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European Green Deal + Poland + hydroelectric plants = Future?

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Abstract

This study considers the current state of hydropower in Poland and the legal and environmental conditions for its development. The research objective was to provide insights into the future of hydropower in Poland. An attempt was made to determine the direction of hydropower development in Poland by 2050, taking into account the requirements of the European Green Deal. The basic method used is logical argumentation, which is in turn based on a critical analysis of planning documents and scientific papers. Statistical data on the production and consumption of hydropower were also analysed. Currently, Poland's potential for hydropower production is not being fully exploited. The main reasons for this are a lack of political support and socio-ecological issues associated with the need to take over inhabited areas or areas of high natural value. The analysis of the state of hydropower in Poland indicates that urgent intervention is required in many areas. This applies, especially, to issues of the control, modernisation and technical condition of hydropower plants and damming facilities. The potential for the development of hydropower in Poland is assessed to be very small. Environmental, socio-economic and legal conditions are unfavourable to the construction of new, large hydropower plants. The exception is pumped-storage power plants, which, acting as energy storage facilities, should in the future constitute an important element of the Polish energy system. The possibility of using defunct lignite mining pits for this purpose is indicated. It is shown that some of Poland's former lignite mines are also conveniently located. The possible beneficial impact of building pumped-storage power plants into the water ecosystem of central Poland is emphasised.

Keywords: water, renewable energy, pumped-storage power plants, Poland, European Union

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Introduction

Hydropower was one of the first sources of energy to be used by humans to facilitate and speed up various types of work. It is based on the simple principle of harnessing the kinetic energy of falling water to drive a turbine. In this way, the movement of the water is converted into mechanical and electrical energy. It is a simple process that can provide electricity very efficiently and reliably (Egré, D. and Milewski, J.C. 2002). This renewable energy source varies in popularity around the world, mainly due to differences in individual regions' potential in terms of size of water resources and appropriate topography. In Europe, it has increased in importance significantly in the last 20–30 years due to many countries' change in approach to climate protection. Countries of the European Union (EU) have particularly ambitious climate protection plans. This is reflected in the fact that 37.5 percent of the electricity consumed in the EU came from renewable sources in 2021. Hydropower accounted for, in turn, 32.1 percent of that, making it the second largest renewable source in total EU electricity consumption (Eurostat, 2021). Gaudard, L. and Romeiro, F. (2014) note that hydropower seems to have a promising future and can play an important role in Europe's energy transformation. However, in recent years,

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hydropower has been developing most dynamically in Asian countries (Zimny, J. *et al.* 2013). Globally, despite various other renewable energy sources growing rapidly, hydropower remains the largest renewable source of electricity, generating more than all other renewable technologies combined. In 2021, global electricity production from hydropower was 4,327 TWh (IEA, 2022).

In December 2019, the European Commission presented the European Green Deal. It is a package of legislative proposals to adapt the EU's climate, energy, transport and tax policies to meet the goal of reducing net greenhouse gas emissions by at least 55 percent by 2030. As an EU member, Poland is obliged to implement common policies in many areas, as defined by relevant regulations, directives and other legal acts. One area to which common EU policy applies is broadly understood environmental protection, including that relating to climate change. For Poland, the most important elements of the European Green Deal include guidelines for decarbonising the EU energy system. The main objective is to reduce, in the EU, greenhouse gas emissions from the use and production of energy (European Commission, 2019). Poland, whose electricity generation is based on bituminous coal and lignite (about 70%), must implement measures to meet the requirements set out in the European Green Deal. It should be noted that Poland has long been working to transform its energy system towards renewable energy sources.

With this in mind, consideration should be given to the place of hydropower in electricity generation in Poland for the coming years. Of the arguments supporting the importance of hydropower in Poland's energy mix, three are perhaps most important. One is the fact that it is far less sensitive to weather variability and seasonality than the other renewable energy sources that are currently most popular (wind and solar). This is an extremely important factor for maintaining the stability of the country's energy system. Another relates to the issue of Poland's limited water resources in the context of changing climatic conditions these resources can be increased by slowing down outflow with hydroelectric dams. A third important argument is the long history of hydropower in Poland. This applies especially to small hydropower plants, as discussed in detail later in the text. These arguments and the need to implement the guidelines contained in the European Green Deal allow us to pose the following research questions: What is the future of the Polish hydropower industry? Is hydropower needed in Poland? Is the European Green Deal the last chance to develop hydropower in Poland? In what direction should hydropower develop in Poland, bearing in mind the environmental, socio-economic and legal conditions? The present work aims to answer these questions. The following specific objectives were helpful in this regard:

- to analyse the current state of hydropower in Poland,
- to analyse the legal and environmental conditions for the development of hydropower in Poland,
- to indicate possible directions for hydropower development in Poland until 2050, taking into account the requirements of the European Green Deal.

