development across the world has two main paths.

The first path is onshore wind power. This category includes:

- large-scale wind energy – single turbines with a capacity usually above 1 MW or wind farms (consisting of several dozen wind turbines) [39];
- medium-scale wind energy – single turbines with a capacity in the range of 200–600 kW, connected to the power grid, owned by individuals, small enterprises or local communities;
- small (distributed) wind energy – single wind turbines with a capacity not exceeding 100 kW, located mainly near houses as an alternative source of energy; small wind farms are also used where there is no economic justification for supplying energy from the power grid (e.g. power supply for lighting road signs, billboards, etc.) [40].

The other path of wind energy development concerns offshore wind power, which includes wind farms located in open sea waters. At the moment, wind farms are structures permanently attached to the seabed; however, the possibility of constructing floating turbines, intended for installation in places far away from land, at greater depths, is also being investigated. Most of the currently installed wind turbines include devices with a horizontal rotor axis and three blades (this number was considered optimal). Large-scale wind turbines are installed on towers with a height of several dozen to over 100 m, which depends on the type of turbine, its power and wind conditions in a given location. The market offers turbines with a very wide power range – from several dozen watts (microturbines for supplying street lighting for example) to several MW. The largest currently commercially available wind turbine has a capacity of 7 MW, but works on the construction of larger installations, with a capacity of 10 MW and more, are at an advanced stage. The efficiency of a wind turbine is described by the so-called power utilisation factor, which defines the amount of energy that a wind turbine is able to produce in a year in relation to the maximum possible production, expressed in [%] or in hours of full-power operation during the year [41].

Modern, well-located onshore wind turbines are characterised by power utilisation factors above 30% (in the best locations above 35%). Offshore wind farms have a much higher efficiency – over 40%, or even 50% for those built in recent years using the latest technologies. A typical wind turbine starts working at a wind speed of 3–4 m/s and reaches its nominal power at a speed of 11–12 m/s [42].

As important a source of energy as wind is water. Water energy is the energy of the movements of marine and inland waters. It has been used by mankind since ancient times. Initially, water power was used to drive water wheels in mills, then hammers in forges and saws in sawmills. Until the invention of the steam engine, water energy was widely used in industries. The use of hydropower was revolutionised by the invention of an electric generator in the 19th century. Thanks to this invention, it became possible to convert mechanical energy (which in turn was derived from water energy) into electricity. The plants transforming the aforementioned types of energy are hydropower plants, and the energy department dealing with obtaining energy from the power of water is hydropower. Nowadays, mainly inland waters with a high flow rate and a significant difference in levels are used. Wave and tidal energy is less used [43].

Due to their size, hydropower plants are divided into small hydropower plants (SHP) and large system units. In Poland, plants producing energy with a capacity of up to 5 MW are considered to be SHPs. Hydropower plants include not only devices that convert one type of energy into another, but also hydrotechnical devices. To increase energy efficiency, water damming is used, the forms of which include weirs, reservoirs, and dams [43]. There are three basic types of hydropower plants: run-of-river, reservoir, and pumped storage.

Another important issue within the renewable energy sector is the use of biomass for energy purposes. Biomass means a mass of organic matter (substances of plant and animal origin). Biomass (wood, biofuel, biogas) is recovered for fuel that does not emit carbon dioxide. This is dictated by the fact that the emission during the combustion of biomass balances the uptake of charcoal during the growth of plants. The last argument for using biomass for energy purposes is the usefulness of land that has been rebuilt so far for nothing. The production of biofuels and biogas reduces dependence on oil and oil imports [44].

Energetic plants such as willow, miscanthus, Jerusalem artichoke and others are becoming more and more popular all over the world. Energetic plants are characterised by long annual growth, high yield, significant resistance to fungi and pests and relatively small soil requirements [44,45]. In Europe, giant miscanthus is grown of about 60 years, initially a very decorative plant, and now on energetic plantations. Like the C-4 photosynthetic cycle plant, miscanthus has greater potential for weight gain, while in optimal weather conditions the use of light is about 40% higher than in the case of C-3 plants. The grass does not have long requirements for soil strength, but in the first period of management, it is not very resistant to frost. Already in the first period of management, up to 8 tons of dry matter can be harvested per hectare, but in the third period, miscanthus reaches the highest yields – even more than 30 tons of dry matter per hectare (d.m./ha) [46,47].

In the case of geothermal energy, it is contained in the interior of the Earth and results from processes taking place in its core (the decay of radioactive elements). Geothermal energy occurs in the form of two carriers: hydrothermal and petrothermal. The first is understood as a mixture of water and steam (at a temperature of 200–300 °C) or a supply of hot water (at a temperature of 50–70 °C). The other refers to hot, dry, porous rocks [37].

Geothermal energy technologies include solutions for the acquisition and use of energy from the Earth's interior. The use of geothermal energy can be direct: swimming pools and swimming pools with geothermal water ("thermal baths", balneology, spas), heating residential buildings, breeding ponds, and greenhouses, drying crops, melting snow, etc. For over 100 years, the generation of electricity in geothermal power plants has been a new chapter in geothermal energy technologies [37].

One of the current trends in the sector is electromobility powered by energy from RES. Electric vehicles were among the first cars used for the movement of people. Between 1832 and 1839, Scottish businessman Robert Anderson built the first electric coach. In 1835 in the Netherlands, professor Sibrandus Stratingh designed an electric car, the scale model of which was made by his assistant Christopher Becker [37]. Until 1900, before the heyday of internal combustion engines, electric vehicles broke many records for speed and distance traveled. One of the most notable events of that time was Camille Jenatzy breaking the speed barrier of 100 km/h on 29 April 1899. Electric vehicles are gradually becoming an important recipient of RES energy in the world. The popularisation of electric cars powered by RES will make it possible to gradually displace fossil fuels in important modes of transport, mainly road, and then also rail. It should also be emphasised that electric cars are more energy-efficient than vehicles with an internal combustion engine. Moreover, an electric car is now an energy store, in which surplus RE can be stored and then used in the home network or while driving the car [37].

4.1. Solar energy

4.1.1. Solar energy in the world

PV had another record year in terms of installed capacity – 139 GW in 2020. The total capacity reached 760 GW (Fig. 2). The PV market developed best in three countries, namely China, Vietnam and the United States, but several other countries saw a notable expansion as well. There have been very large investments in distributed rooftop PV installations. Australia achieved one of the world's biggest solar "penetration" levels in 2020. This country has successfully implemented the use of rooftop PV for energy purposes [37].

China added 48.2 GW of PV capacity in 2020. The largest PV capacity was installed in the provinces of Qinghai (4.1 GW), Hebei (4.9 GW) and Guizhou (5.2 GW). At the end of the year, the total grid-connected capacity in China exceeded 253.4 GW [37,48]. Vietnam saw another increase in the number of installations; after adding 4.8 GW in 2019, the country commissioned 11.1 GW in 2020. The 2019 growth was driven by the impending expiry of the Vietnamese FIT1 program, which encouraged large-scale ground-mounted projects, with most of the 2020 PV power increment being in rooftop systems [37].

Japan was the fourth-largest PV market in the world. After four years

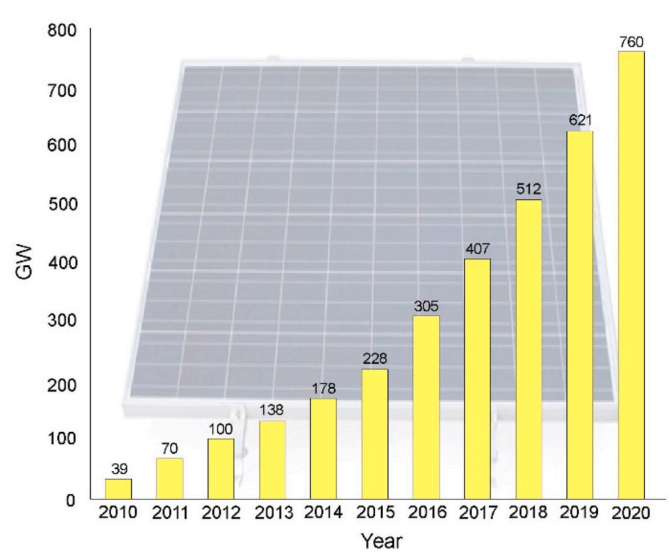

Fig. 2. Increase in PV power in the world (own study after [37]).

of decline, in 2020 Japan added about 8.2 GW for a total of 71.4 GW. The Japanese sector still has many problems, including a lack of land for PV and an overload of the power grid. Despite this, PV in Japan accounted for around 8.5% of total electricity generation in 2020 [37].

Due to the pandemic crisis, solar PV investments in the EU-27 turned out to be lower than previously assumed. Nevertheless, the year 2020 turned out to be the second-best year for the EU-27 solar sector. Moreover, in 2020, the added power of PV in the EU-27 was the highest in relation to the increase in power of other energy production sectors. The share of PV power in the EU-27 went up by 15%, which meant an increase of 19.3 GW. The total power of PV is 140.5 GW. It is worth emphasising that in many EU-27 countries, photovoltaics is currently not only the fastest technology to implement but also the cheapest source of electricity [37].

In more and more countries, PV plays a significant role in the energy mix. Solar energy accounted for 8.5% of the annual production of Japan, 9.4% of Italy, 9.9% of Australia, 10.4% of Greece, 10.5% of Germany and 11.2% of Honduras. In 2020, Poland, Great Britain, and Spain broke records in solar energy production. Plans in many countries indicate that PV will play an increasingly important role [37].

