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REVIEW ARTICLE

Hydro energy in Poland: the history, current state, potential, SWOT analysis, environmental aspects

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Abstract
The history of hydro energy in Poland was shown in the article. The first mills were built in the ninth century and the first hydro energy plant was opened in 1896. In 1935, there were 8000 water energy plants and dozen other installations using water energy. War action and nationalisation have caused the crash of hydro energy in Poland. At the moment, there are 761 water energy plants amounting to 994 MW. The Lower Vistula Cascade was described but also use of water for energy purposes in heat plants and waste treatment plants. Technical potential of hydro energy is major. Using already exciting heaps (there are 16,005), it is possible to obtain 14.27 PJ. SWOT analysis has shown that hydro energy in Poland is a well-mastered technology and allows small water retention. Investing in hydro energy in Poland requires a lot of documents. In addition, energetic law is constantly changing. Influence of hydro energy on environment was presented. It was concluded that small hydro energy development is definitely advised in Poland. Small hydro energy stations allow to produce energy and allow small retention in steppe Poland.

Keywords Small hydropower plant · Technical potential · Water energy · Water mill

Introduction

Life on earth is possible thanks to water. Energy can be also obtained from it. It can be renewable energy source, is cheaper than conventional sources, and it does not cause climate change. Big water stations require dam building, interfering water flow in the river, and changing fish migration, and cause many different damages to the environment (Singh and Singal 2017; Lu et al. 2018). Small hydro stations have much lower impact on environment. In recent years, big technological development in SHP (small hydropower plants) sector has been observed. Moreover, nowadays attitude to water energy production is changing; it aims at minimising influence on environment, even at cost of income. Small hydro plants cause water retention in environment (Blok and Tomaszewska 2015; RESTOR HYDRO 2015; Chen et al. 2018).

The aim of work was to present the history, current state, technical potential, SWOT analysis and environmental aspects of hydro energy in Poland. The work is also the last part of my articles describing renewable energy in Poland: bioenergy (Igliński et al. 2011), geoenergy (Igliński et al. 2012), helioenergy (Igliński et al. 2016a) and aeroenergy (Igliński et al. 2016b).

The history of hydro energy in Poland was shown in the article. The first mills were built in the ninth century and the first hydro energy plant was opened in 1896. In 1935, there were 8000 water energy plants and dozen other installations using water energy. War action and nationalisation have caused the crash of hydro energy in Poland. At the moment, there are 761 water energy plants amounting to 994 MW. The Lower Vistula Cascade was described but also use of water for energy purposes in heat plants and waste treatment plants. Technical potential of hydro energy is major. Using already exciting heaps (there are 16,005), it is possible to obtain 14.27 PJ. SWOT analysis has shown that hydro energy in Poland is a well-mastered technology and allows small water retention. Investing in hydro energy in Poland requires a lot of documents. In addition, energetic law is constantly changing. Influence of hydro energy on environment was presented. It was concluded that small hydro energy development is definitely advised in Poland.

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Hydro energy: literature overview

Hydropower plants, large and small, have remained by far the most important of the "renewable energy" for electrical power production worldwide, providing 19% of the planet's electricity. Small-scale hydro is in most cases "run-of-river", with no dam or water storage. It is also considered one of the most cost-effective and environmentally benign energy technologies to be considered for rural electrification in less developed countries (Pang et al. 2015; Sachdev et al. 2015). Below there is a short description of water energy sector (mainly small hydropower) in selected countries.

The first hydropower plant was successfully built in France around 1880 (Pang et al. 2015) and this is the reason why the history of hydropower is linked to this country. Water energy is the second source of electric power generation in France. The total of small hydropower stations were 1825 in 2007 and 1935 for year 2010. France is one of the largest producers of hydroelectric power in Europe in terms of SHP and refers to generating 6820 GWh in 2010 (Larinier 2008; Pang et al. 2015). Taking example from France, Poland should also use SHP fully.

Similarly to Poland, in Colombia small hydro power plants have been used for more than 100 years. Now it is 784.44 MW of capacity (Gómez-Navarro and Ribó-Pérez 2018). Potential of 25 GW was calculated in Colombia. The negative environmental influences associated with the use of large water energy plants have helped to focus the attention on small-scale plants, which reduce these impacts significantly. Both small- and large-scale hydropower projects, which have been exploited mainly in large plants (Morales et al. 2016), will be implemented in Colombia.

In 2001, the number of small hydropower plants in Brazil was 303 with installed capacity of 855 MW (Ferreira et al. 2016). In 2010 the number of installations has reached 387, with an installed capacity of 3428 MW. Today, there are 475 SHPs working with the capacity in the country, around 4799 MW, representing 3.5% of all Brazilian energy matrix. In 2020, the installed capacity will be about 6500 MW, but there is more potential available in the country for SHPs that has great environmental and technical characteristics. It is important that more focus is given by the government policies of the electricity sector to reach the full potential of SHPs available in Brazil in the future (Ferreira et al. 2016). Similarly as in Brazil Polish law concerning hydro energy should be investor friendly. Today, investors in Poland have to fill in a lot of documents and get many permissions to start a hydro station.

Prabil and Mohapatra (1998) concluded that of the renewable energy sources, SHP is the most attractive, mature and reliable energy source for India. The SHP potential of 15,000 MW is available in irrigation dams, canal falls, run-of-the rivers and natural streams in the hilly regions of India. Less than 6% of this potential, i.e., about 900 MW, has been tapped so far. Also in Poland SHP seems to be the most attractive, mature and reliable energy source. Poland has over 16,000 heaps where SHP can be placed.

Wang (2008) gave explanation of the functioning of a small hydro-power system using outlet-water energy of a Southern Taiwan reservoir. The capacity of this SHP system is 8.75 MW and the generated power is delivered to the 69-kV system. This document presents some details of the finished SHP system including electricity prices, engineering, revenue of power generation, capital cost, etc. Cleansed water in treatment plants and electricity production should also be managed in Poland.

Gupta et al. (2007) presented the availability of hydropower potential, operation and control system for small hydropower plants. SHP is one of the best options to meet increasing energy demand specifically in countries such as Sri Lanka and India where a huge power potential is available. It is renewable and clean energy in contrast to fossil fuel-based generations which generate pollution in the environment and also their resources are running out at a fast pace. As Sri Lanka and India, Poland also produces energy from coal and contaminates environment. In autumn and winter seasons in many cities in Poland, there is smog. Development of water energy in Poland would allow not only environment contamination but also achieve Union production aim 15% RES in 2020.