Methods and materials

The research issues discussed herein are considered comprehensively, taking into account environmental, socio-economic and legal conditions. This required the use of several research methods. The basic method was logical argumentation, which was based on a critical analysis of planning documents and scientific papers – in total, about 100 of them were collected (all were available online). Ultimately, only a portion of these studies were used in the work, mainly due to the validity of the data and information they contained. *Table 1* summarises the most important planning documents and reports used in the work. The remaining literature (scientific articles) included in the study are cited in the body of the text. The descriptive method and the formal dogmatic method were used in

Table 1. The most important planning documents and reports used in the work

Document name	Document type	Main focus	Scale	Year of issue	EU connection
National renewable energy action plan	Planning and design	Information on goals and course for the use of renewable energy in Poland until 2020	National	2011	Reflecting EU values
Water management in Poland in 2020–2021	Report on completed task	Contains information on state of water resources in Poland and implementation of water management plans in river basin areas	National	2022	Reflecting local legal regulations
National energy and climate plan for 2021–2030	Planning and design	Sets Poland's climate and energy targets for 2030	National	2019	–
Poland's energy policy until 2040	Planning and design	Sets the framework for energy transformation in Poland up to 2040	National	2021	Implementation of EU energy and climate policy
Report: Small hydropower plants in Poland	Conceptual	Report contains proposals for regulatory changes to support development of small hydropower plants	National	2022	Reflecting local legal regulations
National Development Strategy	Conceptual	Development goals for the country	National	2019	Reflecting EU values
Krakow spatial plan	Planning and design	Technical realisation for infrastructure	Local	2022	Reflecting local legal regulations
Energy transformation in Poland	Report	Contains analysis of energy market in Poland over the last 10+ years	National	2023	Reflecting EU values
Report: Polish energy transition path	Report	Presents Poland's achievements in energy transformation. Also indicates near-future challenges for energy sector	National	2022	Reflecting local legal regulations and reflecting EU values

the legal analysis. The legal analysis also included comparative legal remarks. The legal analysis cites relevant legal acts. To achieve the research goal, research techniques such as literature review, geo-analysis and data interpretation were used. The literature review was used to determine the current state of knowledge about the research problem. The geo-analysis included data on electricity generation in Poland and on the relationship between electricity consumption and generation by voivodeship. These data were obtained from the Local Data Bank of Statistics Poland. The data were interpreted and the spatial relationships between them and selected natural conditions were identified.

Environmental conditions for hydropower development in Poland

For water to play a significant role as an energy source in a country, appropriate natural conditions are required. The most important elements in this respect are adequate water resources and topography. Poland has some of the lowest water resources in Europe. The average annual sum of precipitation is 600 mm. Long-term average total surface water resources do not exceed 62 km^3. Most of Poland has a typical lowland topography. Only the south is decidedly more diverse, with an upland and mountainous character. The arrangement of southern uplands and central and northern lowlands means that the main direction of water outflow is northward. As a result, 95 percent of Poland belongs to the Baltic Sea catchment basin (Gutry-Korycka, M. *et al.* 2014).

An important factor limiting the development of hydropower in Poland is the spatial differentiation of surface water resources. This is well portrayed by the unit outflow coefficient, which ranges from 4 dm^3/s/km^2 in the Wielkopolskie-Kujawskie Lakeland to over 50 dm^3/s/km^2 in the mountain areas. The average value for Poland is 5.5 dm^3/s/km^2 (Jokiel, P. 2004). Attention should also be paid to the high seasonal and annual variability of precipitation sums. For example, in the city of Toruń in north-central Poland, over the last 15 years, annual precipitation has varied between 380 mm (2015) and 832 mm (2010).

The location of large hydropower plants in Poland has been determined by the presence of the most favourable natural conditions. In the case of small hydropower plants (SHPs), regional cultural considerations and histories have been an additional important factor. This results directly from the original function of dams on small watercourses in what is today Poland. They were used to drive water mills that ground grain into flour and groats.

The current state of hydropower in Poland

The potential for hydropower in Poland is small, ranging, according to various sources, from 8 to 14 TWh per year (Kowalczyk, K. and Cieśliński, R. 2018). At the same time, it is estimated that about 5 TWh falls on SHPs of up to 10 MW each (Gajda, P. 2022). These values are very small relative to European or global resources (rational European resources are technically estimated at about 1,120 TWh/year, and global resources at 8,000–26,000 TWh) (Szulc, P. and Skrzypacz, J. 2022). Poland's hydropower potential is concentrated mainly in the basins of its two largest rivers, i.e., the Vistula basin and the Odra basin, which account for 9.3 and 2.5 TWh per year, respectively *(Figure 1).* Meanwhile the potential of the Vistula river itself is 6.2 TWh per year. Taking into account Poland's annual electricity consumption of about 180 TWh (which translates into 4,700 kWh *per capita*), this hydropower potential is very small. The share of hydropower in electricity generation in Poland has been below 2 percent for many years.

Hydropower in Poland is mainly based on run-of-river power plants, conventional impoundment plants and pumped-storage plants (Novak, P. *et al.* 2007). In the 1920s and 1930s, there were over 6,800 hydropower plants operating in the country. After World War II, the number decreased, but until the 1950s there were an estimated 6,500 hydropower plants (Wiatowski, M. and Rosik-Dulewska, C. 2012). Currently, there are 788 hydropower plants operating in Poland, only 18 of whose capacity exceeds 5 MW *(Figure 2).*

The largest hydropower plant in Poland in terms of power (excluding pumped-storage power plants) is the Włocławek Power Plant. It has six hydropower units with a total installed capacity of 160.2 MW (Igliński, B. 2019). Other power plants have a much lower capacity, ranging from a few (e.g., Bielkowo Power Plant – 7.2 MW) to a few tens of MWs (Rożnów Power Plant). The capacity of commercial hydroelectric power plants in Poland is 2,042 MW, but as much as 1,366 MW is at pumped-storage power plants (Małecki, Z.J. *et al.* 2015). There are currently six pumped-storage power plants operating in Poland *(Table 2, Figure 2).* They are tasked with stabilising the power grid during the day (Igliński, B. *et al.* 2022). The total capacity of hydropower plants in Poland is 2,042 MW, of which the vast majority (~ 67%) is in pumped storage, which is best suited to catering to peak demand (Kalda, G. 2014).