Despite the pandemic, power increased also in the case of solar collectors – by 23 GW. This means that the increase was almost 5%, and the total power in the world in 2020 was 501 GW (Fig. 3) [37].

Once again, China has built the largest number of collector installations in the world, followed by Turkey, India, Brazil and the United States. Many PV investments in the world have been slowed down by the pandemic, but the deceleration was still lower than expected due to stabilising factors, which included a higher demand for PV installations from individual investors (e.g. in Poland [37].

4.1.2. Solar energy in Poland

The conditions for the development of solar energy in Poland are moderate due to the specificity of the climate characteristic for this latitude. On average, energy in the range of 950–1100 kWh/m^2 (insolation) reaches Poland during the year. About 80% of this value is generated during the six spring and summer months (from early April to late September). The average annual sunshine duration is in the range of 1350–1800 h [49].

Until 2012, there were practically no PV installations in Poland. Recent years have seen a real boom in PV. In 2020, Poland took first place in the EU-27 in terms of the rate of increase in the power of PV installations, calculated on the basis of the cumulative annual growth rate. Globally, Poland took 13th place. The current development and numerous plans of investors make it possible to predict that the Polish PV market will continue to develop very well in the coming years [50].

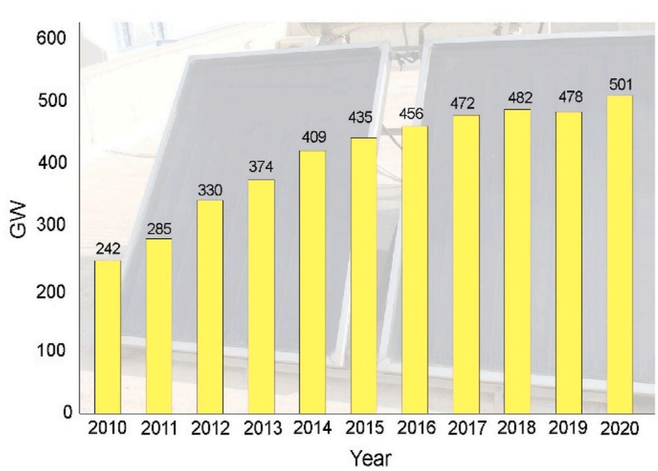

Fig. 3. Increase in the power of solar collectors in the world [GW] (own study after [37]).

The year 2020, another year in a row, was the best year in the history of the development of the PV sector in Poland. There was an increase of 2,463 MW, bringing the total capacity to 3,939 MW. It translates into an over 200% increase year on year. It is worth pointing out that in recent years, prosumer micro-installations have dominated in Poland. According to the forecasts of the Institute for Renewable Energy [50], in 2021, once again in a row, Poland is to maintain the high growth rate of PV power. Initial estimates show that at the end of 2021, the installed PV capacity in Poland exceeded 6 GW and it stemmed mainly from prosumer micro-installations. The development of photovoltaics in Poland means economic recovery and new jobs. Estimates indicate that the turnover in PV in Poland in 2021 amounted to nearly PLN 10 billion.

In 2020, 1.5% of the electricity produced in the country came from PV sources. In 2021, it will be 3.5%, and in 2025 solar energy will provide about 10% of electricity. PV is becoming a permanent element of the national energy system, and in the daily and summer peaks, energy demand becomes its basis, providing a power reserve and reducing energy costs in the entire energy system for all energy consumers, not only prosumers [50]. The estimated PV capacity in October 2021 was about 6 GW, and by the end of the year, as already mentioned, it may be over 7 GW. In 2021, the number of prosumers in Poland increased to around 755,000 (Fig. 4) [50].

According to the forecast of the Institute for Renewable Energy [50], there are no signs of a slowdown in the PV market in Poland in the near future. Perhaps the reduction of discount systems for prosumers will reduce the demand for PV, but the share of small and large projects will increase. And it is large PV farms that won RES auctions that will increase the share of PV in Poland to the greatest extent. Moreover, the role of "business" prosumers will increase by about 200 MW, and it will grow in the coming years.

According to the forecast of the Institute for Renewable Energy, in 2022 the installed PV capacity in Poland will be at least twice as high as in 2020, and in 2025 it may amount to 15 GW [30]. The current year (2022) and subsequent years will bring records of installed PV capacity in Poland, primarily in the segment of PV farms. The won auctions show that only in the case of "large" solar farms, the 2022 power will exceed 1.5 GW. In 2023, the market of prosumer installations in Poland will be equal to the market of PV farms in terms of total installed capacity, and thus the entire PV market will change from the current typically prosumer one to a sustainable one with prosumers and professional solar power plants being on par [50].

In Poland, the solar collector market is developing quite well, but its

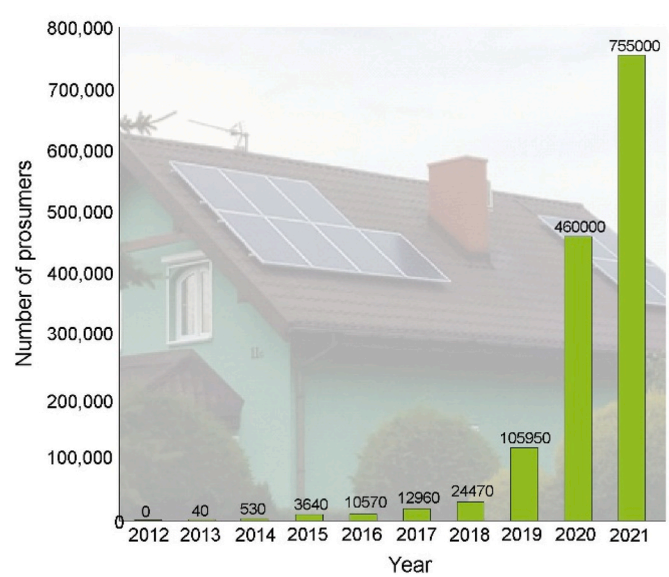

Fig. 4. The number of prosumers (mainly PV) in Poland (own study after [50].

saturation is still much lower than in European countries having long-term experience in this field. The ratio of the installed surface area of solar collectors to the number of inhabitants in our country is about 35 m^2/1,000 inhabitants [49].

4.2. Wind energy

4.2.1. Wind energy in the world

The global wind energy market reached a record 93 GW of new installations in 2020, bringing the total capacity of onshore and offshore wind energy to 743 GW (Fig. 5) [37]. The United States and China maintained a steady record increase in wind power capacity. Several other countries also achieved record increases in the number of installations, while the rest of the world built roughly the same number of installations as in 2019. In several countries, wind energy contributed to a significant proportion of electricity production in 2020, including Denmark (over 58%), Uruguay (40.4%), Ireland (38%), and Great Britain (24.2%) [37].

For the first time, global investments in offshore wind energy over the year has exceeded investments in offshore oil and gas. Turbine manufacturers have focused on technological innovations to continuously reduce costs and achieve ever lower energy costs. Moreover, they expanded their cooperation with scientific units in order to increase the durability of wind turbines during production and at the end of their service life [37].

China increased its dominance in the market despite the pandemic-related delays in connecting to the grid at the beginning of the year. It is estimated that 52 GW of power (48.9 GW onshore and 3.1 GW offshore) was added in 2020; it was more or less what the whole world installed in 2018. The total wind power of this country is over 288 GW. Approximately 72 GW (including 3.1 GW offshore) of wind power was connected to the national grid in 2020, 281 MW of which were officially connected to the grid by the end of the year. In 2020, China accounted for 67% of the 33.7 GW of onshore wind capacity allocated worldwide in auctions, and most of the allocated Chinese capacity was based on grid parity [51].

US countries added almost 22 GW (an increase of 62% compared to 2019), with the majority of the turbines being installed in the US. The country launched almost 17 GW of new capacity in 2020, which is an increase of 85% compared to 2019. For the ninth consecutive year, the leader in terms of annual wind power installations was Texas (4.2 GW), followed by Iowa (1.5 GW), Wyoming (1.1 GW), Illinois (1.1 GW), and Missouri (1 GW). At the end of the year, total capacity in the US exceeded 122 GW, enough to provide electricity for almost 40 million American homes. Texas continues to lead in terms of total capacity (over 33 GW), which is 27% of total capacity in the US [37].

In 2020, Europe added almost 14 GW of new wind capacity, 21% of which are offshore, for a total of almost 211 GW in the region. The increase in onshore wind energy capacity was halted by the COVID-19 pandemic, which was mainly due to restrictions in the flow of people and goods. Nevertheless, the year 2020 was the third-largest year for new installations in Europe, after 2017 and 2019. The wind sector already employs 300,000 people across Europe. It contributes EUR 37 billion to EU GDP and pays about EUR 5 billion in taxes annually. Each new turbine installed in Europe generates economic activity valued at an average of EUR 10 million through the so-called multiplier effect [37].

In the offshore wind energy segment, two countries in Asia, five in Europe and the United States connected over 6 GW in 2020 (Fig. 6), increasing the cumulative global offshore capacity to over 35 GW. Offshore wind turbines accounted for 6.5% of all newly installed global wind energy capacity in 2020. Interest in offshore wind energy is growing – including among corporations willing to sign energy purchase agreements – due to large-scale production, high power indicators, fairly uniform production profiles and falling costs [52].

China added a record 3.1 GW of offshore capacity, bringing total capacity to about 10 GW. There were plans to put more power into service in 2020, but progress was hampered by the pandemic, including supply chain problems and a shortage of vessels to install turbines at sea. China has set itself an offshore wind energy target of 60 GW by 2030 [37].

