



Can energy self-sufficiency be achieved? Case study of Warmińsko-Mazurskie Voivodeship (Poland)

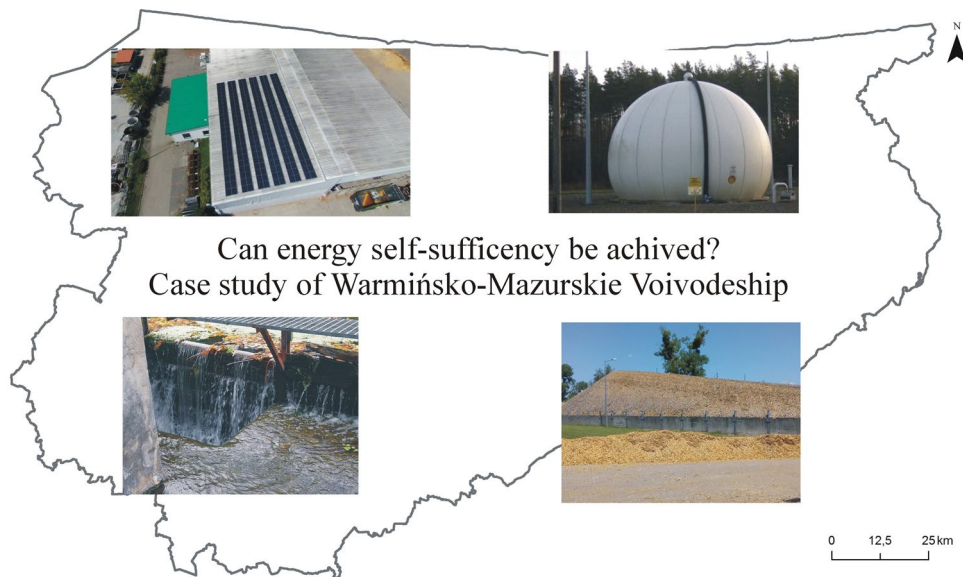
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Abstract

An analysis was carried out to show whether the Warmińsko-Mazurskie Voivodeship (Poland) could become energy self-sufficient. The technical potential of electricity and heat from renewable sources has been calculated. The calculated values are 6.93 TWh/year of electricity and 15.84 PJ/year of heat—these amounts would ensure the energy independence of the Voivodeship. The Warmińsko-Mazurskie Voivodeship is an example of transformation towards “green” energy, it shows that such transformation is also possible in Poland even in short term. This would reduce air pollution as well as limit the import of energy resources. It is very important, it allows us to think with optimism and implement Poland’s energy transformation towards renewable energy (RE). Additionally, a SWOT analysis of each type of RE in the Warmińsko-Mazurskie Voivodeship was presented. The SWOT analysis makes it possible to identify the strengths, weaknesses, prospects and threats for RE in the Voivodeship and the whole country. It has been found that there is a great interest of investors in RE in the Voivodeship, there is usually a great public support for new energy sources, and the biggest barriers are high investment costs and complicated law in Poland.

Graphic abstract



Keywords Renewable energy · Energy transformation · SWOT analysis · Warmińsko-Mazurskie Voivodeship

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Introduction

In the twentieth century, the global population tripled, while the consumption of fossil fuels increased by as much as 20 times. In a situation of drastic reduction of mine resources, the aim is to develop effective methods of obtaining energy from renewable resources such as biomass, the Sun, wind, water and natural heat of the Earth (Ray 2019). For this reason, in recent years, there has been an increase in the importance of electricity and heat from renewable energy (RE) sources, which is an important component in the efforts to prevent global climate change (Njoku and Omeke 2020; Lo et al. 2021).

The development of RE not only involves the development of technologies and the reduction of greenhouse gases emissions, but also contributes to the creation of new jobs, called “green jobs”. Clean energy is most often generated and consumed in close distances. This offers opportunities to benefit directly or indirectly consumers themselves, as new jobs are created and the outflow of funds to countries with fossil fuels is eliminated (Igliński et al. 2020a).

The development of RE favours a decentralised society, powered by a grid of smaller and safer power plants and the strengthening of local communities (Yadav 2020). Today, financial resources to purchase fuel and electricity flows out of the countryside in a wide stream, impoverishing it. The development of RE means that it is the rural population that will become the beneficiaries—and will supply waste to biogas and waste water treatment plants (Pilarski et al., 2020), while some will successfully search for jobs in new facilities (and what is more important as the Voivodeship has the highest unemployment rate in Poland). The ability to produce the own energy will also improve the quality of infrastructure and rural life (Igliński et al. 2020b; Piechota and Igliński 2021).