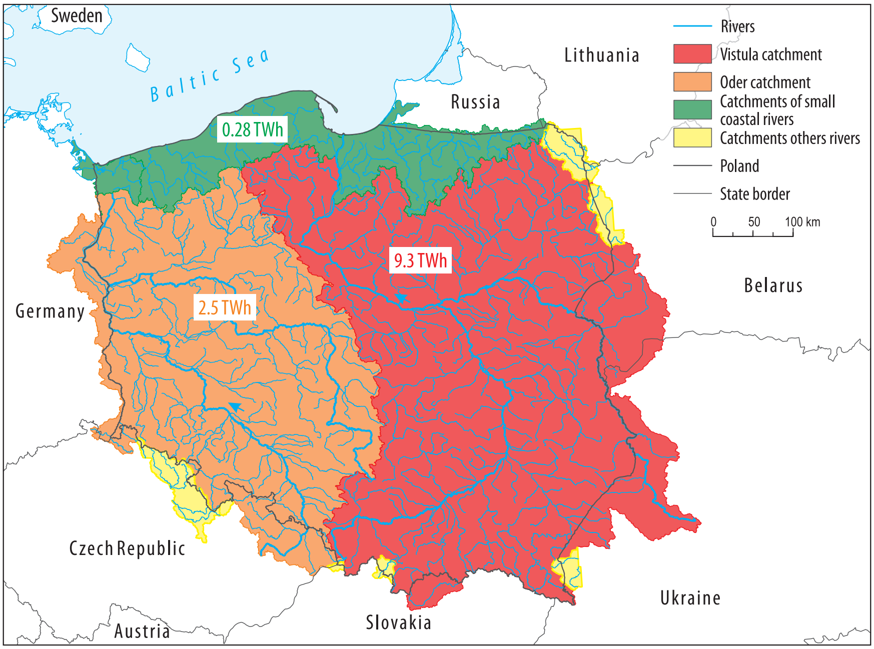

Fig. 1. Hydropower potential of Polish rivers

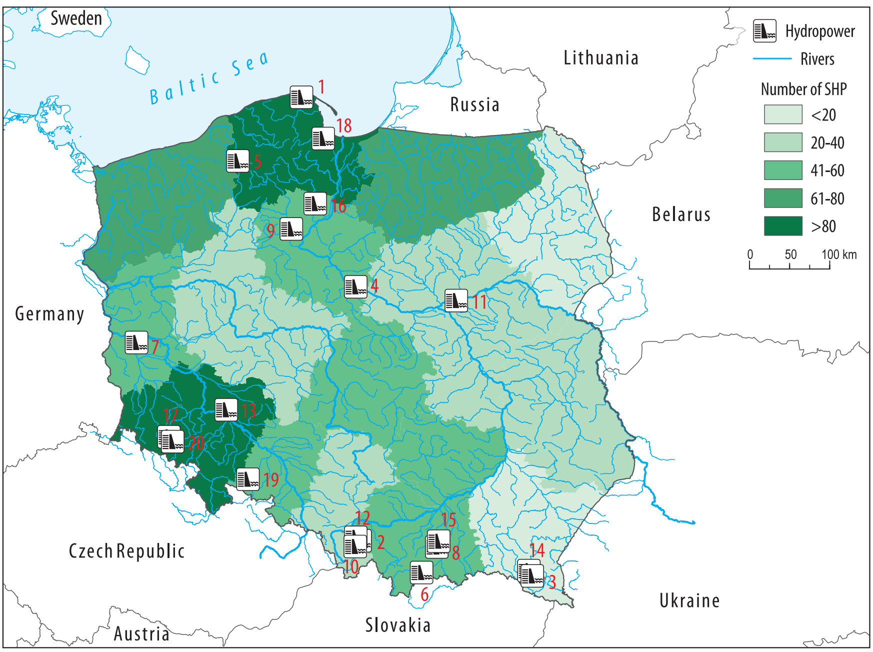

Fig. 2. Locations of the largest hydroelectric power plants in Poland and concentrations of small hydropower plants (SHPs) of ≤ 5 MW by voivodeship. 1–20 in red colour = numbering of power plants (see *Table 2.*)

Table 2. The largest hydroelectric power plants in Poland

Number	Hydroelectric power plant	Power plant type	River/Lake	Installed power, MW	Reservoir volume*, million m^3	Year of built
1	Żarnowiec	pumped-storage	Żarnowieckie	716.0	13.8	1983
2	Porąbka - Żar	pumped-storage	Soła	500.0	2.0	1979
3	Solina	pumped-storage	San	200.0	472.0	1969
4	Włocławek	run-of-river	Vistula	160.2	408.0	1970
5	Żydowo	pumped-storage	Jezioro Kamienne/ Jezioro Kwiecko	157.0	8.9	1971
6	Niedzica	pumped-storage	Dunajec	92.7	168.6	1997
7	Dychów	pumped-storage	Bóbr	88.0	4.0	1951
8	Rożnów	impoundment	Dunajec	50.0	165.0	1941
9	Koronowo	impoundment	Brda	26.0	80.6	1961
10	Tresna	impoundment	Soła	21.0	94.6	1966
11	Dębe	run-of-river	Narew	21.0	94.3	1963
12	Porąbka	impoundment	Soła	12.6	26.6	1954
13	Brzeg Dolny	run-of-river	Odra	9.8	5.3	1912
14	Myczkowice	run-of-river	Soła	8.3	10.9	1960
15	Czchów	run-of-river	Dunajec	8.0	8.0	1951
16	Żur	run-of-river	Wda	8.0	16.0	1930
17	Pilchowice	impoundment	Bóbr	7.9	50.0	1912
18	Bielkowo	impoundment	Radunia	7.2	no data	1930
19	Otmuchów	impoundment	Nysa Kłodzka	4.8	130.0	1933
20	Bobrowice	impoundment	Bóbr	2.5	54.0	1925