Europe remained the world leader in offshore wind energy. In 2020, the region added 2.9 GW through nine completed wind farms, for a total of 25 GW. The Netherlands doubled its offshore capacity (1.5 GW), which accounted for more than half of the installations in Europe; it was followed by Belgium (0.7 GW), the UK (0.5 GW), Germany (0.2 GW) and Portugal (about 17 MW). There are plans for further, larger offshore projects, also in Poland [37].

Wind turbines with a vertical axis of rotation (VAWT – Vertical Axis Wind Turbine) are in operation in many countries. It is believed that one of the precursors of the VAWT turbine was the French Georges Jean Marie Darrieus, who patented it in 1931. The Darrieus turbine has 2 or 3 long thin blades in the shape of a "C" loop, connected at the top and bottom of the axis of rotation, or straight blades parallel to the axis of rotation [53]. The most important advantage of VAWT turbines is their effective operation regardless of the wind direction. The turbine has good performance, but the disadvantages are:

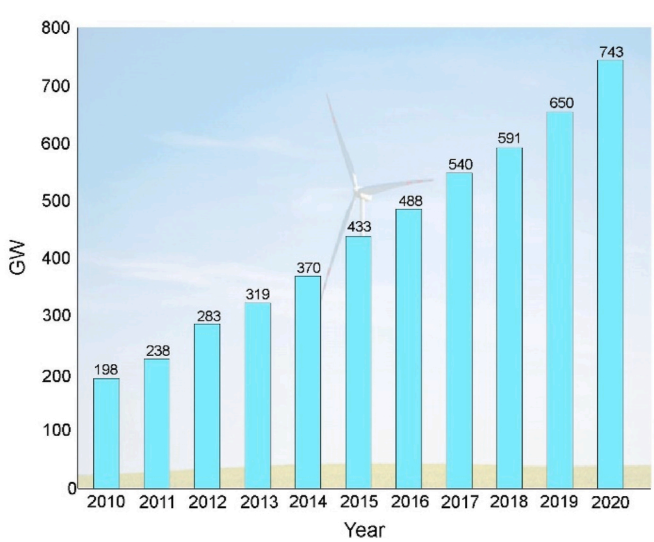

Fig. 5. Increase in wind energy capacity in the world in 2010–2020 (own study after [37]).

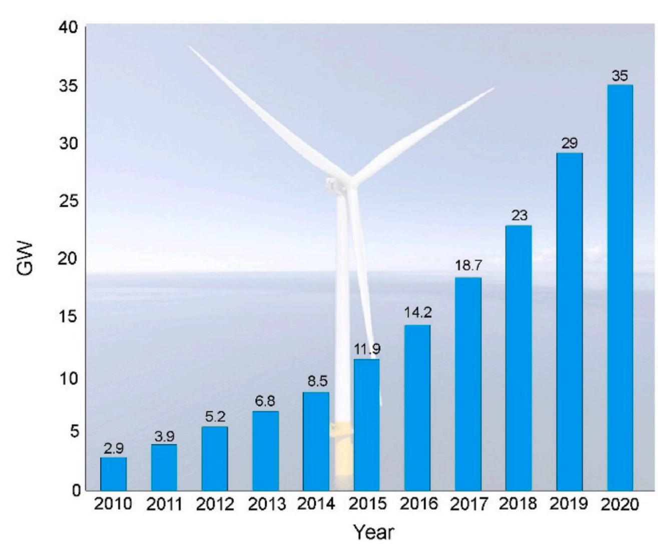

Fig. 6. Increase in the power of offshore wind energy in the world in 2010–2020 (own study after [37]).

1) pulsating torque (reduced by increasing the number of blades to 3),
2) difficulties with mounting the high vertical axis of rotation, so the tower works in a slower, more turbulent air flow near the ground,
3) low starting torque and therefore requires an additional power source or a Savonius rotor. In recent years, turbines with a vertical axis of rotation around the world are being placed more and more often at homes [53].

4.2.2. Wind energy in Poland

Looking at the wind speed map at the height of 140 m (Fig. 7), it should be stated that central and north Poland is especially predestined for the development of wind energy – not only on land (onshore) but also at sea (offshore). Offshore wind energy may become a driving force for companies from the region, including shipyards that already produce components for the offshore industry. For the time being, though, it is used for projects in the North Sea or the German part of the Baltic Sea [54].

The share of RES in Poland is growing consistently and the fastest. For several years, most clean energy has been produced in onshore single turbines and wind farms. In 2020, the installed capacity of onshore wind installations was more than 6.3 GW. Electricity production from RES amounted to nearly 28 TWh, including almost 16 TWh from wind energy. The strategic goal is to release the full potential of Polish onshore wind energy. The Polish Wind Energy Association estimates it to be at least 22–24 GW in 2030–2035 [52].

Onshore wind energy has all the conditions to be a response to both the economic and climate crisis. The COVID-19 crisis hit global supply chains and highlighted their weaknesses. However, the wind industry has emerged unscathed from this, showing exceptional resilience to the turmoil of the global economy. Poland, too, showed real determination to implement planned investments according to tight schedules in these difficult circumstances and created a multitude of valuable, knowledge-based jobs. Moreover, onshore wind farms also strengthened the image of the cheapest sources of energy that have been built over the years. Even today, the cost of acquiring a 1-MW hour is less than PLN 200 [55].

The real picture of the dynamics of the wind market in Poland is reflected in the data of the Energy Regulatory Office on the evolution of the installed capacity of installations using onshore wind energy. The years 2010–2016 were a period of a constant and fast increase in wind capacity in Poland (Fig. 8). The implementation of the Distance Act significantly impeded the development of the sector. From 2017 to 2019, virtually all activities related to the development of new wind projects were abandoned. The legal framework for wind energy significantly affects investment development. An increase in installed capacity in 2020 as well as the 2019 and 2020 auctions that were excellent for wind energy should be noted with satisfaction here. The full onshore potential will be unlocked with the lifting of the rigid 10H regime [52]. The Act on Investments in Wind Power Plants, in force since 16 July 2016, also known as the “Distance Act” [56], has significantly changed the situation of wind power on the market. The Act introduces a definition of a wind power plant and stipulates that this type of installation will be located only on the basis of the local spatial development plan. According to the Act, a new wind power plant could be constructed at a distance no smaller than tenfold of its height (including blades) from housing and mixed-use buildings as well as areas of significant environmental value (e.g. national parks or landscape parks, nature reserves). It needs to be stressed again that a wind power plant can only be built on the basis of the local spatial development plan. In reality, this

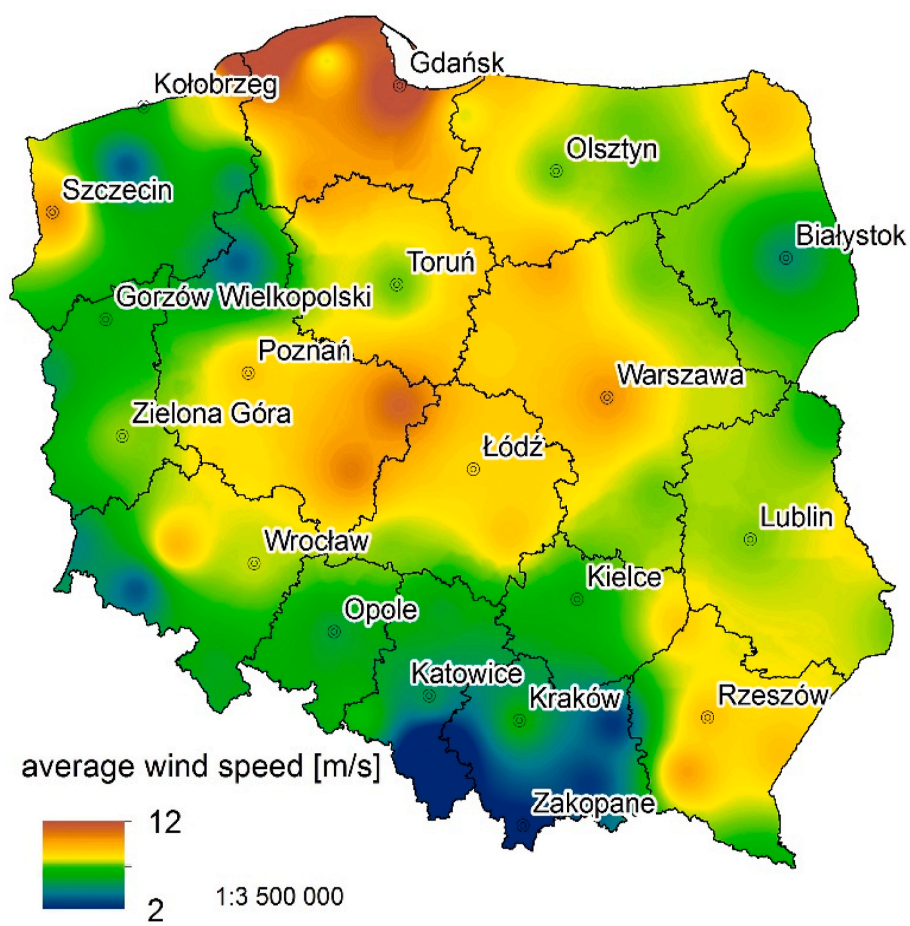

Fig. 7. Wind speed at a height of 140 m in Poland (own study after [54]).