The overall amount of power plants in Portugal rose slightly in 2007–2011: the total of SHPs was 137 in 2007 and 157 for year 2011 (Mazano-Agugliaro et al. 2017). The gross installed capacity expanded slightly in the same period, the maximum gross installed capacity was 453 MW in 2011. What is more, the maximum gross electricity generation equaled 1605 in 2010.

The research (Yah et al. 2017) pointed that the estimated small hydropower resource in Malaysia is 500 MW. Only 17.5% from it has been registered. It means Malaysia has huge small hydropower potential. In Poland water stations are registered. Similarly as in Malaysia, Poland has high potential of SHP.

Hydropower is historically the most important electric source in Sweden; that is why hydro power takes almost half of producing energy. The number of SHP in Sweden increased a little bit through the period 2007–2011, so the total number of SHPs was 1813 in 2007 and 1867 in 2011 (Mazano-Agugliaro et al. 2017).

Norwegian Water Resources and Energy in 1992 made a study on the annual energy potential from upgrading and refreshing hydropower plants, with an installed capacity less than 1000 kW (Mazano-Agugliaro et al. 2017). The study showed that about 400 GWh might be harnessed by improving old schemes, and about 300 GWh could be produced in new plants. In Norway, the main increase in number of new hydro power plants was after World War II and the middle part of the 1980s. Nowadays, there are 565 hydropower plants working with an installed capacity of more than 1 MW, and it means annual production of about 118 TWh. The total capacity is approximately 28,000 MW. The number of SHPs is about 44% (IEA Hydropower 2018). The number of existing micro- and mini-hydropower plants was thought to be 300, with an annual production of about 300 GWh (Mazano-Agugliaro et al. 2017). Comparing Poland and Norway, it is worth mentioning that in 1980s there were only 200 SHP in Poland. Since then, this number has been increasing. Now there are 746 SHP what make 98% of all hydro energy stations in Poland.

The number of employees in small hydropower is a challenge because certain activities of the supply chain are shared with large hydropower plants and significant share of the jobs is informal (IRENA 2017). China accounts for half of the estimated jobs in small hydropower, followed by Brazil, India and Germany. Large hydropower gave jobs to more than 1.3 million people, with the majority in maintenance and operation segment of the value chain.

Now in Poland, the water energy resources are utilised in only 12%. In comparison, Germany uses them in 80%, Norway—84%, and France—almost 100% (Mazano-Agugliaro et al. 2017). Poland has big potential for hydro energy development in the future.

History of water energy sector in Poland

Milling was a trade essential to the functioning of an old village in Poland. It was mainly linked to the staple nature of flour and cereal products in the diet of the local community.

According to Gloger (1902), water mills started to become widespread in Poland as early as in the 9th century whilst according to Baranowski (1977) they appeared in the 12th century. According to the research carried out by Buczek (1969) and Dembińska (1973), the latter of whom assessed reliability of the dates of construction and location of the oldest water mills, the first water mill to be constructed was the one in Zgorzelec (Fig. 1), mentioned in an original document from 1071. Moreover, the same author confirmed that water mills operated in 1204 in the locality of Dobra in Silesia and in 1207 in Brzeźnica in Mazowsze region. The monastic rule of the Cistercian monastery established in 1228 in Mogiła near Kraków says among others that a monastery was to be built in such a way as to include onsite water, mills, garden, bakery and numerous trades (Malepszak 1995). In 1244, Prince Bolesław Wstydliwy granted prerogative for mills in Podolinec (now Slovakia) and four mills in Sandomierz i Zator (Fig. 1) (Małyszczycki 1890).

Fig. 1 Localization of first water mills in Poland (current borders)

On the Polish land, there was only *The Book of Henryków* written in Latin in 1270–1310 that contained the first sentence written in Old Polish. The chronicler of the book noted that Boguchwał, married to a local peasant from Silesia, said to her: "*day ut ia pobrusa a ti poziwai*" (Old Polish), which means "let me to the grinding and you have some rest" (Grodecki 2004).

The energy of water was initially used in monastery households. It is impossible to overestimate the contribution of the Cistercians to the civilisation of Europe, including the introduction of technical novelties such as the mill wheel. They introduced mills to Wielkopolska, Kujawy, and Małopolska regions as well as Ziemia Dobrzyńska (*Dobrzyń Land*) (The Cistercian Route, Fig. 2) (Kanior 2002; Kubicki 2013; The Cistercian Route 2018). The Cistercian forges harnessed water power to move bellows and trip hammers. The monastic rule of the Cistercian monastery in Mogiła stipulated that a monastery was to be built in such a way as to include onsite water, mills, a garden, a bakery and numerous trades. The Cistercians are mentioned in connection to water mills in the western Wielkopolska region, where the Cistercian Order was brought to Obra from its primary monastery in Łękno near Wągrowiec (Kanior 2002; Kubicki 2013; The Cistercian Route 2018).

According to Dembińska (1973) there were 485 water mills operating in Poland in the 13th century: 120 in Pomorze Gdańskie region, 119 in Wielkopolska region, 116

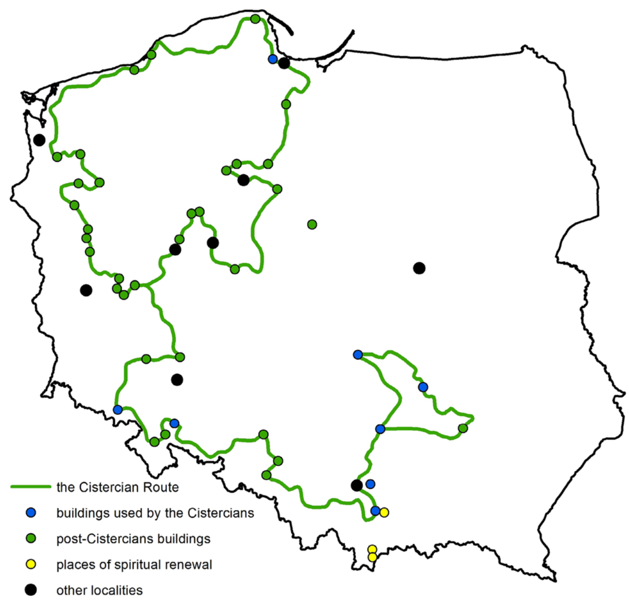

Fig. 2 The Cistercian route within the current borders of Poland

Fig. 3 The water mill in the Ethnographic Museum in Toruń (photography: B. Igliński)

in Silesia, 102 in Małopolska region, and 28 in Mazowsze and Kujawy regions.