*For pumped-storage plants, the usable volume of the upper reservoir is given.

There are 770 SHPs of capacity up to 5 MW in Poland. These are significantly fewer SHPs than the 6,800 SHPs of the 1920s and 1930s. However, it should be noted that a significant proportion of the SHPs from the beginning of the 20th century were water mills that used mechanical energy to, for example, grind grain into flour. The requirements for and purposes served by SHP were entirely different at the beginning of the 20th century than today. This should, thus, be taken into consideration when comparing current numbers of SHPs against those of over 100 years ago. Currently, most are located in northern Poland, where precipitation, topography and geological structure are favourable. The second area with a higher density of SHPs is the mountain and foothill areas in the south of the country. The high hydropower potential of these areas results from their having significant differences in terrain elevation and the country's largest sums of precipitation.

The total installed capacity of SHP is 255.5 MW, i.e., 26.2 percent of the total capacity of hydropower plants in Poland. In terms of the breakdown of electricity production in Poland, hydroelectric power plants supply only about 2 percent of energy to the system (Marszelewski, M. and Piasecki, A. 2022). In 2021, over 180 GWh of energy was produced by small hydropower plants. This source provided 34 percent of the energy generated by all small renewable energy sources (RES) installations in Poland (Energy Regulatory Office, 2022).

As noted by Kasperek, R. (2020), Poland is currently using about 20 percent of its technical hydropower potential. Of the approximately 14,000 dams in Poland whose head exceeds 0.7 m, less than 5 percent is used for energy purposes (Gajda, P. 2022). Therefore, Poland has significant opportunities for hydropower development, especially in SHPs.

The development of hydropower in Poland until 2050

Strategic plans for the development of Poland's energy system, including hydropower, must take into account global changes in the approach to obtaining, storing and transmitting energy. In this regard, attention should be paid to the approach of the International Energy Agency (IEA). This institution's publications are the most authoritative source of analyses and forecasts of energy supply and demand for the coming decades. In one of its latest reports, the IEA drew attention to the need for more work on obtaining net-zero emissions by 2050 as the basic thrust of activities. The goal is to limit global warming to 1.5 °C and avoid the worst impacts of climate change (IEA, 2021). This approach is fully in line with EU actions and the European Green Deal. In its report, the IEA emphasises that hydropower is the largest source of renewable energy in terms of power and generation. At the same time, the observed upward trends in power generation are insufficient to place the energy source on a trajectory congruent with the net-zero scenario. The reason is the too-slow increase in hydropower capacity, along with the simultaneous increasing disruptions to water availability caused by climate change. Another important element is the poor technical condition of many hydropower plants as a result of their long-term operation. Many developed countries' hydropower plants were built mainly in the 1960s and 1980s (Farfan, J. and Breyer, C. 2017). It is estimated that almost 40 percent (476 GW) of the world's hydropower plants are at least 40 years old (the average age is 32). When hydropower plants are 45–60 years old, major upgrades and renovations are required (IEA, 2022). Environmental and legal changes since most power plants were commissioned also constitute an important issue. This mainly concerns changes in the flow (ensuring the minimum flow required to maintain ecological status in the watercourse), as well as detailed environmental protection regulations. These factors mean that it may not always be possible to temporarily shut down hydropower plants for refurbishment and then restart them at the previous level. Under current legal and environmental conditions, some hydropower plants may be able to produce only a certain percentage of the energy previously generated.

When planning the development of hydropower in Poland, experiments – and changes – in the approach to this energy source in other highly developed countries should be taken into account. The United States is a good example, where The New Deal initiated in the 1930s contributed to, among other things, the construction of many hydropower plants. As a result, within 20 years, hydropower generation tripled, providing about 40 percent of the electricity in the United States. In the following years, rapid growth in nuclear, gas and coal-fired power plants saw the share of hydropower in the USA fall to ~ 6 percent. However, importantly, since the 1990s there has been a rapid increase in the number of damming structures being liquidated in the USA. According to O'Connor, J.E. *et al.* (2015), 147 dams were closed in the years 1986–1995, 298 dams in 1996–2005, and 548 ones in 2006–2014. The reason was the poor technical condition of many dams built before 1950. They require urgent repair, which in many cases is too expensive. Furthermore, many of them no longer fulfil their original function, and their negative environmental impacts have become unacceptable. A similar trend towards liquidating dams is seen in Europe (Moran, E.F. *et al.* 2018). In the European Union, much of the available hydropower potential was developed in the 20th century. As noted by Kougias, I. *et al.* (2019) Europe's aging hydropower plants will soon need refurbishing to extend their lifespan, resolve ownership and operational issues, and increase safety. These activities should focus mainly on electromechanical instrumentation and control systems.