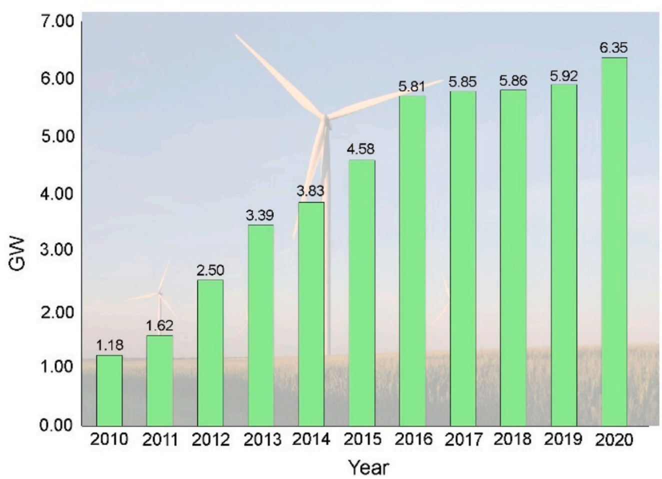

Fig. 8. Wind energy capacity in Poland (own study after [57]).

means that many investments will never be implemented.

4.2.3. *Offshore wind energy in Poland*

Offshore wind energy is also of importance in Poland. According to the calculations of the Maritime Institute in Gdańsk, the total surface area of locations where offshore wind farms can be situated in Poland is 3,590 km^2; however, taking into account economic conditions (e.g. depth and distance from land), it should go down to about 2,000 km^2 by 2030. In the longer term, the remaining areas may be used as new foundation technologies develop and investment costs decrease. According to the project "Offshore wind energy and maritime industry development program taking into account the available area of the Polish exclusive economic zone" (2,000 km^2 by 2030), wind conditions, productivity and installed power density (about 6 MW/km^2), the theoretical potential was estimated at 12 GW, with a generation potential of approximately 48–56 TWh [26].

4.3. *Hydropower*

4.3.1. *Hydropower in the world*

In 2020, further increases in hydropower capacity were recorded worldwide, with China responsible for more than half of the increases in capacity. The effects of the COVID-19 pandemic were also noticeable in this RES sector, and the market slowed down as construction was temporarily halted, component supply chains were disrupted and energy demand fell [37]. In the world in 2020, 19.4 GW of new capacity was installed, which increased the total global installed capacity to 1,170 GW. World production of hydropower increased by 1.5% in 2020, reaching 4,370 TWh, representing approximately 16.8% of total world electricity production. China added about 12.6 GW of new hydropower capacity in 2020, the biggest increase in the last five years, and regained an advantage over Brazil in the amount of new hydropower installed. They are followed by Turkey, India, and Angola (Fig. 9) [37,58].

As already mentioned, China added about 12.5 GW of hydropower in 2020, reaching a total capacity of 338.7 GW at the end of the year. In 2015–2020, the country's capacity increased by 15%, with new hydropower plants accounting for 7% of newly installed hydropower capacity in 2020. The largest investments were the Datengxia power plant in the Guangxi Zhuang Autonomous Region with a capacity of 1.6 GW and with eight 200 MW turbines and the Wudongde power plant between the provinces of Sichuan and Yunnan. Wudongde will be the seventh-largest power plant in the world once built, with a total installed capacity of 10.2 GW. Total hydropower production in China reached 1,360 TWh, 4.1% more than in 2019, and accounted for 18% of the country's electricity supply [57].

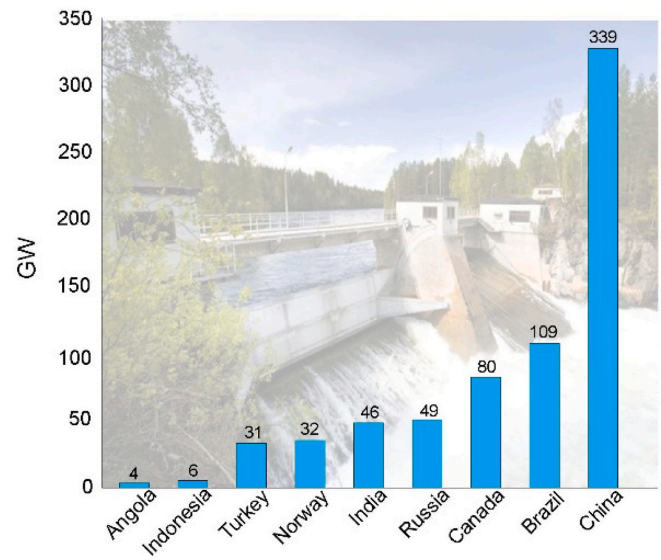

Fig. 9. Hydropower capacity in selected countries (own study after [37]).

Turkey added about 2.5 GW of new hydropower energy capacity, bringing total capacity to 30.9 GW. The largest hydropower plants launched in 2020 were the Yusufeli Dam with a capacity of 540 MW, the Lower Kaleköy plant with a capacity of 500 MW, the Cetin plant with a capacity of 420 MW, and the Ilisu Dam with a capacity of 1.2 GW (the second largest dam in the country, located on the Tigris River, which started production with some delays). By the end of 2020, hydropower accounted for almost a third of the country's energy mix and about 56% of new capacity added that year [37].

India added 473 MW of new hydropower energy capacity, bringing total capacity to 46 GW. The government promotes hydropower energy as a source of flexibility and grid stability, aiming to reach the installed capacity of 70 GW in 2030. About 13 GW of capacity was under construction in 2020. In mid-2020, the government proposed an electricity bill (amendment) to strengthen India's RE sector [57].

In most European countries, the possibilities for building large hydropower plants are limited; Mainly small-scale hydropower solutions develop (e.g. in Poland). Norway added the largest amount of new hydropower energy capacity – 324 MW. In total, Norway already has 32 GW of hydropower energy capacity, constituting 89% of the country's electricity production. It is worth noting that Norway is a country where almost 100% of electricity is obtained from renewable sources. In France, the Romanche-Gavet power plant with a capacity of 97 MW was commissioned. In the case of this hydroelectric power plant, to reduce the visual effect of the facility, investors built the power plant underground. In Albania, which, like Norway, relies on hydropower and energy imports, the Moglicë power plant with a capacity of 197 MW was commissioned [37].

The capacity of pumped-storage power plants (storage facilities) saw a slight increase, 1.5 GW (i.e. 0.9%), mainly in Israel and China, bringing total capacity to about 160 GW. Several large pumped-storage projects are underway in Greece, Australia, Portugal, India, Turkey and Scotland [37].

4.3.2. *Hydropower in Poland*

The first hydroelectric power plants in Poland were built at the end of the 19th century. In the years 1925–1935, the number of mills and hydroelectric power plants in the country was around 8,000. After World War II, their number dropped significantly due to the policy pursued by the authorities in charge at the time. Hydropower facilities were decommissioned. In 1968, there were only about 200 SHPs. Hydropower development was renewed in the 1980s, after the approval of the resolution on the development of small hydropower [58,59].

Larger power plants are usually located in the foothills and mountains, while SHPs are often located in the lowlands. The theoretical hydropower potential (taking into account natural and climatic conditions) in Poland is estimated at 25 TWh/year, and the technical hydropower potential (taking into account available technologies) is estimated at 12 TWh. In Poland, only 17% of the potential is exploited [59].

In 2020, the capacity of devices producing electricity with the use of water turbines in Poland was about 1,000 MW and was provided by about 800 hydroelectric power plants (Fig. 10) [33]. The largest hydropower plant in Poland is the Włocławek (center of Poland) power plant (at the water barrage on the Vistula River). The Włocławek barrage consists of the following elements: a front earth dam, a weir closed with steel shell gates, a power plant and a navigation lock measuring 12 × 115 m, designed for a capacity of 6 million tons per year, and a fish ladder located in the partition pillar between the weir and power station. The power plant has six Kaplan hydro sets with a total installed capacity of 160.2 MW [57].

In Poland, the largest pumped-storage power plant with a capacity of 716 MW is the power plant in Żarnowiec (Fig. 10).

When analysing the hydrographic network (Fig. 11), it can be concluded that Poland has great potential to build hydropower plants, in particular SHPs, also using old dams (often 1–2 m high) [38]. It is realistic to bring the number of power plants and watermills to the pre-World War II level (even several thousand). This would cover Poland's energy needs to some extent.

According to the data from the National Water Management Authority, the number of damming structures in Poland is over 16,000 (Fig. 11) [60].

4.4. Biomass energy

4.4.1. Use of biomass in the world

Bioenergy met 5.1% of the total global energy demand in 2019, which is about half of the total RE in final energy consumption. Biomass reached 9.5% of heat extracted from agriculture and industry in 2019. Moreover, bioenergy reached as much as 5% of the heat needed by buildings, while consumption increased by 7% over the past decade [37].

The global bioenergy capacity increased by 5.8% in 2020 to reach about 145 GW (Fig. 12) compared to 137 GW in 2019. By the end of 2020, China had the greatest operational power, followed by the United States, Brazil, India, Germany, Great Britain, Japan and Sweden. Total bioenergy production increased by about 6.4% to reach approx. 602 TWh in 2020 compared to 566 TWh in 2019 [37].

Biofuels – mainly biodiesel and ethanol – consume about 3% of transport energy. In 2020, global biofuel production in general energy demand in transport fell by 5% due to the COVID-19 pandemic. Global biodiesel production increased slightly due to an increase in fuel consumption in Brazil, Indonesia, and the United States. The most notable trend in the industry was investments in hydrotreated vegetable oil (HVO), with a 12% increase in production in 2020. Plans for the construction of a number of new foundations were announced, possibly increasing the promised production capacity more than fourfold. HVO production is higher than biodiesel production [37,61].