In the Middle Ages and Early Modern Period, great attention was paid to the water management (Związek 2014). Therefore, the issue of appropriate regulation of river navigability was raised during the Jagiellonian parliamentary sessions in 1447, 1496 and 1511. The main rivers of the Kingdom included: Vistula, Dniepr, Dniestr, Styr, Narew, Warta, Dunajec, Wisłoka, Bug, Wieprz, San, Nida, Prosna and Noteć at that time among others. These watercourses were of particular importance in terms of transport. The construction of water mills could seriously threaten their navigability, and in the longer term, impede all transport. As a result, most of the water mills were located on small but numerous streams and specially made small water courses linked to bigger rivers and used to power the mill wheel (Związek 2014).

Water mills could most simply be classified as either used for food purposes (grinding grain, production of porridge and malt) or industrial purposes (fulling of cloth, bog iron treatment etc.). In the sixteenth century, there were 3000 different water wheels operating in Poland. Harnessing of water and wind power led to the "first" industrial revolution in the country (Balińska and Balińska 2003; Adamczewski 2005). The next boom in the milling industry (both water and wind mills) occurred in the nineteenth century and at the beginning of the twentieth century. In 1924, there were 6287 water mills in use (Michałowski and Plutecki 1975; Skuza 2006; Podgórski 2009).

At the turn of the nineteenth century, water turbines started to be introduced onto the Polish territory, which led to further changes in the mills' equipment. The traditional transmission belt mechanism (the drive mechanism) was replaced with a new metal one. This had different gears, crown wheels and pulleys placed and attached to it, which by means of transmission belt moved the mill machinery (Świtała 1989).

The significance of water mills in Poland's culture

Harnessing renewable energy by means of water mills is inseparably linked to the history and culture of Poland. Numerous stories, poems and songs about mills and millers pay tribute to the important role of water mills in the Polish culture. Over a dozen of localities in Poland have a mill wheel in their coat-of-arms. For example, the coat-of-arms of Piechowice has a light blue emblem. The coat-of-arms of Piechowice (Dolnośląskie Voivodeship) shows a mill wheel of wood colour, with eight rectangular scoops on its perimeter. Above the wheel, a troth of the same colour can be seen, from which a blue stream of water flows into the waves of blue water. The whole coat-of-arms is placed on a light blue background (Coat of Piechowice 2018; Information about Piechowice 2018).

Water mills are of interest also from an architectural perspective. They often have a balanced silhouette and proportional construction of all their parts, the appropriate ratio of the edge beam's height to the roof's height as well as preserved walls of darkened natural wood (Fig. 3).

The work of a water miller in Poland, although well-paid, was very hard. The winter period was the most difficult

(Janicka-Krzywda 1987; Święch 2005). During that time a miller had to work in terribly cold conditions and the water wheel had to be thoroughly cleared of ice. When the thaw weather came, floating ice would accumulate near the wheel and had to be cleared. Debris such as twigs, roots and leaves caused a problem when they accumulated on a grid in the working canals or at the water wheel itself, virtually blocking any rotations of the wheel. It was then necessary to seek assistance from a family member who would clear the area from the floating debris. A mill, like a forge, was a centre of social life in the neighbourhood. It was there, whilst waiting for the grain to be ground, that politics was discussed, trade agreements were made and news was exchanged (Janicka-Krzywda 1987; Święch 2005).

Nowadays, water mills can be most often found in open-air museums; they are used for education and tourism purposes (Jackowski 1971). For example, there is the Museum of Milling and Water Equipment of Rural Industry in Jaracz (Wielkopolska region), which is one of the few branches of the National Museum of Agriculture and Agricultural-and-Food Industry in Szreniawa. The water mill building was constructed around 1871 and was in operation until 1976. In 1989, a permanent exhibition "The Industrial Technology in Milling" was organised there. The exhibition includes the machinery and equipment mainly from the 1920s as well as millstones, a flour mixer, grain hullers, feed hoppers, sifters, and a groover for mill rollers. There are also models of water mills from different development stages of the grinding technology (Jackowski 1971).

The boom and decline of milling and small hydropower sector in Poland

In the 1880s within the Polish territory, especially in Galicia (*part of modern Poland and Ukraine land that was under Austrian partition*), the Haag turbine, which had a similar construction to the Francis turbine, was on offer. A particular feature of this type of turbines was that they required the water flow of 70 dm^3/s to function correctly. The rotations were regulated by the turbine having a double rotor with two inlets. When the water level was lower, then only the bottom part of the rotor could work. The water turbines introduced in the nineteenth century are sometimes still used nowadays, for example, as reserve energy sources (Mrugalski 2008).

In the post-war years in Poland, it was recommended, and sometimes even compulsory, to abandon water turbine energy for the electric engines. Currently, there is a trend to return to using them as so-called small hydropower generation, which is not harmful to the environment (Jackowski 1971). In 1896, the first hydropower plant was "officially" open in Poland—Struga on the Słupia river (Pomorskie Voivodeship). In 1898 in the Austrian partition, a hydropower plant of power 45 kW was opened in Nowy Targ. In 1901 as a result of Stanisław Niementowski's proposal, the issue of harnessing water energy was first raised at the Sejm of Galicia. In their report of 4th of July 1901, the Water Committee proposed the construction of hydropower plants on the rivers managed by the state (Świtała 1989).

In total, 130, seemingly most favourable locations were selected for the construction of hydropower plants of combined power 520 MW; studies were carried out and even general designs were partly prepared. Among the most interesting facilities included in the plans were Porąbka, Rożnów, Myczkowce and Solina (southeastern Poland) of power 30 MW. In 1936, a pumped-storage hydropower plant of power 95 MW was opened in Dychów on the Bóbr river (southwestern Poland) (Kozicki 2001).

During the interwar period, there was an increase in the importance of the hydropower sector in the economy of the Second Polish Republic (Michałowski and Plutecki 1975). In 1935, there were over 8000 small hydropower plants and over a dozen thousand other facilities harnessing the power of water. Moreover, in the interwar period there was a growth in the domestic production of milling machinery, which enjoyed great demand both in Poland and abroad (Świtała 1989).

The first blow to the Polish milling industry was delivered by World War II; many mills were burnt down and millers were either killed or taken away to forced labour (Świtała 1989). The second blow came from the communist government after World War II. According to the Manifesto of the Polish Committee of National Liberation from 22nd of July 1944, all the industrial works (including mills) had to be under the state management. This led to gradual destruction of private mills and hydropower plants, and at the same time it fostered the development of "the central" coal-based power sector under the communist government's management. Only very small mills and hydropower plants, especially those directly linked to houses, remained in private hands. Unfortunately, the owners were troubled by unfair and excessive taxes, audits and penalties until they quit their activity (Świtała 1989).