Currently, new hydropower plants are mainly being built in developing countries, where environmental standards are much lower or entirely disregarded. These are very commonly huge projects that often repeat mistakes already identified in highly developed countries. This applies particularly to disrupting river ecology, deforestation, loss of water through evaporation, loss of terrestrial biodiversity, and the displacement of thousands of people (Stone, R. 2011; Fearnside, P.M. and Pueyo, S. 2012; Benchimol, M. and Peres, C.A. 2015; Moran, E.F. *et al.* 2018; Frolova, M. *et al.* 2019). In Europe, hydroelectric power plants are considered to have a negative impact on protected areas. Their interference in the natural environment is also one of the reasons for the failure of many river sections to be assessed as satisfactory according to Water Framework Directive indices (Lange, K. *et al.* 2018). Furthermore, according to recent studies, hydropower reservoirs annually emit methane, carbon dioxide and other greenhouse gases approximately equivalent to 1.07 Gtons of carbon dioxide (Harrison, J.A. *et al.* 2021; Mikulski, A. 2022). Particularly large amounts of greenhouse gases are generated by hydroelectric power plants located in tropical regions (Fearnside, P.M. 2005). Studies have confirmed that this negative phenomenon also applies to the reservoirs of hydropower plants in temperate climatic zones (Trojanowska, A. *et al.* 2009; Scherer, L. and Pfister, S. 2016; Miller, B.L. *et al.* 2017).

In the last few years, along with the EU's increasing promotion of the zero-emission policy and the adoption of the European Green Deal strategy, interest in small hydropower plants has increased in Poland. According to Renewable Energy Sources Transforming Our Regions (RESTOR) Hydro, an EU-funded project, there are over 8,000 potential locations for the construction of SHPs in Poland (Marszelewski, M. and Piasecki, A. 2022). According to another study prepared for the Minister of the Environment, nearly 13,500 damming structures have been identified in Poland that, for socio-economic reasons, can be used for energy purposes (Malicka, E. 2022). A great advantage of SHP is its location close to its energy consumers. This eliminates the energy losses to transmission, transformation and distribution that large power plants incur and that in Poland amount to more than ten percent (Igliński, B. 2019). Other positive aspects of the construction of SHPs are efficiency, safety and being based on a domestic energy source. Importantly, however, in many cases, SHPs are created in places that have already been transformed by man for the needs of watermills, sawmills, etc. (Radtke, G. *et al.* 2012). SHPs also negatively affect the natural ecosystem by disturbing existing hydrological and hydro-morphological processes. They can also significantly change and deplete flora along dammed sections of rivers (Jansson, R. 2002) and cause declines in invertebrate taxa (Growns, I.O. and Growns, J.E. 2001). However, it should be emphasised that the occurrence of any of these negative effects related to the construction and operation of an SHP is conditioned by local natural factors and technical solutions applied.

In March 2021, the document *Polish Energy Policy until 2040* was published. It sets out a framework for the energy transformation in Poland. It contains a strategy for selecting technologies for the construction of a low-emission energy system. The study clearly shows that, due to its low potential in Poland, hydropower will not play a significant role in the country's energy transformation. The document concludes that generation by hydropower plants in Poland will increase from 2.4 TWh in 2020 to 3.1 TWh in 2040 – an increase of just 0.7 TWh. The analogous increases for wind and solar generation are estimated at 31.7 and 12.8 TWh, respectively.

The age and technical condition of Poland's hydropower plants accord with the IEA's description of the world's hydropower plants. Most hydropower plants in Poland were built in the 1960s and 1970s. Inspections of structures that permanently dam water (and, thus, not only hydroelectric power plants) carried out in the years 2000–2009 showed that the condition of 17 structures was hazardous, and 82 structures were potentially hazardous. The main reasons, apart from the aging of the construction, were insufficient financial outlays for renovations, and the theft and vandalism of construction elements (Świderska, I. and Lebiecki, P. 2011). The rating for the largest run-of-river power plant in Poland, i.e., the Włocławek power plant, should be considered particularly disturbing. It has indicated that the Włocławek dam may pose a threat to safety (Świderska, I. and Lebiecki, P. 2011). This is mainly due to the Włocławek facility being operated in completely different hydraulic conditions than were originally assumed in its design. The dam in Włocławek was designed as part of the Lower Vistula Cascade of eight dams planned in the lower section of the Vistula. The plans were not implemented, and only one stage was built. This has had many unfavourable consequences – in particular, accelerated erosion of the riverbed causing rapid and excessive lowering of the bottom. As a result, the water level in the river was lowered over a more-than-30-km section downstream of the dam. The lowering of the bottom has already exceeded the projected values several times over (Bagiński, L. 2007). Inspections of the technical condition of dams in Poland in successive years have confirmed the poor condition of some of them.

According to a report by the Supreme Audit Office (2016), which covered only the most important damming structures in Poland (122 first- and second-class objects were assessed), the safety condition of 12 constructions was assessed as potentially dangerous and one as dangerous. The main reasons for the deteriorating technical condition of the constructions were: age (about 70% are more than 30 years old), design errors, faulty execution of works and delays in renovation and modernisation works (SAO, 2016). The last assessment of the technical condition of dams, covering 313 structures, was carried out in 2020–2021 and showed that the condition of 19 structures poses a threat to safety (Ministry of Infrastructure, 2022). With this in mind, one might be concerned that increasing the number of such facilities will further degrade the technical condition of the damming structures. One of the main reasons for this assessment is that the limited financial resources would have to be allocated to a larger number of facilities.