In the electricity sector, the share of bioenergy increased by 6.3% in 2020, reaching 602 TWh. China remained the largest producer of biomass yarn, followed by the United States and Brazil [62]. According to the provisions of the 13th annual plan (2016–2020), bioenergy capacity in China increased by 26% to 22.5 GW in 2020. Production

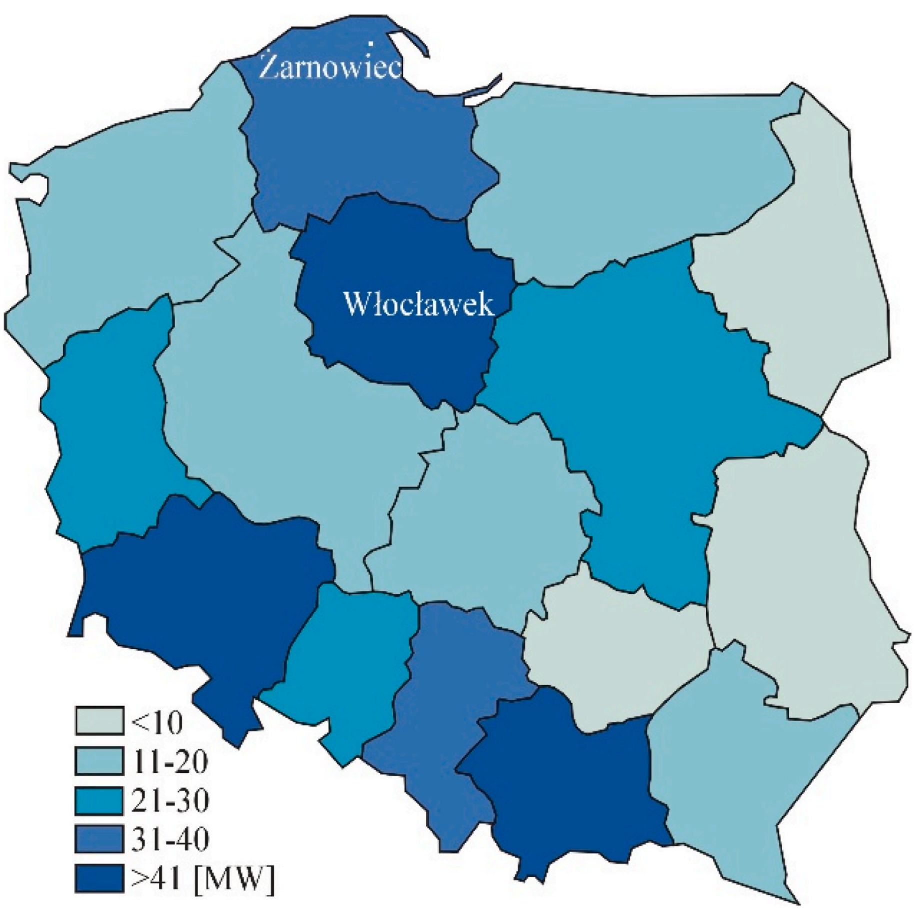

Fig. 10. Power of hydropower plants in Poland (own study after [57]).

Fig. 11. Location of damming structures in Poland according to the National Water Management Authority (own study after [60]).

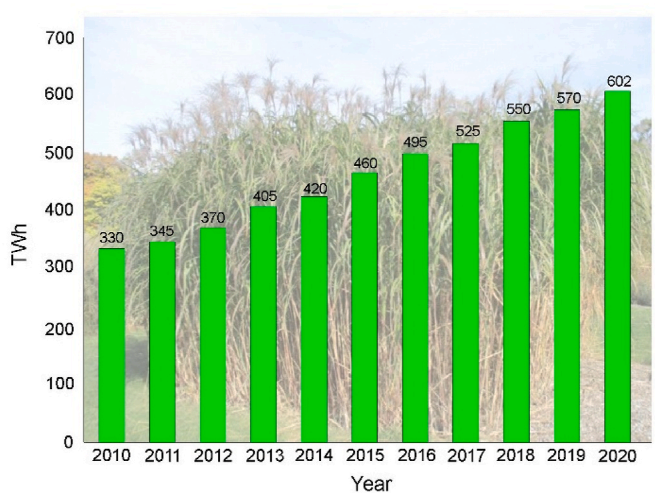

Fig. 12. The increase in the energy production from bioenergy in the years 2010–2020 in the world (own study after [37]).

increased by 23% to reach 111 TWh. In 2020, 77 additional projects providing the capacity of 1.7 GW were approved in 20 voivodships until the financial year. Those projects used municipal waste (1.2 GW), raw forestry (0.5 GW) and biogas energy (21 MW). The United States has the second largest regional power and bioenergy production in 2020. Brazil was the third-largest producer of bioenergy in the world, with the majority of production in that region relying on waste from sugar cane [37, 63].

In the EU, bioenergy capacity increased by about 4% in 2020 to reach 48 GW and production also increased by 4%–205 TWh, accounting for 6% of total energy production. The Germans remained the largest producer of biomass yarn in the EU, mainly from biogas: power increased by 400 MW in 2020 to 10.4 GW, and production increased by 0.8%–51 TWh. Significantly, production increased in the Netherlands (about 90%) to 11 TWh [37,64]. Biogas production is the optimal solution on the basis of which locally available agricultural products are available. It is estimated that in the world, 125 million people use biogas for cooking, which has been essentially unchanged for the last decade. The largest number of people preparing food using biogas lives in Asia (99.7%), while the per capita production is in China, Nepal, Vietnam, India, and Bangladesh [37].

In Africa, biogas production increased by 28% between 2015 and 2020. It is based mainly in Rwanda, Senegal, and the areas of the Africa Biogas Partnership (Burkina Faso, Kenya, Ethiopia, Uganda and Tanzania) [37].

Disposal of municipal waste storage facilities is a reducing factor for people and the environment. The main component of this mixture, methane, is a gas-repellent and explosive gas, in addition to having a very long effect on the deepening impact of the greenhouse gases and the depletion of the ozone layer. From the point of view of effective risk prevention, risk avoidance consists of capturing biogas and using it for energy purposes or only for combustion. It is done actively by applying the suppression of the dominant gas in the composition [65].

4.4.2. *Use of biomass for energy in Poland*

Poland has one of the greatest bioenergy potentials in Europe. Its greater use will secure Poland's energy security [66]. At the end of 2020, there were 45 biomass power plants in Poland with a capacity of 1,249 MW [57].

Until recently, coal and biomass co-firing was used on a large scale in Poland. Unfortunately, imported biomass was often used for this purpose and co-fired in outdated boilers of low efficiency. This phenomenon led to the collapse of the green certificates market (oversupply of certificates) in Poland, which was most felt by small RE installations in Poland [67].

Nowadays, the co-firing of biomass with fossil fuels in large power units seems to be the most optimal rational solution when biomass resources are located about 50–70 km from the place of its combustion. In power plants and combined heat and power plants co-firing biomass with coal, we see compensation for periodic changes in the quality and quantity of biomass and the stabilisation of the entire fuel system. Low investment and operating costs for co-firing alternative fuels with coal in heat blocks compared to thermal systems that use only biomass is the main reason for the popularity of co-firing in Poland and worldwide [44, 68].

For many years, the co-firing of biomass with coal was carried out by many power plants and combined heat and power plants in Poland. This was due to the so-called "green certificates" (support system) that encouraged co-firing. In the Grudziądz CHP plant (center of Poland), biomass is co-incinerated/combusted in a somewhat unusual way. Depending on the town's energy needs, only coal or agricultural biomass (Fig. 13), from which pellets are obtained, is burned.

Only wood of low wood strength, pulp, and some other industrial processing wastes should be classified as fuel. It is estimated that wood waste is up to 60%, and the final product (e.g. desks) is 40% of the biomass of extracted trees [69].

The largest biomass plant in Europe is being built in the Kwidzyn area. The rapidly growing hybrid poplar has already been planted on an area of almost 1,000 ha. Ultimately, energy trees are to take up about 25,000 ha. Hybrid poplar is an ideal raw material for producing fuel for installations using cogeneration, and its cultivation improves the indicator of ecological land use and soil quality. After about 3–4 years, it can be used as biomass in the IP heat and power plant in Kwidzyn. It is assumed that approximately 300,000 tons of biomass will be obtained from about 3,000 ha of poplars, and about 500–1,000 people will have to be employed to service 10,000 ha of plantations [70]. The most popular energy plants in Poland, apart from poplar, are *Salix viminalis* and *miscanthus* [71].

After 2004, Poland's market for biofuels and biocomponents was developing rapidly. In recent years, however, stagnation in the biofuel market in Poland has been observed. According to the Agricultural Market Agency data from 23 March 2021, 13 plants produced bioethanol with a total volume of 789.4 million dm^3; eight plants produced biodiesel with a total volume of 1,674.5 million dm^3, and one plant produced biohydrogen with a volume of 1,120 million dm^3. In addition, nine plants generated 603.7 million dm^3 of other biofuels annually (Fig. 14). In 2021, 331 large biogas plants were operating in Poland with a total capacity of 248 MW [72].

Fig. 13. Biomass for co-firing in Grudziądz (Poland) (photo by B. Igliński).

In 2021, 331 large biogas plants were operating in Poland with a total capacity of 248 MW [72].

4.4.3. *Other use of biomass for energy and chemical compounds*

During the pyrolysis process, complex chemical compounds are broken down into lower molecular weight compounds [73]. Organic materials (e.g. biomass, waste) and inorganic materials (ceramic raw materials) can be subjected to pyrolysis. The pyrolysis of organic substances leads to a solid residue, the so-called carbonisation and the separation of volatile parts in pyrolysis tar and pyrolysis gas. On an industrial scale, the pyrolysis of organic materials is the processing of raw materials (coal, biomass) into useful forms of energy, raw material recycling (waste polymers) and the production of raw materials for their further use. The pyrolysis process is widely researched in Poland, which will result in its greater practical application in the future [74,75].