Warmińsko-Mazurskie Voivodeship (Fig. 1) purchases electricity externally, paying the highest rates in Poland. This is affected by the fact that no coal-fired power plant is in operation in the Voivodeship, so the price of energy is increasing, as transmission charges are added. High coal and electricity prices are holding back the economic development of the region (Igliński et al. 2020b).

As it has been mentioned above, electricity flows to the Warmińsko-Mazurskie Voivodeship from the distant power stations placed hundreds of kilometers away. Storms or wet snow very often tear off powering cables, as a result of which electricity is no longer supplied to certain regions. The solution to the problems indicated above is the faster development of own energy based on local energy sources, i.e. RE. RE involves small generation units located close to the recipient, which allows to increase the



Fig. 1 Location of Warmińsko-Mazurskie Voivodeship

local energy security and to reduce transmission losses. Generation of energy from RE source is characterised by low or zero emissions, which ensures the positive ecological aspect and this is important especially because the Warmińsko-Mazurskie Voivodeship is considered to be the “Green Lungs of Poland” due to its high level of forest cover, numerous lakes and ecological sites.

Poland is a country where over four-fifth of energy still comes from burning coal. However, coal resources are limited, and burning coal implies the emission of greenhouse gases and the formation of smog (low emission). In the coming years, the Polish energy sector will face a revolution and a transition to low- and zero-emission sources (Igliński et al. 2020b).

The aim of the study was to calculate the technical potential of RE, to carry out SWOT analysis of each type of RE, as well as to present perspectives for the development of RE in the Warmińsko-Mazurskie Voivodeship. The analysis may constitute an example of the transformation of the region in Poland towards environmentally friendly energy sources. The authors wanted to show that the Warmińsko-Mazurskie Voivodeship can fully cover its energy needs from the RE mix. Such an analysis should be performed for the 15 remaining voivodeships to prove that the transformation towards “green” energy is possible in Poland even in short term. Therefore, all Poland can be energy independent, based on RE sources. It is very important, it allows us to think with optimism and implement Poland’s energy transformation towards RE. Additionally, the SWOT analysis conducted allows to identify

the strengths, weaknesses, prospects and threats for RE in the Voivodeship and the whole country.

It is worth emphasising that no potential analysis or SWOT analysis for the Warmińsko-Mazurskie Voivodeship has been conducted so far. The conducted research allows to determine the current state and development prospects in the region, as well as throughout Poland.

Biomass in the Warmińsko-Mazurskie Voivodeship

In the Warmińsko-Mazurskie Voivodeship, there are three biomass power plants with a total capacity of 26.044 MW (Installations of RES 2019).

According to the data of the Agricultural Market Agency of July 1, 2020, in the Warmińsko-Mazurskie Voivodeship, there is a plant producing bioethanol in the amount of 16 million dm³ in Olecko (south-eastern part of the Voivodeship) (Agricultural Market Agency 2020).

20 biogas plants with a total capacity of 16.503 MW are currently in operation in the Warmińsko-Mazurskie Voivodeship (Installations of RE 2019). The first agricultural biogas plant in Warmińsko-Mazurskie Voivodeship was launched in 2012. Initially it had an electrical capacity of 1 MW, which was increased to 2 MW. Figure 2 shows a picture of a biogas plant in Nowa Wieś Elcka (eastern part of the Voivodeship).

It is worth mentioning that the largest district heating plant in Poland with a capacity of 21 MW operates in Pisz (south-eastern part of the Voivodeship). The facility is equipped with 3 boilers type VRF 6000 with nominal output of 6 MW each and one boiler type VRF 3000 with output of 3 MW. The boilers are manufactured by a Swiss company named Polytechnik. The boilers are designed to burn biomass in the form of wood chips and bark. Waste



Fig. 2 Installation for the energy use of biogas from a sewage treatment plant in Nowa Wieś Elcka (Igliński et al. 2020b)



Fig. 3 Waste chips stored on the Pisz heating plant site (photo by B. Igliński)

chips are delivered to the Pisz heating plant by the numerous sawmills in the region (Fig. 3), while waste biomass (mainly branch biomass) is delivered to the Pisz heating plant by municipal services (tree pruning), as well as by local residents (Igliński et al. 2020b).

Technical potential of energy from waste wood directly from forests and indirectly from the wood industry.