Pumped-storage power plants are the exception to these remarks concerning the development of hydropower in Poland. Such hydropower plants have the potential to significantly increase in importance in the Polish energy system. The main reason is related to the dynamic growth in other renewable energy sources in Poland – particularly of wind and photovoltaic energy. Wind and solar energy entail problems stemming from their heavy dependence on inherently unpredictable weather conditions. This variability means that they do not generate a reliably steady supply of energy. This is one of the biggest drawbacks of renewable energy. In Poland, despite the still relatively small amount of energy from renewable sources, there have been days on which energy production needed to be curtailed (mainly on wind farms). Therefore, installations that allow electricity to be stored temporarily are urgently required. Pumped-storage power plants are a very good such solution. It should be noted that their construction and operation also have a significant environmental impact, but one that is usually significantly lower than for run-of-river power plants. In Poland, the area with the most urgent need to build pumped-storage power plants is the north. In this area, the temporary overproduction of energy from renewable sources is most common. This is due to the area having the most favourable conditions for wind farms (onshore and offshore) but lower-than-average energy consumption (fewer large cities and energy-intensive industries).

Piasecki, A. and Krzywda, M. (2018) have indicated 37 potential locations for pumped-storage power plants in northern Poland. They also determined their storage potential at 62.8 GWh. Another interesting direction for the expansion of pumped-storage power plants is to exploit disused coal-mining pits. This solution helps limit interference with the environment, while also significantly reducing total project costs (those related to the purchase of land, the construction of a reservoir basin, etc.). There are open-pit lignite mines in central and south-western Poland. Of particular importance may be open-pit lignite mines exploited in central Poland, within the Wielkopolsko-Kujawskie Lake District *(Figure 3).*

In recent years, this area has seen a dynamic growth in wind and photovoltaic power plants. This fact should be assessed as very positive, given the insufficient level of electricity generation in this part of the country. In all voivodeships of western Poland (except West Pomeranian Voivodeship) there is an electricity generation deficit in excess of 20 percent (see *Figure 3*). The shortfall in energy must be sent from other parts of the country, resulting in losses to transmission networks. Nevertheless, the continued rapid growth in power plants generating energy from renewable sources in the area will, over time, create conditions for the construction of energy storage facilities. The use of disused mining pits for this purpose seems like the best solution. Especially if we also consider this area's difficult water relations. This is due to low precipitation totals (about 500 mm) and to evaporation that is both high and, in recent years, trending upwards (Piasecki, A. and Marszelewski, W. 2014). The construction of pumped-storage power plants will allow a large amount of water to be retained in this area and will somewhat stabilise the water table. At the same time, there will be a significant increase in evaporation from the water surface. However, the resulting water losses could be largely compensated by retaining the elevated amounts of precipitation that every few years occur in the area. This would require the introduction of appropriate solutions for the management of local water resources. This topic requires a detailed analysis and additional research that are beyond the scope of this study and will therefore be developed in a separate study. Therefore, in the publication below, this solution should be treated as a concept of sorts. Nevertheless, simulations and models of the operation of pumped-storage power plants in disused mining pits in Poland have confirmed the significant potential of this solution (Jurasz, J. *et al.* 2018; Oprychał, L. and Bąk, A. 2022).

Summarising the above considerations, it needs to be clearly recognised that significant growth in hydropower in the coming years is very unlikely in Poland (other than pumped storage power plants). The main reason is the low hydropower potential of Polish rivers. Social and environmental aspects are also extremely important. As indicated, the greatest hydropower potential in Poland is to be found in the Vistula river, particularly its lower section and the unfinished plan for the so-called Lower Vistula Cascades. However, any serious attempt to implement the abandoned plans would be met with numerous protests from local communities and pro-ecological circles, as has been the case in other countries (Operacz, A. 2017). This is especially so given that the area that would be flooded is currently covered by various forms of nature protection, e.g. reserves, Natura 2000 areas (bird areas, habitat areas), landscape parks and ecological land uses. There is a much better chance of measures aimed at building new SHPs being implemented. It should be emphasised that, even if all the locations indicated in the aforementioned studies were developed, this would allow for only a relatively small increase in the amount of energy generated – estimates say about 5 TWh (Gajda, P. 2022).

Discussion

Compared to other countries in Europe and the world, Poland has a relatively low hydropower potential (Kjaerland, F. 2007; Berkun, M. 2010; Cyr, J.F. *et al.* 2011; Pereira, M.G. *et al.* 2012; Kowalczyk, K. and Cieśliński, R. 2018). The main reason for this is the country's natural conditions, which, as already mentioned, largely determine the technical and economic possibilities. According to the *Hydropower-Europe Report* (2022) (implemented as part of the European Union's Horizon