Additionally, pyrolysis shows scientific and technical progress in optimising higher biofuel yields and lower energy consumption by applying renewable energy resources. Moreover, current and future trends in biomass pyrolysis are developed, e.g. microwave pyrolysis, solar pyrolysis, plasma pyrolysis, hydrogen production by biomass pyrolysis, selective preparation of fine chemicals, biomass co-pyrolysis with synthetic polymers and wastewater, pyrolysis of exotic biomass (coffee grounds and cotton husks), comparison of pyrolysis of algae biomass and terrestrial biomass [76].

Gasification of biomass is the conversion of solid fuels into a mixture of combustible gases that can be burned in a suitable burner or unit generating electricity and heat. Different types of biomass are usually used in this process, and it involves only partial combustion when the air supply is correspondingly smaller than for complete combustion. Biomass gasification with the production of electricity and heat is a technology rarely used in Poland. This is due to many unsuccessful projects of these installations carried out in both industrial and heating companies. Installations for gasification of biomass and sewage sludge were mainly the subject of research at universities. Further research is needed to use pyrolysis and gasification for energy purposes in Poland [77].

4.5. *Geothermal energy and heat pumps*

4.5.1. *Geothermal energy in the world*

Estimates show that 133 MW of new geothermal generation capacity was added to the grid in 2020, which gives globally approximately 14.1 GW. A characteristic feature of 2020 was the relatively small increase compared to recent years, mainly due to the pandemic. The most significant power increase occurred in Turkey, the USA, and Japan (Fig. 15) [37].

The 10 most powerful countries at the end of 2020 are the US, Indonesia, the Philippines, New Zealand, Turkey, Italy, Mexico, Kenya, Japan, and Iceland [37].

In 2020, the power of geothermal heating plants in the world increased by 2.4 GW of thermal energy (an increase of about 8%), reaching a total capacity of 32 GW. The countries that used geothermal heat the most in 2020 (in descending order) were China, Iceland, Turkey, and Japan, which together accounted for around 75% of the global total [37].

Geothermal heat has many practical applications. Swimming and bathing (in thermal baths) remain the largest category, accounting for around 44% of total use. Thermal baths and balneotherapy are developing in many countries, growing on average by about 9% per year. The second but fastest-growing category was heating (around 39% of direct use). Other applications are greenhouse heating (8.5%), heat use in industry (3.9%), aquaculture (3.2%), agriculture (0.8%), melting ice and snow (0.6%) and other uses (0.5%) [37].

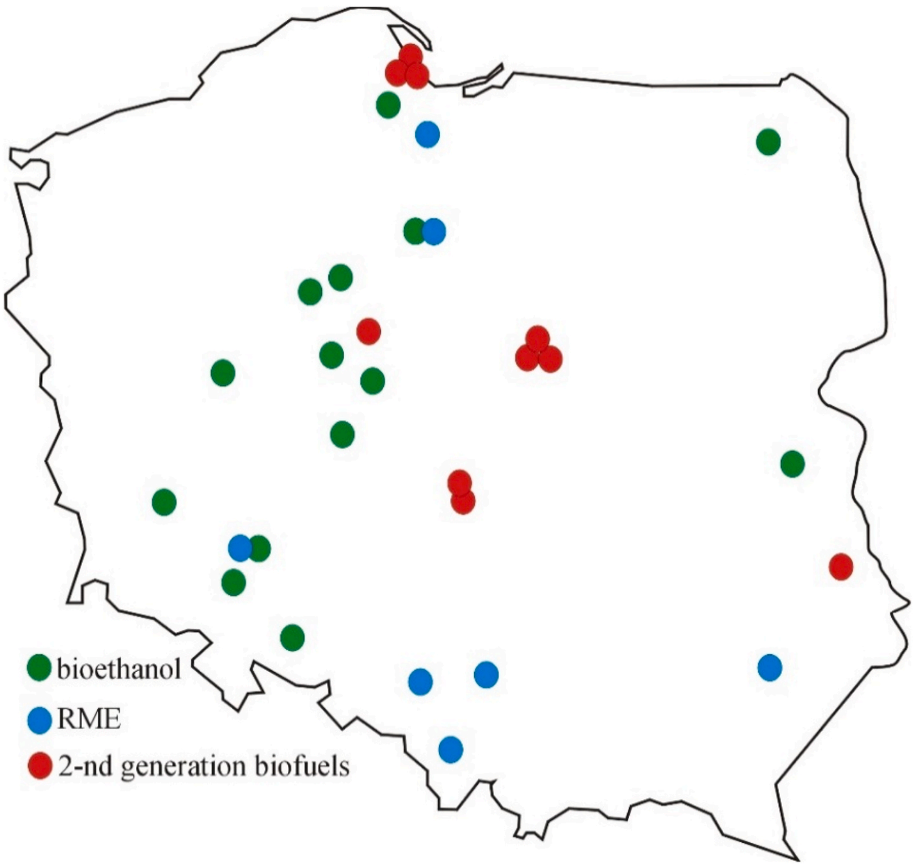

Fig. 14. Localisation of biofuels installations in Poland (own study after [72]).

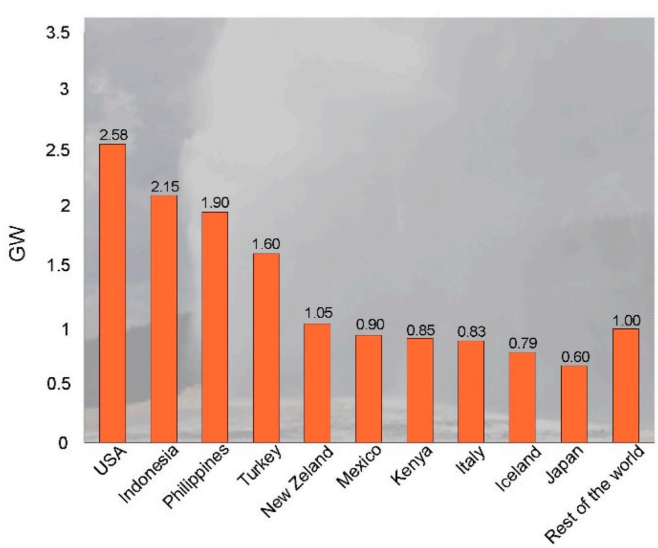

Fig. 15. The power of geothermal power plants in the world (own study after [37]).

4.5.2. Geothermal energy and heat pumps in Poland

In the mid-1980s, research and implementation work began on the management of geothermal energy in heating: for heating and on a semi-technical scale also in agriculture and fish farming. It led to the commissioning of geothermal heating plants operating today in Bańska Niżna, Pyrzyce, Uniejów, Mszczonów, Stargard, Toruń and Poddębice (Fig. 16) [78].

Currently, several dozen or tens of thousands of heat pumps are installed in Poland annually. Most are ground-to-water, air-to-water, and water-to-water pumps (the first word means the lower heat source). Forecasts for the development of the heat pump market in Poland (by analogy with other countries) indicate an annual demand of 60–70 thousand pieces [78].

The heat pump market is developing better and better. Poles are increasingly replacing old coal stoves with heat pumps (Fig. 17) [79].

5. Electromobility

5.1. Electric vehicles in the world

For nearly a decade, the electric vehicles market has been systematically developing, improving the efficiency and functionality of this type of vehicle year by year. For electromobility, 2020 was the key year, where the main focus was on electric cars (electric passenger vehicles), while efforts to electrify marine and aviation vehicles remained limited. The increase in the number of electric vehicles can be explained by the favourable context of the support policy (e.g. fiscal tightening emission standards, incentives, support for charging infrastructure) and the benefits they offer. Consumers in the United States and Europe are continually attracted by, in order of importance, environmental benefits, economic savings, ease of operation, and the novelty of having new technology [37].

As a result of the crisis caused by the pandemic, global car sales in 2020 dropped by as much as 14%. However, this did not apply to electric cars, the sale of which increased by 41%. As a result, the share of electric cars in new car sales in 2020 was 4.6%, exceeding the 2019 record of 2.7%, and the number of electric cars in the world exceeded 10 million units [37].

China remained the most important market for electric buses in 2020 (up 9% in 2020) and accounted for 99% of global sales in 2016–2020;

Fig. 16. Geothermal heat plants in Poland (own study).

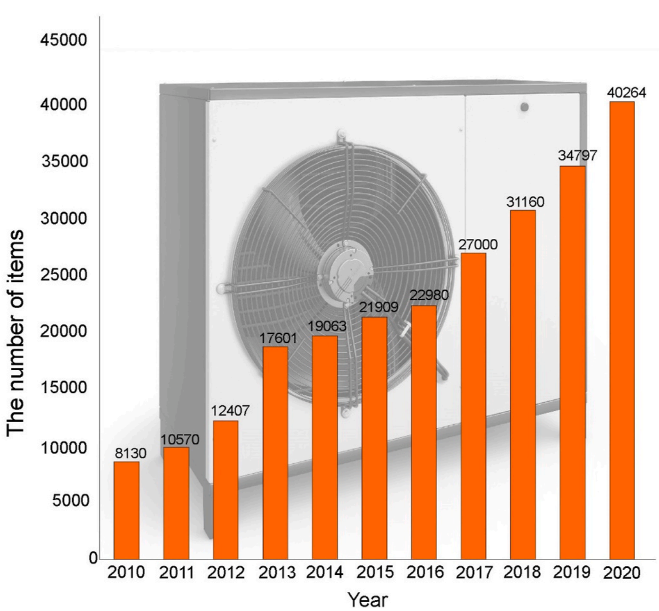

Fig. 17. Heat pumps market in Poland (own study after [79]).

however, the take-up of buses has increased worldwide, especially in Europe (7% increase) [37].