The destruction of hydropower facilities resulted in increased unemployment and reduced tax income for communes. Moreover, 25,000 water facilities ensured small retention, increasing water resources and at the same time prevented flooding during heavy rainfall (Świtała 1989). Other factors that contributed to the water deprivation of Poland included: deforestation, badly organised land irrigation and drainage, and excessive water usage by mining and the coal power sector. The results of these inconsiderate actions became quickly evident—the whole Poland was plagued by long periods of drought, hampering the agricultural output and bringing the threat of coal power plants' blackout (the lack of water for cooling). Thus, in 1982 the

Prime Minister, General Wojciech Jaruzelski, issued a permit for private persons to open small hydropower plants (Świtała 1989). Since then there has been development of not only commercial hydropower industry but also small hydropower generation.

The current state of the hydropower sector in Poland

The power of the equipment generating electric energy using water turbines in Poland reaches currently 994 MW (611 MW excluding pump-storage objects) in 761 hydropower plants (The Energy Regulatory Authority 2018), of which 746 facilities are small hydropower plants. The following voivodeship regions have the highest power in the hydroenergy sector: The Kujawsko-Pomorskie Voivodeship, The Dolnośląskie Voivodeship and The Małopolskie Voivodeship. The largest power plant in Poland is the power plant (dam on the Vistula River) Włocławek (Fig. 4).

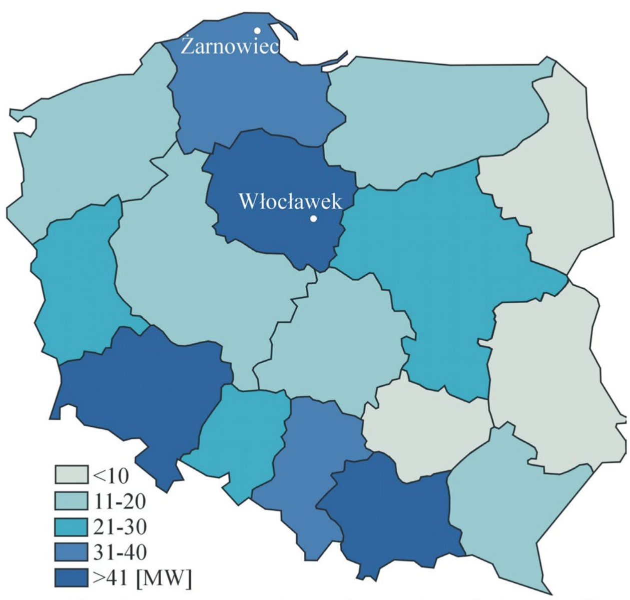

Fig. 4 The power of hydropower plants in Poland (excluding pump-storage objects)

The Lower Vistula Cascade

Work on "Assumptions of the Perspective plan of Water Management in Poland" was started by the Water Management Committee in 1952. The plan included, among others, the construction of navigational and energy dams on the whole length of the Vistula river, which was considered as the waterway linking Silesia with the Baltic Sea. It was especially important to use major energy potential of the lower Vistula river in that concept (Gronek and Ankiersztejn 2012).

In the years 1956–1957, the idea of constructing the cascade of dams with hydroelectric power stations on the section of the Vistula river from the mouth of the Narew river to Tczew was improved in CBS and PBW Hydroprojekt in cooperation with the Polish Academy of Sciences (Table 1) (Gronek and Ankiersztejn 2012). The Lower Vistula Cascade was to be a coherent system of nine low head dams with flow reservoirs dammed to the level of average annual flow in the lower position of the preceding dam. It was crucial to obtain relevant water depth below the dams and to prevent bottom erosion and river bed devastation. The planned Lower Vistula Cascade was joined by Warsaw-North located above the mouth of the Narew river, which was to be a natural upper limitation of development of the lower Vistula river, and which was to be constructed simultaneously with the cascade. Table 1 contains the description of dams with the compilation of installed power and electricity generation (Gronek and Ankiersztejn 2012).

The dam in Włocławek consists of the following parts: the front earth dam, coated steel gated weir, a power plant and a navigation lock of dimensions 12 × 115 m,

Table 1 The dams of the Lower Vistula Cascade according to the concept from 1957 (Gronek and Ankiersztejn 2012)

No	Name of dam	River stretch (km)	River gradient (m)	Average flow (m^3/s)	Power (MW)	Average electricity generation (GWh/year)
1	North Warsaw	539.5	9.0	557	70	280
2	Wyszogród	585.5	8.0	860	90	410
3	Płock	618.0	6.7	922	85	350
4	Włocławek	674.8	11.3	930	160	640
5	Ciechocinek	713.0	8.5	948	100	460
6	Solec Kujawski	759.0	7.5	980	95	410
7	Chełmno	808.0	8.0	1005	100	516
8	Nowe	868.0	9.5	1019	100	516
9	Tczew	903.5	8.5	1030	90	440

designed to have a flow capacity of 6 million tons per year, as well as a fish ladder located in the pier separating the weir and the power plant. Six Kaplan hydro turbines of installed power 160.2 MW operate in the hydroenergy plant (Gronek and Ankiersztejn 2012).

The pump-storage power plant in Żarnowiec

In Poland, there are six pump-storage hydropower plants, of which the largest one is the hydropower plant Żarnowiec of power 716 MW. The location for the construction of the pump-storage hydropower plant Żarnowiec at the Żarnowieckie Lake was due to favourable topographic conditions. A vast tunnel valley located between two hills of Pleistocene moraine upland met all the conditions to install a pump-storage power plant there. Additionally, in the vicinity the nuclear power plant Żarnowiec was supposed to be built. Thus, the hydropower plant would function as an energy "accumulator." The power plant Żarnowiec is equipped with four reversible, diagonally positioned hydro turbines with a wide range of power for regulation purposes of value 1516 MW:800 MW absorbed from the system and 716 MW of generated power (Tokarz and Hryckiewicz 2003).

Individual turbine systems operate in a block, creating four independent process lines and power outlets, with autonomous control for each block. The individual work of these turbines establishes the global character of the power plant's operation determining its regulation and intervention functions in the National Grid System. These functions include:

- Balancing the daily load curve,
- Covering sudden losses and peaks in power consumption that occur in the system,
- Optimising the operation of the national grid system by quick and continuous regulation of active power supplied to the system,
- Regulating reactive power flow in the system (Tokarz and Hryckiewicz 2003).