The following assumptions have been made in order to estimate the energy possible to be obtained annually from waste wood from forests in the Warmińsko-Mazurskie Voivodeship:

- 15% of the wood obtained directly in the forest is waste wood (part of the bark, chips and cuttings from pruning) (Igliński 2019a),
- The calorific value of wood from forests is on average 7 GJ/m³ (in Polish forests, pine is the dominant species) (Igliński 2019a),
- The efficiency of obtaining energy is 80% (Igliński 2019a).

Formula 1 shows the annual amount of energy that can be obtained from waste wood pruned directly, i.e. pruning in forests:

$$E_f = 0.15 \cdot 0.8 \cdot A_f \cdot C_w \quad (1)$$

where: E_f —annual energy from waste wood generated during forest pruning [PJ/year],

A_f —amount of wood obtained annually in the forest (3.75 million m³/year),

C_w —calorific value of wood from forests (7 GJ/m³).

Significant amounts of waste are also generated in the wood industry—in sawmills, furniture manufacturing plants, paper and pulp industry plants. Another source of biomass constitutes the post-consumed wood. Most of it is produced in the construction industry—it is wood obtained from demolition and reconstruction operations. Large amounts of waste biomass are produced in households and public institutions: furniture, fences, benches, arbours, etc. An important source of post-consumed wood in Poland involved packaging (mainly used in trade and transport) (Ratajczak et al. 2003).

In order to estimate the energy that can be obtained annually from waste wood from the woodworking industry, assumptions have been made as before, except that waste industrial and post-consumed wood is assumed to represent 25% of the wood obtained in the forest (Igliński 2019a).

Formula 2 shows the annual amount of energy that can be obtained from waste wood harvested indirectly, i.e. during wood processing in the wood industry.

$$E_i = 0.25 \cdot 0.8 \cdot A_f \cdot C_w \quad (2)$$

where: E_i —annual energy from waste wood generated during forest pruning and wood processing in wood industry [PJ/year]

A_f —volume of timber harvested annually in forests of the Voivodeship (3.75 million m³/year),

C_w —calorific value of wood from forests (7 GJ/m³).

A total of 40% of waste wood from forests can therefore be used for energy purposes (formula 3):

$$E_{fi} = 0.4 \cdot 0.8 \cdot A_f \cdot C_w \quad (3)$$

where: E_{fi} —annual energy from waste wood produced during forest pruning and wood processing in wood industry [PJ/year],

A_f —volume of timber harvested annually in forests of the Voivodeship (3.75 million m³/year),

C_w —calorific value of wood from forests (7 GJ/m³).

The calculated amount of energy possible to be obtained annually from waste wood in the Warmińsko-Mazurskie Voivodeship is 8.3 PJ/year.

Technical potential of energy from waste wood generated directly from orchards.

As a result of grubbing off orchards, about 80 Mg/ha of biomass can be obtained for older plantations (age about 30 years) and about 60 Mg/ha for modern dwarf plantations (age about 15 years) (Jasiulewicz 2010); annually, this gives an average of 3.5 Mg/(ha•year) (assuming grubbing off once every 30 or 15 years, respectively). However, the amount of biomass produced annually during maintenance works varies, depending on age and tree species, from 4 to 10 Mg/(ha•year), i.e. approximately an average of 7 Mg/(ha•year) (Jasiulewicz 2010).

The following assumptions have been made in order to estimate the energy that can be obtained annually from waste wood from orchards:

- 30% of wood obtained in the orchards can be dedicated for energy purposes (Igliński 2019a),
- 3.5 Mg/(ha•year) of wood is produced as a result of grubbing off (Jasiulewicz 2010),
- 7 Mg/(ha•year) of wood is produced as a result of the maintenance operations (Jasiulewicz 2010),
- Average calorific value of fruit tree wood is 11.5 GJ/Mg (Igliński 2019a),
- Energy efficiency is 80%.

The annual amount of energy that can be extracted from waste wood from orchards is presented below in formula 4:

$$E_o = 0.3 \cdot 0.8 \cdot (A_g + A_m) \cdot S_o \cdot C_o \quad (4)$$

where: E_o —annual energy from waste wood generated from the orchards [PJ/year],

A_g —amount of wood obtained annually as a result of grubbing of 1 ha of orchard (3,5 Mg/(ha•year),

A_m —amount of wood obtained annually as a result of the maintenance operations on 1 ha of the orchard (7 Mg/(ha•year),

S_o —surface of the orchards [million ha],

C_o —calorific value of wood from the orchards (11.5 GJ/Mg).