There were approximately 4,000 electric buses in operation in Europe. In 2020, around 2,100 new electric buses were registered, 22% more than in 2019. Denmark led in terms of market share of new e-buses (78%), followed by Luxembourg (67%) and the Netherlands (65%) [37].

In 2020, there were around 2,000 electric buses in Latin America. Santiago, Chile, has the largest number of electric buses of any city outside of China (400 added in 2020, over 800 total). Bogota (Colombia) added 470 electric buses in 2020 and placed an order for another 596 [37].

Electric railways – they dominate the world – account for 75% of the rolling stock. Rail electrification is carried out in many countries. In Great Britain, 251 km have recently been electrified. India wants to electrify 100% of the railways by 2023 [37].

By the end of 2020, there were approximately 290 million electric single and three-wheel vehicles on the roads worldwide. About a third of all units sold during the year were electric, and 99% of new registrations took place in China. The European market, which is still a relatively young market, is developing rapidly [37].

5.2. Electric vehicles in Poland

According to data from the end of May 2021, we have a total of 25,407 electric passenger cars registered, and their owners can use approximately 1,500 public electric charging stations [80].

The fleet of electric vans and trucks consisted of 966 vehicles. The fleet of electric mopeds and motorbikes continues to grow, which at the end of May consisted of 10,105 vehicles. In May 2021, the electric bus park in Poland increased to 526 vehicles. From January to May 2021, the electric bus fleet increased by 94 zero-emission vehicles. Compared to the corresponding period of 2020, when 31 such buses were registered, this means an increase of 203% y/y [80].

For example, Volvo has produced a total of 24 electrified buses for

Inowrocław (center of Poland). In addition to the now fully electric buses, eight electric-hybrid (plug-in) buses have been operating in Inowrocław since last year [80].

As the number of electricians grows, so does the charging infrastructure. At the end of May 2021, there were 1,495 publicly accessible charging stations for electric vehicles in Poland (2,897 points). 33% of them were fast DC charging stations and 67% were slow AC chargers with a power less than or equal to 22 kW. On May 2021, 39 new, generally accessible charging stations (59 points) were launched [80].

It is worth adding that in May 2021, 46 hydrogen cars were registered, and currently in Poland their park consists of 53 units [80].

It is worth adding that in May 2021, 46 hydrogen cars were registered, and currently, in Poland, their park consists of 53 of them [80]. There are 15 tram systems in Poland – ten of them are standard (1,435 mm), and five are narrow (1,000 mm). The youngest municipal tram network was established in 2015 in Olsztyn, while the smallest is in Grudziądz and has 9 km of tracks. In the years 1945–2020, these systems were expanded and modernised in larger cities: Warsaw, Poznań, Gdańsk, Wrocław, Kraków, Bydgoszcz, Toruń [80].

As of August 2021, there were three trolleybus systems in Poland: Gdynia, Lublin, and Tychy. According to Statistics [81], Poland has 19, 398 km of railway lines in operation in Poland, including 12,018 km of electrified ones. Two or more tracks include 8,800 km of railways.

6. Discussion

Despite the coronavirus pandemic, the RES sector is developing faster and faster in Poland and worldwide. The capacity of RES installations and employment in this sector is increasing too. Importantly, a mix of renewables and electromobility is developing in most countries. Table 1 presents renewable energy, conventional energy, and nuclear energy production shares in 2010, 2015, and 2020. Positive changes in renewable energy production and decreases in conventional and nuclear energy production in the studied years are evident. In 2010, the share of renewable energy generation was 20.06% points and increased to 28.97% points in 2020. Considering two consecutive five years, the share increased by 17.75% in 2010–2015 and 22.65% in 2015–2020. Conventional and nuclear energy recorded declines in production in both periods. While in the 2010–2015 period, significantly higher declines were recorded for nuclear energy production (−16.98%) than for conventional energy production (−2.04%). However, in the subsequent 2015–2020 period, the declines in conventional energy production compared to nuclear energy were slightly higher, at −7.23% and −5.51%, respectively. These facts confirm the occurrence of energy transition processes and the importance of the topic of this article on the development of the RES sector.

In turn, Table 2 and Fig. 18 present the evolution of energy production from RES in 2010, 2015, and 2020. Four main sources of renewable energy were distinguished: biomass, wind, water, and sun. The data are presented in absolute values, as in relative values representing the share of selected energy sources in the total production of renewable energy. Additionally, the aggregated data for world production are presented, followed by production in China, the EU, and Poland. Taking into account 2010, it is visible that wind energy dominated the global production of renewable energy (65.78%). A much lower but still high level was recorded in the case of energy from biomass (20.60% and solar power (13.29%), while the share of hydropower in the total production of renewable energy is negligible and amounts to 0.34%. It should be stressed that due to their physical conditions and RES and the level of socio-economic development, individual countries may have different shares of renewable energy production compared to global trends, which is evident in the case of China, where hydropower production dominates (81.20%). The share of wind energy production is also high (17.4%), while the energy production from biomass and solar energy slightly exceeds 10%. Accordingly, the share for energy from biomass is 2.08%, and for solar energy is 8.88%. On the other hand, in the case of the EU, wind energy production dominates, the share of which was 78.07%.

The energy transition processes are currently very dynamic in most countries, causing a systematic development of the RES sector. This development is manifested primarily in the increase of the share of energy production from RES and in increased awareness of end consumers in the use of energy. Undoubtedly, in the functioning of the RES sector, the problem of effective use of different energy sources is of key importance. Therefore, this article discusses both global trends and the situation in Poland with regard to solar energy, wind and water, biomass, geothermal energy, and heat pumps.

In the case of PV Poland is currently experiencing a "PV boom". Both solar farms and, above all, prosumer (roof) installations are being built. It is estimated that the number of prosumers (mainly PV) in Poland at the end of 2021 will already reach over 750,000. The rapid development

Table 1
Dynamics of changes in the shares of energy production from selected sources.

Year	Renewable [%]	Conventional [%]	Nuclear [%]
2010	20.06%	67.04%	12.9%
2010–2015 (percent change)	17.75%	−2.04%	−16.98%
2015	23.62%	65.67%	10.71%
2015–2020 (percent change)	22.65%	−7.23%	−5.51%
2020	28.97%	60.92%	10.12%

Table 2
Use of RES in the world, EU and China.

2010					
Origin	Biomass	Wind	Hydro	PV	**Total [GW]**
World					
Capacity [GW]	62	198	1.01	40	301.01
Percent [%]	20.60	65.78	0.34	13.29	100
China					
Capacity [GW]	4	44.7	213	0.6	262.3
Percent [%]	1.52	17.04	81.20	0.23	100
EU					
Capacity [GW]	10.4	84		13.2	107.6
Percent [%]	9.67	78.07	0.00	12.27	100
Poland					
Capacity [GW]	0.365	1.118	0.937	0	2.42
Percent [%]	15.08	46.20	38.72	0.00	100
2015					
Origin	Biomass	Wind	Hydro	PV	**Total [GW]**
World					
Capacity [GW]	106.4	433	1.064	227	767.464
Percent [%]	13.86	56.42	0.14	29.58	100
China					
Capacity [GW]	10.3	145.362	296	44	495.662
Percent [%]	2.08	29.33	59.72	8.88	100
EU					
Capacity [GW]	21	147.771	lack of data	17.3	186.071
Percent [%]	11.29	79.42	lack of data	9.30	100
Poland					
Capacity [GW]	1.123	4.582	0.982	0.071	6.758
Percent [%]	16.62	67.80	14.53	1.05	100
2020					
Origin	Biomass	Wind	Hydro	PV	**Total [GW]**
World					
Capacity [GW]	145	743	1.17	760	1649.17
Percent [%]	8.79	45.05	0.07	46.08	100
China					
Capacity [GW]	22.5	288.3	338.7	253.4	902.9
Percent [%]	2.49	31.93	37.51	28.07	100
EU					
Capacity [GW]	48	179.3	32	150	409.3
Percent [%]	11.73	43.81	7.82	36.65	100
Poland					
Capacity [GW]	1.513	6.347	0.976	0.887	9.723
Percent [%]	15.56	65.28	10.04	9.12	100