The top reservoir of the power plant is totally man-made body of water, constructed on a plateaux, and one of the highest located around the Żarnowieckie Lake. With the total area of 135 ha and storage volume of 13.8 million m^3 of water, the reservoir acts as an electric power accumulator in the amount of 3600 MWh. This amount of water is enough to supply the maximum power to the power grid system for about 5.5 h. To be refilled with water, the top reservoir requires four hydro turbines to operate in a pumping mode for about 6.5 h (Tokarz and Hryckiewicz 2003). Daily variations in the water level in the top reservoir are 16 m.

A new direction of hydropower generation in Poland

The energy from waste utility water could be harnessed by a set of hydropower plants installed on route of water transported in or out (Orlewski and Siwek 2010). Hydropower plants of this type are categorised as run-of-the-river small hydropower plants. The best opportunities to get rid of utility water occur in the power generation sector in the cooling systems of traditional fuel or nuclear fuel thermal power plants. The utility water from the industrial processes is the energy carrier. It is considered to be a renewable energy source and is free. The continuity of the flow of utility water does not depend on weather conditions and thus the flow can be virtually assumed to be constant. As the already existing part of the hydrotechnical structure of the cooling system is used, the cost of installing a hydropower plant is considerably lower. Generation of electric energy from utility water is environmentally clean and improves the quality of water returned to the environment (cooling and oxygenation of water as a result of it flowing through a turbine) (Orlewski and Siwek 2010).

The small hydropower plant Skawina II

The installed power of the plant Skawina II (Małopolskie Voivodeship) amounts to 1.6 MW. Water can be dropped via the barrage with a hydro-generator or directly to the river, by-passing the hydropower plant. The amount of water fed to the plant depends on the level of cooling of condensers, which in turn depends on the amount of electric energy produced by a condensing power plant and a season of the year. The available water flow capacity for a hydropower plant is 23.3 m^3/s during the summer season whilst in winter it amounts to 17.8 m^3/s. The minimum flow, 10 m^3/s, can occur over 10–15 days per year. The highest temperature of dropped water is +35 °C during summer. Another interesting characteristic of the small hydropower plant Skawina II is that it has been working with a high number of hours per year without any interruptions, not having any changes to equipment or large significant renovation works, since 1960 (The small hydropower plant Kraków 2018).

The small hydropower plant Toruń

The design to construct a small hydropower plant installation at a sewage treatment plant in Toruń (Kujawsko-Pomorskie Voivodeship) (Francis turbine, Fig. 5) is a pioneering solution aimed at energy recovery (Igliński et al. 2017).

The system of turbines has a fully automatic control system, which implements automated operation and process control in the small hydropower plant, including:

- Automatic positioning of turning vanes,

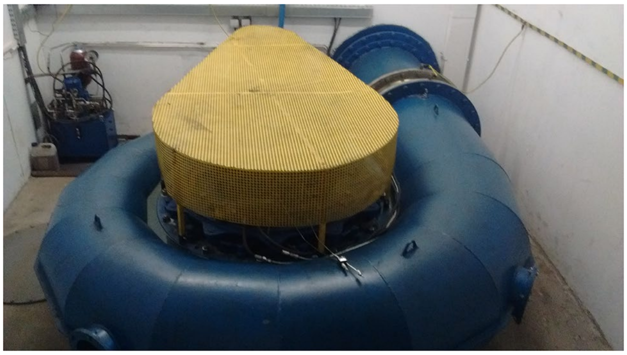

Fig. 5 "The heart" of the hydro system with a Francis turbine in Toruń (photography: B. Igliński)

- Maintaining top water at a constant level,
- Control of the top and bottom water level,
- Automatic switching on and off of the turbine when there is no voltage,
- Servicing and viewing the turbine's parameters on-line.

This innovative approach will improve the economic, environmental and financial outlook of the company, and will make it stand out against other companies of this type all over the world (Igliński et al. 2017).

Technical potential of water energy in Poland

Calculations of the technical potential of hydropower in Poland using GIS method, existing damming facilities have been carried out. According to the National Water Management Authority, the number of damming facilities in Poland is 16,005. Data on damming objects in Poland were obtained from National Water Management Board: location, damming height, flow, type of damming. Assuming efficiency of hydropower plant at the level of 85%, a formula was obtained:

$$P = 8.34 \cdot \Theta \cdot H, \tag{1}$$

where P capacity (MW), Θ volume of water stream flowing through the turbine within 1 s (m^3/s), H is damming height (m).

Technical potential was set on 25% level of theoretical potential. The highest potential is characteristic for the following voivodeships: Kujawsko-Pomorskie Voivodeship (2729 TJ), Dolnośląskie Voivodeship (2308 TJ) and Małopolskie Voivodeship (2141 TJ) (Fig. 6). The total energy potential that can be obtained from damming points in Poland is 14.27 PJ. The calculated technical potential includes mainly mini and small hydropower plants.

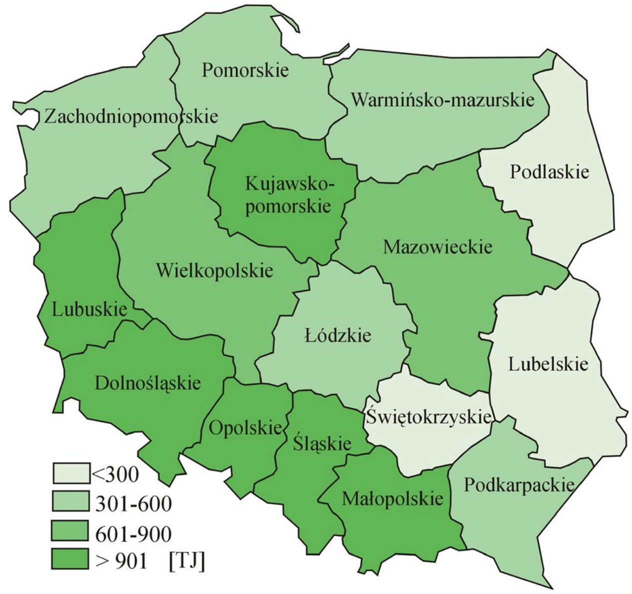

Fig. 6 Technical potential of hydropower in Poland

SWOT analysis of hydropower in Poland

A SWOT analysis is a structured planning method used to evaluate the strengths, weaknesses, opportunities and threats involved in a project or in a business venture. Hydropower SWOT analysis for Poland is presented in Table 2.