The calculated amount of energy that can be obtained annually from waste wood from orchards in Warmińsko-Mazurskie Voivodeship is 0.12 PJ/year.

Technical potential of energy from the surplus of straw.

In recent years, Polish agriculture has been dominated by the cultivation of cereals: wheat, rye, barley, triticale, oats and cereal mixtures. According to the Central Statistical Office, the annual weight of grain harvested in the Warmińsko-Mazurskie Voivodeship is 594 thousand Mg/year for wheat, 90 thousand Mg/year for rye, 133 thousand Mg/year for barley, 62 thousand Mg/year for oats, 200 thousand Mg/year for triticale (Central Statistical Office 2019a).

The decline in the stock of farm animals in Poland and the introduction of litter-free breeding contributed to the significant surplus of straw in Poland (Igliński et al. 2012).

The following assumptions have been made in order to estimate the energy that can be obtained annually from the surplus of straw:

- The grain/straw ratio shall be equal to the respective value: 0.8 for wheat, 1.4 for rye, 0.9 for barley, 1.05 for oats, 0.95 for triticale (Igliński 2019a),

- 30% of the straw produced is a surplus that can be used for energy purposes (Igliński 2019a),
- Calorific value of straw (about 20% humidity) is 15 GJ/Mg on average (Igliński 2019a),
- Energy efficiency is 80%.

Formula 5 shows the annual amount of energy that can be generated from straw:

$$E_s = 0.3 \cdot 0.8 \cdot (H_w/r_w + H_r/r_r + H_b/r_b + H_o/r_o + H_t/r_t) \cdot C_s \quad (5)$$

where: E_s —annual energy from straw [PJ/year],
 C_s —calorific value from straw (15 GJ/Mg) [61],
 H_w, H_r, H_b, H_o, H_t —annual harvest of cereal grains (wheat, rye, barley, oats, triticale) [million Mg/year],
 r_w, r_r, r_b, r_o, r_t —the grain/straw ratio, respectively: 0.8, 1.4, 0.9, 1.05, 0.95.
 C_s —caloric value of straw (15 GW/Mg)

The calculated amount of energy that can be obtained annually from straw surpluses in the Warmińsko-Mazurskie Voivodeship is 3.51 PJ/year. The potential estimated above indicates the possibility of using straw in boiler plants and combined heat and power plants on a larger scale than at present.

Technical potential of hay energy from unused meadows and pastures.

The Warmińsko-Mazurskie Voivodeship has a considerable area of meadows and pastures; according to the data of the Central Statistical Office, it amounts to 217 thousand ha and 98 thousand ha, respectively (Central Statistical Office 2019a). Due to a reduction in the number of livestock (mainly cattle), as well as a change in the animal feed system, most meadows and pastures are not used. Hay can be used both as solid fuel in the combustion process and as substrate in agricultural biogas plants. This study assumes that hay will be used as the solid fuel.

The following assumptions have been made in order to estimate the annual hay energy yield from unused meadows and pastures:

- 15% of meadows and pastures can be used for growing hay for energy purposes (Igliński 2019a),
- The volume of hay obtained annually per hectare of meadows is 4.9 Mg/(ha•year), and per hectare of pastures is 3.6 Mg/(ha•year) (Igliński 2019a),
- Calorific value of hay is on average 14 GJ/Mg (Igliński 2019a),
- Energy efficiency is 80%.

Formula 6 shows the annual amount of energy that can be extracted from hay from unused meadows and pastures [PJ/year]:

$$E_{mp} = 0.15 \cdot 0.8 \cdot (V_m \cdot S_m + V_p \cdot S_p) \cdot C_h \quad (6)$$

where: E_{mp} —annual energy from hay from meadows and pastures [PJ/year],

V_m, V_p —volume of hay obtained per hectare of meadows and pastures per year (relatively 4.9 Mg/(ha•year) and 3.6 Mg/(ha•year),

S_m, S_p —surface of meadows and pastures [million ha],

C_h —calorific value of hay (14 GJ/Mg).

The calculated amount of energy that can be obtained annually from hay from unused meadows and pastures in the Warmińsko-Mazurskie Voivodeship is 2.5 PJ/year.

Technical potential of the energy from the basket willow cultivated on fallow land and wasteland and 5% of the cultivated area.

The Warmińsko-Mazurskie Voivodeship has a considerable area of fallow land and wasteland (devastated and degraded land); according to the data of the Central Statistical Office, it amounts to 10.7 thousand ha and 67.7 thousand ha, respectively (Central Statistical Office 2019a).