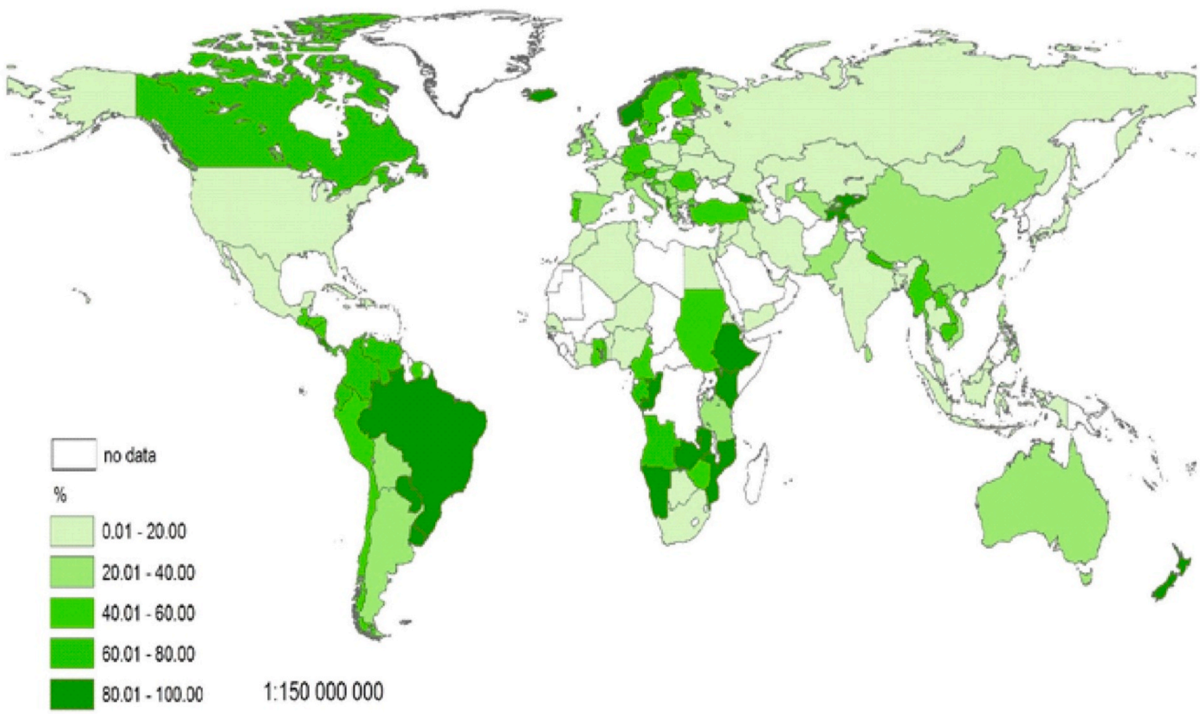

Fig. 18. Percentage share of RES in electricity production (own study).

of the PV sector in Poland will be maintained, which means that it will play an increasingly important role in the country's energy mix.

The rapid development of wind energy in Poland took place between 2010 and 2016. This development was slowed down by the "distance act". Every year, the increase in capacity is at the level of several tens of MW, while it was at the level of several hundred MW. On the other hand, small domestic wind power plants are becoming increasingly popular. In the coming years, offshore wind farms will be built in Poland; their potential is estimated at 12 GW by 2030. The chances for their creation should be very high, as energy and fuel companies have become involved in the investments.

As far as hydropower in Poland is concerned, a slow capacity increase is noticeable. There is quite a considerable interest from investors who want to develop small hydropower. However, they are discouraged by a huge number of documents and permits – the investment implementation time is even four years. Therefore, it is important to simplify legal regulations, especially since Poland already has 16,000 dams (locks, weirs, etc.) on which small hydropower plants can be built.

As for the biomass sector in Poland, the situation stabilised a few years ago. Poland is an agricultural country, so the potential of waste biomass is considerable. It should be used for direct combustion or as a substrate in agricultural biogas plants. Biomethane from biogas can be used as a substitute for natural gas and car fuel.

As for geothermal in Poland, several projects are at an advanced investment stage, which means that both geothermal heat plants and swimming pools using geothermal heat will be built in the coming years. In addition, interest in balneology is growing. Poles are increasingly choosing heat pumps as their heat source. Further development of the heat pump market will contribute to reducing air pollution. It is vital in Poland, where smog occurs in the autumn and winter.

The fight against smog in Poland favours the development of electromobility. New tram lines or electric and hybrid buses will be used in large cities. When it comes to electric cars, it can be said that their market in Poland is in the early stages of development. On the other hand, scooters, bicycles, and most all-electric scooters are becoming very popular. More and more people in large cities choose electric scooters for transport (own or rented).

Each country independently (or within the EU) should gradually strive for energy independence, reducing the import of fuels and energy. For example, Poland imports significant amounts of crude oil, natural gas, and hard coal (even though Poland has large resources of hard coal and lignite). Import, especially one delivery, causes economic and political dependence on a given country. This country may inflate the price of fuel, threaten to stop exporting, exert political pressure, or even finance and build the army with our money. Poland must strive to diversify fuel and energy supplies from various suppliers from different countries. This will improve the country's energy security.

Poland's energy security is primarily based on producing energy from its own resources. These will still be carbon resources for some time, gradually being replaced by renewable sources. Poland has a significant potential for renewable energy, which with increasing energy efficiency means that there are scientific grounds that Poland can obtain 100% of energy from RES. It is worth emphasising here that it will not be ensured by one source (e.g. only wind energy) but by a mix of RES sources: bioenergy, wind energy, hydropower, solar energy, geothermal, and heat pumps. They must complement each other and be supported by energy storage (batteries, pumped storage plants) or by producing "green" hydrogen.

Energy prosumers play an increasingly important role in Poland. The goal is to make prosumers more focused on energy consumption. And this is what is happening; more and more are installing a heat pump or buying an electric car. An electric car can be used for driving and as an energy store. Given the rising fuel and energy prices, more and more Poles (including companies, offices, schools, etc.) decide to install RES installations and cover at least part of their energy needs. Although RES installations are still quite expensive, economic calculations show that such an installation pays off after a few years.

Renewable energy is usually produced by small installations located more or less evenly in the country. They can supply electricity to the nearest towns, and transmission energy losses are minimal in this case. For example, electricity transmission from a coal-fired power plant in Silesia to the northeast of Poland amounts to several per cent of transmission losses. In biomass CHP plants or biogas plants, energy is most often produced in cogeneration, thanks to which the installation efficiency is about 80%. The average efficiency of Polish power plants is 36.5%, and heat is treated as "waste".

Large thermal power plants are an easy target for enemy troops, terrorists, or cyberattacks. For example, a cyberattack on the power plant in Bełchatów in Poland would destabilise the energy system throughout the country and maybe even cause a blackout. On the other hand, a cyberattack on an agricultural biogas plant has no impact on the electricity network. The more but less powerful installations for energy production, the greater energy security.

RES installations are also an important economic aspect. Each installation provides jobs, often in rural areas with an increased unemployment rate. For example, an agricultural biogas plant can work with local farmers and collect agricultural waste from them. In return, the biogas plant can provide them with digestate, which is a better fertiliser than, for example, slurry. The development of RES also means jobs in laboratories or research institutes, thanks to which the share of women in the RES sector is approximately 35%. For comparison, only 2% of women work in coal mines in Poland.

Poland has a huge problem with smog, especially in winter. Estimates of various institutions (including the Supreme Audit Office and the WHO) are consistent and show that due to poor air quality in Poland, about 50,000 people a year die prematurely, and several hundred thousand fall ill. The development of ecological heat sources and electric and hydrogen transport can solve the problem of smog in Poland within two to three decades. There are special biomass boilers (for briquettes or pellets) and heat pumps, and more and more cities are investing in geothermal heat.

7. Conclusions

This article deals with the problem of global and regional development of the RES sector. The main objective of this article is an attempt to assess the RES sector in Poland against the background of the development trends in this sector worldwide. It should be emphasised that RES is one of the fastest-growing branches of the economy in the world, including Poland. Every year, RES in the world is growing faster and faster. Production PV and wind energy are growing particularly fast. The remaining RES sources develop more slowly but also in this case an upward trend is observed. It has to be emphasised that the development of RES in the world is turning into an increase in employment in the energy sector. In this sector currently working more than 12 million people work here and employment is gradually increasing.

Extensive research carried out in scientific centers results in an increase in the effectiveness of gaining energy from renewable sources and a decrease in the prices of renewable energy installations. The development of renewable energy is an impulse for further research and the development of new technologies. It is expected that investment costs, which currently constitute a significant barrier in their implementation and development, will fall along with their development and a further increase in production. Despite the extensive bureaucracy, Polish investors show outstanding entrepreneurship and activity in constructing RES installations. Often these are their own ideas for improving existing technologies.

Poland, although still using in the main conventional fuels, is also developing RES sector more and more rapidly. It should be noted that in Poland until 2016 the most dynamic development was onshore wind energy. However, this development was hampered by the introduction of "the distance act". Currently, offshore projects in the Baltic Sea are at the initial stage of investment – the capacity of wind farms is to amount to several/a dozen GW in the next decade. Production PV is very popular in Poland, both the "large" and the prosumer one. Currently (June 2022), there are over 1 million PV prosumers in Poland, and the estimated PV capacity is 10 GW. The development of prosumer PV is expected to slow down, and the growth of "large" PV in Poland. It should be noted that other types of RES must also develop in a sustainable way. Poland has great potential for biomass and biogas too. Biogas is currently used for the production of electricity and heat, but it is planned to be used in the near future as biomethane for injection into the gas network and as fuel for cars. Undoubtedly, the systematic development of the RES sector and the expansion of the share of renewable energy production should be the basis of the economic policy of each country. Poland's energy independence in the production of electricity, heat, or transport will have a positive effect on the economic development of the country and may, over time, reduce fuel and energy prices. Further development of the RES sector in Poland may enable Poland to become an exporter of energy from RES and profit from it.

Summing up, it should be stated that further development of the RES sector is expected both in Poland and in the world. The current geopolitical situation has made politicians and energy engineers aware of the importance of having their own fuel and energy resources, both from conventional and renewable sources. Energy independence is, to some extent, also economic and political independence. The development of the RES sector is the development of innovative, friendly technologies, an opportunity for scientific and economic development.

CRediT authorship contribution statement

Bartłomiej Igliński, Michał Bernard Pietrzak: Conceptualization, methodology, writing - original draft, preparation of revised version of manuscript. Grzegorz Piechota: project administration, formal analysis and investigation, writing - review response & editing. Urszula Kiełkowska, Gopalakrishnan Kumar: Supervising. Mateusz Skrzatek: graphics drawings, and sources.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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