Strengths

It must be said that hydropower is a well-mastered technology, since many hydropower plants have been operating in Poland for several dozen years. In 1896, the first hydropower plant was "officially" open in Poland—Struga on the Słupia river (Pomorskie Voivodeship). Since then hundreds of hydro energy stations have been started, some of which have been working for over a 100 years.

Moreover, in contrast to, for example, wind turbines, hydroelectric plants allow to produce electricity in a stable and predictable manner.

Among the strengths is the fact that small hydropower plants are part of water regulation system, they improve soil moisture and groundwater level. Therefore, they co-create a small water retention thanks to numerous accumulations and retention reservoirs. Small water retention will improve hydrology situation in Poland which is getting more and more steppe.

In Poland there are 16,005 existing dams on which small and mini-hydropower plants can be built. The energy produced should be used on site, increasing the local energy security.

Table 2 Hydropower SWOT analysis for Poland

Strengths	Weaknesses
Well-mastered technology Stable energy production Increasing the retention of surface and groundwater Small power plants can be built in many places High technical potential	Damming the river often needed Resistance of ecological groups (large hydropower plants) Impact on the fish population Unable to work during log-term drought
Opportunities	**Threats**
Possibility of using water reservoirs for tourist and recreational purposes Fishery development New directions for the development of small hydropower	Unclear regulations Not much interest by the investors Progressive climate change

The total energy potential that can be obtained from damming points in Poland is 14.27 PJ. The calculated technical potential includes mainly mini and small hydropower plants (SHP).

Weaknesses

The weaknesses include the fact that the construction (in particular) of large, reservoir power plants involves the need of river partition. This is connected with flooding of a large area, which in turn implies social protests, protests of ecological groups and the need for resettlement.

Weirs, dams and barrages cause physiochemical and biological processes in water, which in turn affect the living conditions for the fish in the dammed stretch of the river. The lands of Salmonidae fish change into the areas of carp fish. River species such as brown trout, grayling, barbel, common nase, chub, dace, asp or ide give way, and are replaced by typical fish for free-flowing or standing waters—e.g., bream, roach, silver bream, perch and other fish.

Another drawback is the fact that work of flow water stations and also reservoirs having a small tank are dependent on water level of a river. Long-term drought causes continuous lowering of water level which results in smaller station power and lower electricity production.

Opportunities

The construction of tanks at a hydropower plant should involve making it available to the local community for tourism and recreation purposes. The tank should be designed to be suitable for water sports and fishing.

The use of waste water is a chance for the development of a hydroelectric power plant. Power plants of this type are qualified as small hydroelectric power plants operating in the flow. The greatest opportunities for using utility water are found in cooling systems of thermal power plants or in sewage treatment plants. What is important, the flow of utility water stream is slightly dependent on weather conditions. As an example, SHP in water treatment plant in Toruń can be described.

Threats

The development of hydropower in the voivodship will continue to be hampered by too many unclear and changing laws. RES Act in Poland is amended very often. Other decrees concerning hydroenergetics are also changed often. As a result, investors are extremely cautious towards building new hydroelectric power plants. Legal stability can influence further development of hydroenergetics in Poland positively.

Another threat is ongoing climate change. It is characterised by long rainless periods, which have a huge impact on the operation of hydroelectric power plant and electricity production. Pelting rains and strong winds (hurricanes) may in turn destroy the infrastructure of a hydroelectric power plant. Steppe Poland might restrict water resources what will influence work of hydro energy plants in a negative way.

Recommendations

- Lessening and simplification of regulations,
- Construction of small hydropower on already existing dams,
- Construction of fish passes and barriers.

At the moment, an investor who wants to put funds into hydroenergetics will meet a lot of law regulations. What is more, he has to complete a lot of documents and contracts. Red tape in Poland does not help in it. Therefore, the most important recommendation is lowering the amount of documents and their simplification. Law and clerks should be investor friendly.

It is advised to build water power plans on already existing heaps. It allows for lower investment costs significantly and it does not influence already existing ecosystem significantly.

New and already existing water power plants have to be eco-friendly, especially for fish. That is why construction of fish passes and barriers is advised.

Hydropower sector in Poland: environmental aspects

As it was already mentioned, in Poland the hydropower resources are utilised in only 12%; in comparison, Germany uses them in 80%, Norway—84%, and France—almost 100%. The implementation of new technologies, e.g., turbo regulators to enable efficient use of flood water or coated-gate weirs enabling damming of water without need to undertake any significant hydrotechnical work, can bring additional power and also, in many cases, significantly lower cost of the investment (National Water Management Board 2018).

Until recently, the hydropower sector has been perceived as "clean" and environmentally friendly. However, it needs to be concluded that very large hydropower stations, especially the ones with reservoirs, have also negative impact on the environment since to construct a dammed reservoir hundreds of people had to be relocated and large areas flooded. In addition, flora and fauna species change. On the other hand, large hydropower plants tend to be long lasting, are highly efficient and do not require fuel. Thus, in the longer perspective, they are much more environmentally friendly than mines (especially open-cast mines) and coal power plants (Rudnicki 2003; Malicka 2012).

It is especially worth developing small hydropower stations, the environmental impact of which is limited, and, in terms of small retention, highly beneficial. Small hydropower plants are part of the system that regulates the hydrographic conditions and improve the soil moisture and the ground water table. This is why the further growth of the small hydropower sector should be linked to creating an inventory of existing damming structures on the main water courses as well as the new planned sites (Rudnicki 2003; Malicka 2012).

When determining a further direction for the investment, possibilities of constructing small hydropower plants should be investigated (Igliński et al. 2017). Moreover, small hydropower plants have a positive influence on the power grid system by improving the parameters of electric power distribution network of high and medium voltage. Electric power generated by small hydropower plants is utilised by consumers from the nearest vicinity. This eliminates energy losses during transportation, distribution and transformation which occur in case of large systemic power plants and which can amount even up to 25%. What is considered the main drawback of small hydropower plants is their negative impact on the ichthyofauna as they interrupt the morphological continuity of rivers and cause damage to fish swimming through the turbines (Rudnicki 2003; Malicka 2012).

Currently, however, the vast majority of structures is constructed almost only on already existing barrages, and it is obligatory to build fish ladders (Fig. 7). Thus, these investments do not interrupt the continuity of rivers at present, but on the contrary, they improve the patency of rivers. As a result, the potamodromous fish species that live there, such as riverine brown trout or European chub, as well as anadromous fish species that migrate periodically from the sea to rivers, such as salmon, sea trout or vimba bream, can reach the previously unavailable mating sites located in the upper parts of rivers. It needs to be noted that in case of small watercourses which are not the key routes of ichthyofaunal migration, the only chance to restore their continuity is to find an investor interested in small hydropower generation (Igliński et al. 2017).