They can be used for production of the energy plants: grass (np. *Miscantus*), crops (straw and bioethanol), trees (poplar tree—*Populus* L.) or bushes (basket willow—*Salix viminalis*). The study assumes that it will be the *Salix viminalis* basket willow; it is a native species (Igliński 2019a). The basket willow tolerates agroclimatic conditions very well, practically all over Poland, and it is also a suitable plant for recultivation of wasteland (Igliński 2019a). It has also been assumed that 5% of the agricultural area will be used for bioenergy production, i.e. 47.7 thousand hectares.

The following assumptions have been made in order to estimate the annual energy yields of basket willow—from fallow land and wasteland:

- 50% of fallow land, 20% of uncultivated land and 5% of agricultural land can be used for energy purposes (Igliński 2019a),
- Annual basket willow yield per hectare is 8 Mg/(ha•year), both on fallow land and wasteland, and on arable land 16 Mg/(ha•year) (Igliński 2019a),
- Calorific value of basket willow is 19 GJ/Mg (Igliński 2019a),
- Energy efficiency is 80%.

Formula 7 shows the annual amount of energy that can be generated from the basket willow trees grown on unused fallow land and wasteland:

$$E_{bw} = 0.8 \cdot [Y_{fw} \cdot (0.5 \cdot A_f + 0.2 \cdot A_w) + Y_c \cdot 0.05A_c] \cdot C_w \quad (7)$$

where: E_{bw} —annual energy from basket willow trees grown on fallow land, wasteland and agricultural land [TJ/year],

Y_{fw} —the annual yield of willow wort per hectare on fallow land and wasteland (8 Mg/(ha·year)),

Y_c —annual yield per hectare of basket willow trees on cultivated land (16 Mg/(ha·year)),

A_f, A_w, A_c —the area of fallow land, wasteland and cultivated land [thousand ha],

C_w —calorific value of basket willow (19 GJ/Mg).

The calculated amount of energy possible to be obtained annually from the basket willow grown on fallow land, wasteland and agricultural land in the Warmińsko-Mazurskie Voivodeship is 13.9 PJ.

Biogas potential from agricultural and food waste.

In Warmińsko-Mazurskie Voivodeship, biogas will be obtained from waste biomass (Maroušek et al. 2020a).

Biogas potential from liquid manure and bird droppings

According to the Central Statistical Office, the number of cattle, pigs and poultry is, respectively, 474 thousand head, 573 thousand head and 4841 thousand head (Central Statistical Office 2019a).

The following assumptions have been made in order to estimate the annual energy available from biogas from liquid manure and bird droppings:

- Conversion factors for livestock units to large livestock units (500 kg) are: for cattle 0.8, for pigs 0.2, for poultry 0.004 (Igliński et al. 2020a),
- Average weight of liquid manure and bird droppings produced by the livestock unit is 44.9 kg/day = 16.4 Mg/year for cattle, 43.5 kg/day = 15.9 Mg/year for pigs and 26.8 kg/day = 9.8 Mg/year for poultry (the conversion factors for livestock units to large livestock units (500 kg) are: for cattle 0.8, for pigs 0.2, for poultry 0.004 (Igliński et al. 2020a, b),
- Biogas yield from cattle liquid manure is 0.050 m³/kg = 50 m³/Mg, from pig liquid manure 0.055 m³/kg = 55 m³/Mg and from bird droppings 0.140 m³/kg = 140 m³/Mg (Igliński et al. 2020a, b),
- Biogas from animal liquid manure or bird droppings contains 60% methane with a calorific value of 35.73 MJ/m³ (Igliński et al. 2020a, b),
- The technical potential of biogas for disposal is 20% of the theoretical potential,
- Energy efficiency is 80%.

Formula 8 presents the annual amount of energy that can be obtained from biogas produced from liquid manure or bird droppings:

$$E_{bl} = 0.2 \cdot 0.8 \cdot 0.6 \cdot (0.8 \cdot N_c \cdot V_c \cdot Y_c + 0.2 \cdot N_p \cdot V_p \cdot Y_p + 0.004 \cdot N_{po} \cdot V_{po} \cdot Y_{po}) \cdot C_m \quad (8)$$

where: E_{bl} —annual energy obtained from biogas from liquid manure and bird droppings (TJ/year)

N_c, N_p, N_{po} —number of cattle, pigs, poultry (million head),

V_c, V_p, V_{po} —annual volume of liquid manure or bird droppings from a large conversion unit of cattle (16.4 Mg/rok), pigs (15.9 Mg/rok), poultry (9.8 Mg/year),

Y_c, Y_p, Y_{po} —yield of biogas from a cattle liquid manure (50 m³/Mg), from pigs liquid manure (55 m³/Mg), from bird droppings (140 m³/Mg) (Igliński 2019a),

C_m —methane calorific value (35.73 MJ/m³) (Malek et al. 2020).