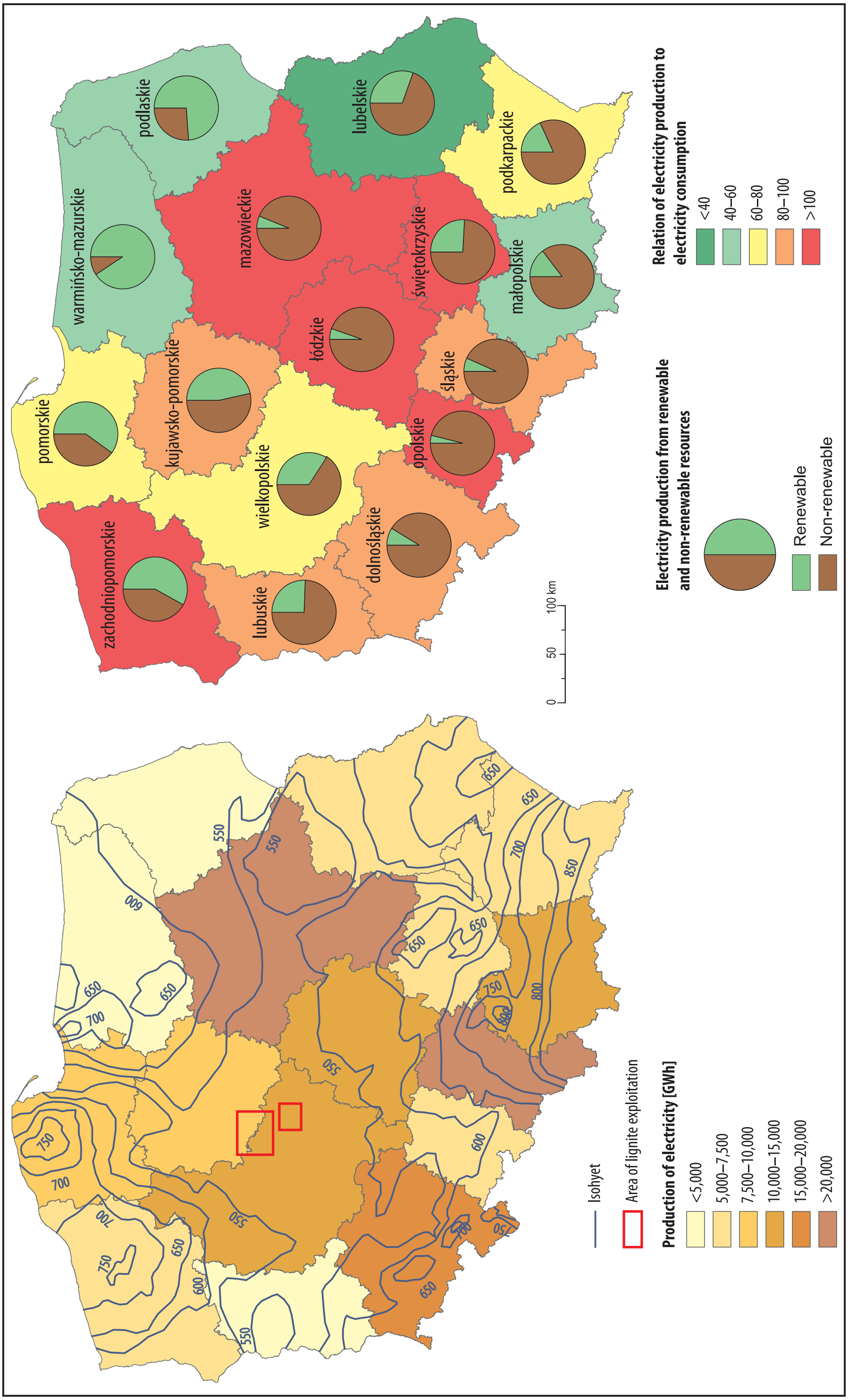

Fig. 3. Selected electricity production data for Poland by voivodeship against the background of precipitation conditions and lignite mining locations

2020), Poland is only 24th in Europe in terms of hydropower potential and 25th in terms of the amount of energy generated from hydroelectric power plants. At the same time, many authors point out that only 20 percent of the technical potential of Poland's hydropower industry is currently being used (Baczyński, D. and Kosiński, K. 2018; Kasperek, R. 2020; Piwowar, A. and Dzikuć, M. 2022). As already shown, no dramatic increase in the use of hydropower potential should be expected in the coming years in Poland. Poland is not alone in this regard; this conclusion can be generalised to all EU countries.

The implementation of the *Water Framework Directive* 2000/60/EC (WFD) and the *Habitats Directives* 92/43/EEC26 and 2009/147/EC have significantly limited the possibility of building new hydroelectric plants in the EU. Many countries that planned to develop hydropower as part of the energy transformation had to change their plans. One example is Slovakia, where more than a decade ago there were plans to build several large hydroelectric power plants. Similarly, Hungary decided to limit the development of hydropower to SHPs, and, thus, uses 5 to 6 percent of its potential (Steller, J. and Malicka, E. 2020). Moreover, attention should be paid to the increasingly frequent demolition of hydropower facilities in Europe. This applies especially to small plants, about 5,000 of which have been removed in the last 25 years (Wagner, B. *et al.* 2019). The international initiative "Dam Removal Europe" (DRE, 2023) is very important in this respect. In 2022 alone, it contributed to the removal of 325 dams on rivers in 16 countries in Europe. However, it should be emphasised that even building SHPs at all possible locations (as indicated, for example, in the RESTOR Hydro programme) would not significantly affect the structure of electricity production in Poland and other EU countries. The amount of energy that new SHPs could generate is decidedly too small, as the example of Poland shows.