The negative impact of turbines has been almost totally eliminated due to the introduction of environmentally friendly technologies, such as the already mentioned Archimedean screws that enable fish to swim through them safely or more frequent use of behavioural barriers (water, light, sound and electric screens) (Rudnicki 2003; Malicka 2012).

It can be noticed that in recent years a significant technological progress has taken place in the small hydropower sector and the positive impact considerably outweighs the negative one (Igliński et al. 2017). Moreover, the current approach to hydropower generation aims at minimising environmental impact, even at a cost of reducing economic profits. Therefore, the further development of small hydropower sector contributes to creation of new technologies that are more efficient and at the same time have a minimal impact on the environment. The small hydropower plant Bieleckie Młyny near Kielce is one of the first hydropower plants in

Fig. 7 The fish ladder at a small hydropower plant Wierzyca (Pomorskie Voivodeship) (photography: B. Igliński)

Poland to have the Archimedean screw installed (Rudnicki 2003; Malicka 2012).

The development of small hydropower sector is important for agriculture and the inhabitants of rural regions as well as the inhabitants of small towns. Apart from accumulating drinking water supplies, small power plants can be used for the purposes of anti-flood defenses, agriculture, small agricultural processing plants, irrigation and drainage, recreation, water sports and health. Consequently, new work places are created. Small hydropower plants also improve the quality of water as mechanical treatment as well as water aeration boost rivers' ability for biological self-cleansing. In addition, they generally fit in nicely with the landscape, and are considered to be the most friendly renewable energy source as they do not cause any gas emissions or sewage generation. Moreover, the small hydropower sector uses small amounts of energy to meet its own needs, about 0.5–1%, whilst energy consumption in case of conventional power plants amounts about to 10% (Rudnicki 2003; Malicka 2012).

Conclusions

For over 1000 years, the water energy has been used in Poland—first water mills were built in the 9th century. Moreover, the first hydro energy station was opened in 1896. In 1935, 8000 small hydro energy stations and dozen thousand other installations using water was working in Poland. The conclusion is that in that time hydro energy sector played a very important role in Polish economy. The Second World War and taking over hydro energy plants by communistic government caused a big crash of hydro energy in Poland. Currently, 761 hydroenergy stations are running in Poland with a total of 994 MW. Only a small amount of hydro energy potential is used. It is necessary to use already existing heaps (i.e., weirs) and put water plants there (mainly SHP). As it was already mentioned, the hydro energy potential in Poland (mainly SHP) is high—it amounts to 14.7 PJ.

The article showed new directions of using water energy. For example, SHP works in a waste treatment plant in Toruń using water after treatment. There are 3319 waste water treatments in Poland. In some of them, small hydro plants (SHP) should be built. SWOT analysis has shown that the hydro energy development is stopped by law and ecological groups. On one hand law should be simplified and on the other hand dialogue with ecological groups should be made. Climate changes are also a big danger. It is characterised by long rainless periods, which have a huge impact on the operation of hydroelectric power plant and electricity production. Pelting rains and strong winds (hurricanes) may in turn destroy the infrastructure of a hydroelectric power plant. The stepping out of Poland can impoverish Poland's water resources, which will have a negative impact on the work of the hydroenergy plant.

As mentioned earlier, for building new hydro energy plants in Poland already existing heaps should be used. There are 16,005 heaps in Poland. New hydro energy stations should have fish ladders and security barriers for fishes.

Large hydro energy stations have big impact on the environment. Dam building makes flooding of huge areas, people migration and changes local biocenosis. Small hydro plants are definitely more friendly for environment. And that's why SHP should be built in Poland. Besides production of electricity, they ensure small water retention. It has big influence on lands turning into steppe in Poland. At the moment water resources are on the similar level to Egypt (Central Statistical Office 2017). Poland should use the potential of hydro energy from before the Second World War which will visibly improve water retention.

References

Adamczewski, J. (2005). *The magical millin*. Wrocław: Polskie Wydawnictwo Ludoznawcze.

Balińska, G., & Balińska, J. A. (2003). *The mills of Łomża Region*. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej.

Baranowski, B. (1977). *The polish mill industry*. Wrocław: Zakład Narodowy im. Ossolińskich.

Blok, M., & Tomaszewska, B. (2015). Global small hydropower plants' potential and the existing support systems for their construction. *Technika Poszukiwań Geologicznych, Geotermia, Zrównoważony Rozwój, 2,* 97–105.

Buczek, K. (1969). From the history of mill industry in the medieval Poland. *Małopolskie Studia Historyczne, 1*(12), 17–51.

Central Statistical Office. (2017). *Environment 2017*. Warszawa: Central Statistical Office.

Chen, O.-C., Alvarado, V., & Hsu, S.-C. (2018). Water energy nexus in city and hinterlands: Multi-regional physical input-output analysis for Hong Kong and South China. *Applied Energy, 1*(225), 986–997.

Coat of Piechowice. (2018). Retrieved May 10, 2018 from https://pl.wikipedia.org/wiki/Herb_Piechowic.

Dembińska, M. (1973). *Cereal processing in the medieval Poland (10th–14th century)*. Wrocław: Polish Academy of Sciences.

Ferreira, J. H. I., et al. (2016). Assessment of the potential of small hydropower development in Brazil. *Renewable and Sustainable Energy Reviews, 56,* 380–387.

Gloger, Z. (1902). *The illustrated old polish encyclopaedia* (Vol. III). Warszawa: Piotr L. Laskauer and Company.

Gómez-Navarro, T., & Ribó-Pérez, D. (2018). Assessing the obstacles to the participation of renewable energy sources in the electricity market of Colombia. *Renewable and Sustainable Energy Reviews, 90,* 131–141.

Grodecki, R. (2004). *The book of Henryków*. Wrocław: Zakład Narodowy im. Ossolińskich.

Gronek, D., & Ankiersztejn, I. (2012). The use of the hydropower potential of the Lower Vistula in the 60 years of experience of Hydroprojekt company. *Energetyka Wodna, 2,* 7–12.

Gupta, R., Singh, S. N. & Singal, S. K. (2007). Automation of small hydropower station. In: *Proceedings of international conference on small hydropower—hydro Sri Lanka* (pp. 22–24). October 2007.