The calculated amount of energy that can be obtained annually from biogas from liquid manure or bird droppings in the Warmińsko-Mazurskie Voivodeship is 1.51 PJ.

Landfill biogas potential

According to the data of the Central Statistical Office, the annual mass of municipal waste generated in households and public utility facilities in the Warmińsko-Mazurskie Voivodeship is about 441 thousand Mg/year (Central Statistical Office 2019a), of which about half is the biodegradable fraction (Kutera and Hus 1998; Sohoo et al. 2021). Due to the large dispersion of bio-waste sources as well as the (still) low degree of waste segregation, the technical potential of biogas from municipal waste can be estimated at 20% of the theoretical potential.

The following assumptions have been made in order to estimate the annual biogas energy yield from the biodegradable fraction of municipal waste:

- Biogas yield from the biodegradable fraction of municipal waste is 90 m³/Mg (Igliński 2019a),
- Biogas from the biodegradable fraction of municipal waste contains 55% methane with a calorific value of 35.73 MJ/m³ (Igliński 2019a),
- The technical potential of biogas for disposal is 20% of the theoretical potential,
- Energy efficiency is 80%.

Formula 9 presents the annual amount of energy that can be obtained from biogas obtained from the biodegradable fraction of municipal waste:

$$E_{bm} = 0.2 \cdot 0.8 \cdot 0.55 \cdot V_{bm} \cdot Y_{bm} \cdot C_m \quad (9)$$

where: E_{bm} —annual biogas energy from the biodegradable fraction of municipal waste.

(TJ/year),

V_{bm} —Annual volume of the biodegradable fraction of municipal waste [million Mg/year],

Y_{bm} —Biogas yield from the biodegradable fraction of municipal waste ($90 \text{ m}^3/\text{Mg}$),

C_m —Calorific value of methane ($35.73 \text{ MJ}/\text{m}^3$).

The calculated amount of energy that can be obtained annually from biogas from the biodegradable fraction of municipal waste in the Warmińsko-Mazurskie Voivodeship is $0.125 \text{ PJ}/\text{year}$.

Biogas potential in sewage treatment plants

In the Warmińsko-Mazurskie Voivodeship, 44.8 million m^3 of municipal sewage is treated (Central Statistical Office 2019b). It has been assumed that from 50% of the sewage flowing to the treatment plant sludge will be obtained (constituting 1% of the incoming sewage) and that from 1 m^3 of sludge 15 m^3 of biogas can be obtained (Igliński 2019a; Maroušek et al. 2020b).

The following assumptions have been made in order to estimate the annual biogas energy yield from (municipal) sewage sludge:

- 50% of the municipal waste water will be used to produce biogas,
- Volume of sewage sludge is 1% of the incoming municipal waste water,
- Yield of biogas from sewage sludge is $15 \text{ m}^3/\text{m}^3 = 15$ (Igliński 2019a),
- Biogas from sewage sludge contains 60% methane with a calorific value of $35.73 \text{ MJ}/\text{m}^3$ (Igliński 2019a),
- Energy efficiency is 80%.

Formula 10 shows the annual amount of energy that can be obtained from biogas produced from sewage sludge:

$$E_{bs} = 0.5 \cdot 0.01 \cdot 0.8 \cdot 0.6 \cdot V_{bs} \cdot Y_{bs} \cdot C_m \quad (10)$$

where: E_{bs} —Annual energy from sewage sludge disposal biogas (TJ/year),

V_{bs} —Annual volume of municipal waste water incoming into the treatment plant (million m^3/year),

Y_{bs} —Biogas yield from sewage sludge ($15 \text{ m}^3/\text{m}^3 = 15$).

C_m —Calorific value of methane ($35.73 \text{ MJ}/\text{m}^3$).

In the Warmińsko-Mazurskie Voivodeship, 3.4 million m^3 of biogas can be obtained, i.e. $0.12 \text{ PJ}/\text{year}$ of energy.

Biogas production from biodegradable waste from the agri-food industry

Biogas can also be obtained from food waste, post-production waste, spoiled food, shop food returns, green waste,

burnt waste, brewery waste, etc. The technical potential of agri-food waste is assumed to be 20% of the theoretical potential (Igliński 2019a; Maroušek et al. 2020c).