Currently, in Poland (and most EU countries), the only significant and realistic potential in the field of hydropower lies in pumped-storage power plants. One of the consequences of the energy transformation underway in Poland and other EU countries is temporary difficulties in balancing the demand and supply sides of the electricity market. The reason is that the most frequently used renewable energy sources – wind and solar – are dependent on weather conditions, which are inherently unstable (Gøtske, E.K. and Victoria, M. 2021). This reality necessitates the temporary storage of generated electricity. The promotion of solutions based on energy storage in the form of batteries and accumulators in the public debate is controversial. Pumped-storage power plants, even small ones, can store much more energy than currently available battery storage facilities. As already mentioned, the construction of pumped-storage power plants involves interfering with the natural environment. However, it should be noted that the production and disposal of batteries used for energy storage also have negative environmental consequences (Mrozik, W. *et al.* 2021).

Many of the mineral raw materials used to produce batteries come from underdeveloped countries, where generally low environmental protection standards apply. In the case of building pumped-storage power plants in EU countries, the legal regulations minimise negative environmental consequences. Moreover, some of these negative consequences can be reduced by using existing facilities. One such solution involves the use of lignite mines in Poland, a discussed in the previous chapter. In addition to the capacity to temporarily store energy, pumped storage also increases local water resources. Another solution exploits the large height differences provided by some mixed-use blocks in cities. In the work of Jurasz, J. *et al.* (2022), it was demonstrated on the example of the city of Toruń (Poland) how to effectively use tall buildings in the city to build an energy storage facility operating on a principle similar to that of pumped-storage power plants.

The construction and operation of run-of-river hydroelectric power plants involve significant interference in the natural environment, as discussed in detail in earlier chapters. Most rivers in the EU are covered by various forms of nature protection, which further complicates the possibility of implementing hydropower projects. In this context, we provide the example of the Vistula river and the unfinished cascade of dams on its lower section. However, similar examples of unimplemented or only partially completed investments can also be found in Hungary, Slovakia, Romania and Serbia (Nakamichi, M. 1997; Szabó, M. and Kiss, Á. 2014; Năstase, G. *et al.* 2017). It should be noted that modern technological solutions can minimise some of the negative consequences of the operation of the type of hydropower plants that we have discussed here. A good example is the use of solutions that ensure free passage for fish and free flow of sediments. This also applies to the use of the latest technological solutions, including damless hydrokinetic energy conversion systems (Wagner, B. *et al*. 2019). The use of these solutions usually significantly increases investment costs, so they are not always profitable. Therefore, investments in hydroelectric power plants usually require additional financial support from state institutions. In the case of EU countries, financial support is mainly dedicated to SHP. For example, in Poland, the "Energy for the countryside" programme came in operation in 2023, providing beneficiaries with funding for investments in hydropower with a capacity of no more than 1 MW. In the case of large run-of-river power plants, co-financing is provided for projects related to modernisation and improved efficiency of operation.

In recent years, the energy transformation process has become more dynamic in EU countries. This was largely due to external factors. This applies especially to the war in Ukraine and the limitation or cessation of imports of Russian raw materials for energy generation. In early 2023, EU lawmakers reached a provisional agreement on the *Renewable Energy Directive* (*RED III*) (European Council, 2023). The goal of *RED III* is to increase the share of renewable energy in total energy consumption in the EU to 42.5 percent by 2030. The current structure of electricity production in individual EU countries is highly diversified. With some exceptions (Romania, Croatia, Lithuania and Latvia), the largest share of renewable energy in the energy production structure (above 35%) is recorded in the so-called old union (Eurostat, 2023). Only in Belgium and France is the percentage of energy from renewable sources lower (27 and 25%, respectively), due to the very high share of nuclear energy (above 45%). In Poland, the share of renewable energy in the electricity production structure is 22 percent.

The legal regulations contained in *RED III* are intended to help achieve the ambitious EU goals for energy from renewable sources. They will provide member countries the opportunity to designate renewable energy acceleration areas in which renewable energy projects will be subject to a simplified and expedited permit process. If hydropower were included among these acceleration areas, it would be possible to implement many investments related to hydropower (European Council, 2023). It should be noted, however, that already at the beginning of 2023, several hundred NGOs operating within Living Rivers Europe asked the EU authorities to at least exclude hydropower from "target areas" and apply strict sustainability criteria to it. Since appeals by environmental organisations are often acted upon by the EU, it is difficult to assume that hydropower will ultimately be included as target areas for renewable energy acceleration.

Conclusions

The analysis of the state of hydropower in Poland indicates that it requires urgent intervention in many areas. This applies particularly to issues of the control, modernisation and technical condition of hydropower plants and damming facilities. The potential for the development of hydropower in Poland is assessed to be very small. Environmental, socio-economic and legal conditions are unfavourable to the construction of new, large hydropower plants. The exception is pumped-storage power plants, which, acting as energy storage facilities, should in the future constitute an important element of the Polish energy system. The possible development of small hydropower plants is also indicated, provided that appropriate incentives and financial assistance, as well as favourable legal conditions, are provided.

Poland faces challenges related to the country's energy transformation towards renewable energy sources. According to the assumptions of *RED III*, in less than a decade the country should double the share of green energy in the total production structure. Wind and solar energy will probably play the largest part in Poland's energy transformation. However, due to their specificity, both of these energy sources require the creation of local energy-storage facilities. Thus, the European Green Deal may contribute indirectly to the significant development of hydropower in Poland. Currently, it is impossible to provide an unambiguous answer to the titular question of this study, because it depends largely on state policy. Nevertheless, the European Green Deal is a great opportunity for the development of hydropower (in the field of electricity storage) in Poland, which would be worth taking advantage of for many reasons indicated in the article.

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