IEA Hydropower. (2018). Retrieved May 7, 2018 from www.small-hydro.com.

Igliński, B., et al. (2011). Bioenergy in Poland. *Renewable and Sustainable Energy Reviews, 6*(15), 2999–3007.

Igliński, B., et al. (2012). Geoenergy in Poland. *Renewable and Sustainable Energy Reviews, 5*(16), 2545–2557.

Igliński, B., et al. (2016a). Helioenergy in Poland: current state, surveys and prospects. *Renewable and Sustainable Energy Reviews, 58,* 862–870.

Igliński, B., et al. (2016b). Wind energy in Poland: History, current state, surveys. Renewable Energy Sources Act, SWOT analysis. *Renewable and Sustainable Energy Reviews, 64,* 19–33.

Igliński, B., et al. (2017). *Hydroenergy technologies*. Toruń: Nicolaus Copernicus University.

Information about Piechowice. (2018). Retrieved May 11, 2018 from http://piechowice.bip.pbox.pl/public/?id=49780.

International Renewable Energy Agency (IRENA). (2017). Renewable energy and jobs. Annual review 2017.

Jackowski, K. (1971). *Hydropower plants*. Warszawa: Wydawnictwo Naukowo-Techniczne.

Janicka-Krzywda, U. (1987). *An attribute, a patron saint, a symbol—what should you know about saints and the blessed—a guide*. Kraków: Oddział Akademicki PTTK.

Kanior, M. (2002). *The role of the church and monastic orders. The history of Polish literature in ten volumes* (Vol. 1)., The middle ages Kraków: Polskie Towarzystwo Teologiczne.

Kozicki, Z. (2001). *A system of hydropower plants Solina-Myckowce*. Zielonczyn: Voith Turbo Sp. z o.o.

Kubicki, R. (2013). The water mills network in the monastic properties in Eastern Pomerania in the 13th–16th centuries. *Hereditas Monasteriorum, 2,* 35–56.

Larinier, M. (2008). Fish passage experience at small-scale hydroelectric power plants in France. *Hydrobiologia, 1*(609), 97–108.

Lu, B., et al. (2018). Geographic information system algorithms to locate prospective sites for pumped hydro energy storage. *Applied Energy, 222,* 300–312.

Malepszak, S. (1995). *Bukówiec Górny in the history of Kraina Przemęcka*. Leszno: Leszczyńskie Towarzystwo Kulturalne.

Malicka, E. (2012). Hydropower and examples of its use in Wielkopolska. *The International Forum, Lisków* 28th November 2012.

Małyszczycki, S. (1890). *Cereal milling* (Vol. 1). Warszawa: Arkonia.

Mazano-Agugliaro, F., et al. (2017). An overview of research and energy evolution for small hydropower in Europe. *Renewable and Sustainable Energy Reviews, 72,* 228–239.

Michałowski, S., & Plutecki, J. (1975). *Hydropower generation*. Warszawa: Scientific and Technical Publishing House.

Morales, S., et al. (2016). An overview of small hydropower plants in Colombia: Status, potential, barriers and perspectives. *Renewable and Sustainable Energy Reviews, 50,* 1650–1657.

Mrugalski, Z. (2008). *The polish engineers in the 19th and 20th centuries* (Vol. 11). Warszawa: Polskie Towarzystwo Historii Techniki.

National Water Management Board. (2018). Retrieved May 14, 2018 from www.kzgw.gov.pl.

Orlewski, W., & Siwek, A. (2010). A hydropower plant harnessing the flow of the usable water. *Rynek Energii, 6*(91), 1–8.

Pang, M., et al. (2015). Ecological impacts of small hydropower in China: Insights from an energy analysis of a case plant. *Energy Policy, 76,* 112–122.

Podgórski, Z. (2009). The water mills in the landscape of Chełmno Lakeland. *Prace i Studia Geograficzne, 41,* 151–161.

Prabil, R, & Mohapatra, N. K. (1998) Micro hydro—a mega VISION (case study). In: *Proceedings of national seminar on energy technologies for sustainable development* (p. 205–221) BIT Sindri, Ranchi.

RESTOR HYDRO (2015). Micro- and small hydropower plants, Retrieved May 4, 2018 from http://trmew.pl/fileadmin/user_upload/current_version/trmew.pl/strona_glowna/aktualnosci/2015/07/Podrecznik_MEW_Restor_Hydro.pdf.

Rudnicki, M. S. (2003). *The recreation of small hydropower plants*. Szczecin: Oficyna Wydawnicza OKP Zachodniopomorskie Centrum Edukacyjne.

Sachdev, H. S., Akella, A. K., & Kumar, N. (2015). Analysis and evaluation of small hydropower plants: A bibliographical survey. *Renewable and Sustainable Energy Reviews, 51,* 1013–1122.

Singh, V. K., & Singal, S. K. (2017). Operation of hydro power plants—a review. *Renewable and Sustainable Energy Reviews, 69,* 610–619.

Skuza, Z. A. (2006). *The disappearing trades in Poland*. Warszawa: Sport i Turystyka MUZA SA.

Święch, J. (2005). *The mysterious world of windmills*. Łódź: Polskie Towarzystwo Ludoznawcze.

Świtała, F. (1989). *A hydropower plant in the electric power network*. Lublin: Wydawnictwo Uczelniane Politechniki Lubelskiej.

The Cistercian Route. (2018). Retrieved May 9, 2018 from https://pl.wikipedia.org/wiki/Szlak_Cysterski.

The Energy Regulatory Authority. (2018). The map of renewable energy sources. Retrieved June 04, 2018 from www.ure.gov.pl/uremapoze/mapa.html.

The small hydropower plant Kraków. (2018). Retrieved May 18, 2018 from http://wodociagi.krakow.pl.

Tokarz, J., & Hryckiewicz, L. (2003). The hydropower plant Żarnowiec—the past and the present. *Energetyka i Ekologia, 8,* 509–515.

Wang, L., et al. (2008). Economic analysis of installing micro hydropower plants in Chia-Nan Irrigation Association of Taiwan using water of irrigation canals. In: *Proceedings of IEEE power and energy society general meeting on conversion and delivery of electrical energy in the 21st century* (p. 1–5).

Yah, N. F., Oumer, A. N., & Idris, M. S. (2017). Small scale hydropower as a source if renewable energy in Malaysia: A review. *Renewable and Sustainable Energy Reviews, 75,* 476–489.

Związek, T. (2014). The development of water mills network using the case study of Konin District (circa 1300–1550). *Studia Geohistorica, 2,* 118–142.