The following assumptions have been made in order to estimate the annual energy available from biogas from biodegradable waste from the agri-food industry:

- 20% of biodegradable waste from the agri-food industry will undergo methane fermentation,
- The biogas yield from biodegradable waste from the agri-food industry is $100 \text{ m}^3/\text{Mg}$ (Igliński 2019a),
- Biogas from biodegradable waste from the agri-food industry contains 55% methane with a calorific value of $35.73 \text{ MJ}/\text{m}^3$ (Igliński 2019a),
- Energy efficiency is 80%.

Formula 11 shows the annual amount of energy that can be generated from biogas obtained from biodegradable waste from the agri-food industry:

$$E_{bb} = 0.2 \cdot 0.8 \cdot 0.55 \cdot V_{bb} \cdot Y_{bb} \cdot C_m \quad (11)$$

where: E_{bb} —annual energy from biogas from biodegradable waste from agri-food industry (TJ/year),

V_{bb} —annual volume of biodegradable waste from the agri-food industry (million Mg/year),

Y_{bb} —biogas yield from biodegradable waste from the agri-food industry ($100 \text{ m}^3/\text{Mg}$),

C_m —calorific value of methane ($35.73 \text{ MJ}/\text{m}^3$).

The calculated amount of energy that can be obtained annually from biogas from biodegradable waste from the agri-food industry in the Warmińsko-Mazurskie Voivodeship is $0.06 \text{ PJ}/\text{year}$.

SWOT analysis of bioenergy in the Warmińsko-Mazurskie Voivodeship

SWOT analysis is a comprehensive method of strategic analysis, which includes both the study of the interior of an undertaking or organisation and the study of its external environment. It consists in identifying key strengths and weaknesses and confronting them with current and future opportunities and threats. SWOT analysis is one of the most commonly used tools for strategic analysis (Chen et al. 2014). Based on the SWOT analysis, a following set is achieved:

- **S** (Strengths)—strong points to be reinforced,
- **W** (Weaknesses)—weak points to be reduced,
- **O** (Opportunities)—opportunities to be exploited,
- **T** (Threats)—threads to be avoided (Fig. 4).



Fig. 4 SWOT analysis diagram (own study)

SWOT analysis allows you to systematise knowledge, to see new opportunities or threats, to be sensitive to certain issues. It is a good method to identify the market or environment, verify design assumptions, research trends, etc. (Chen et al. 2014).

Table 1 presents the SWOT analysis of bioenergy in the Warmińsko-Mazurskie Voivodeship.

Strengths

The strengths include the fact that Warmińsko-Mazurskie Voivodeship has a large technical potential of solid biomass

(both forest waste, agricultural waste and energy crops), which can be burnt or co-incinerated, as well as subjected to pyrolysis or gasification processes (Koniecko et al. 2013).

The combustion of biomass, mainly wood, has been known for thousands of years, is a well mastered and relatively simple technology. Of course, wood or straw should only be combusted or co-combusted in boilers for the correct type of fuel (Igliński et al. 2020b).

The strength of biogas energy is that it is a technology that deodorises and neutralises waste. The biogas plant allows for controlled management of waste organic matter. As a result of the natural processes of biomass decomposition, methane is produced, which, if released into the atmosphere, increases the greenhouse effect. The energetic use of agricultural biogas reduces the CO₂ emissions that would be generated by burning conventional fuels (Koniecko et al. 2013).

The use of a combined heat and power unit ensures higher efficiency of the whole system, allowing for more economical energy production. The efficiency of electricity generation in the latest agregators is in the range of 35–40% and the efficiency of heat recovery is 40–45%, which allows for a total fuel efficiency of 75–85% (Igliński et al. 2020b).

Another strength of biogas power is that the post-digestion pulp is a good, natural agricultural fertiliser that can increase yields. The post-digestion pulp can be directly poured into fields or dried and processed into pellets. Pellets can be successfully used as fuel or as dry, almost odourless agricultural fertiliser (Igliński et al. 2020b).

Table 1 SWOT analysis of energy from biomass in Warmińsko-Mazurskie Voivodeship

Strengths	Weaknesses
High potential of forest biomass	Low and fluctuating price of green certificates
High potential of agricultural biomass	Poor interest of farmers in perennial energy crops
Area potential for energy crops	Poor knowledge of the agrotechnical and economic conditions of multiannual energy crops
High potential for residues from agricultural production and waste from the agri-food industry	High investment costs
Technology known and quite simple to implement	Low interest in converting biomass into pellets or briquettes
Biogas technology is a technology that deodorises and disposes of waste	Lack of a stable biomass market
Cogeneration of bioenergy	Problem with heat management
Increase the yield by using the post-digestate pulpas a fertiliser	Sometimes social resistance to the construction of biogas plants
Surplus of manpower in rural areas	
Opportunities	Threats
Additional revenue in the agricultural sector	Seasonal price fluctuations for solid biomass fuels
Cultivation of new species of energy plants	Difficulties in ensuring stability of supply
The development of 2nd and 3rd generation biofuels	Price volatility of agricultural substrates
Use of biogas for automotive purposes	Excessive fiscalism
Heat management from biogas combustion to heat greenhouse crops	

The Warmińsko-Mazurskie Voivodeship is a region with a dominant population of villages and small towns. And it is precisely this population that could find employment in the heat and power plants or biogas plants, what would reduce unemployment in the rural areas (Igliński et al. 2020b).

Weaknesses

Low and fluctuating prices of green certificates have a negative impact on the financial liquidity of bioenergy plants in the Warmińsko-Mazurskie Voivodeship (Igliński et al. 2020b).

Energy crops are becoming increasingly popular in Poland, but still many farmers have little knowledge of their cultivation and harvest. The reason for this is the unstable biomass market, its low and volatile prices. The situation could be improved by introducing fixed, previously contracted biomass prices. Moreover, in recent years there has been a price "swing" in biomass and unfortunately many farmers (Zyadin et al. 2017) believe that this will continue to happen in the future.

Pellets and briquettes are more eagerly purchased; however, their market is still too narrow. It is a result of an overly volatile biomass market and volatile biomass prices (Zyadin et al. 2017).

Investors and owners stress that capital-intensive construction of bioenergy plants faces economic barriers, including a shortage of financial aid schemes during project implementation. It is difficult for investors to pin down the financial assembly, because the banks have withheld financial support for this type of undertaking, and the money from the banks is affecting the investors' own contribution, which is necessary (Zyadin et al. 2017).

Roughly every second investment in an agricultural biogas plant has encountered or is encountering social resistance. The main reasons for opposition can be cited as:

- Lack of reliable sources of information on biogas plants,
- The NIMBY effect—accepting the need to develop the RE sector, but “not in my neighbourhood” (Igliński et al. 2020b).

Opportunities

The development of the bioenergy sector will increase farmers' incomes. They will be able to supply straw, biomass of energy plants or agri-food waste to bioenergy plants.

There are good chances that farmers from the Warmińsko-Mazurskie Voivodeship will convince themselves to energy plants. Apart from the basket willow, the farmers will be able to cultivate silvergrass, *Virginia fanpetals*, *Jerusalem artichoke* or reed (Igliński et al. 2020b).

Opportunities include the development of second and third generation biofuels. They do not compete with products intended for nutritional purposes. Scientists from the University of Warmia and Mazury in Olsztyn are working on the energetic use of algae (Zieliński et al. 2021).

In Poland, biogas is used to produce electricity and heat. In other countries, its role as automotive fuel is growing. In Sweden for example where after the enrichment, biomethane is used to power the passenger cars, buses and slow-running vehicles (Energigas Serige 2019).

As is has been mentioned before, the heat management is problematic in some of the existing and planned biogas plants. A good solution is to use the heat of biogas combustion to heat greenhouse plants. This idea was first implemented by a biogas plant in Koczergi (Poland) (Igliński et al. 2015). The heat from the biogas plant warms greenhouses, mainly tomatoes, on a 4 ha area all year round. Combining greenhouses with a biogas plant makes it possible to reduce or completely eliminate mineral fertilisers, as they can be replaced by digestate from the biogas plant (Igliński et al. 2015).

Threats

The main threats to the development of agricultural biogas plants in the Warmińsko-Mazurskie Voivodeship include the volatility of substrate prices and the supply itself. A sudden increase in the price of raw materials, e.g. for methane digestion, puts the biogas plant almost on the verge of bankruptcy. A good solution to the problem is to sign long-term contracts for the supply of substrates for bioenergy plants. Already at the stage of selecting a location for a bioenergy plant, this problem must be considered a priority—the plant must be close to the raw material (Igliński et al. 2015).

The construction of a bioelectric power plant requires the signing of contracts with many entities and at various stages of the investment. Typical contracts related to the construction and operation of a bioelectric power plant are contracts for: technology supply, investment execution, comprehensive execution of design works, supply of substrates, connection to the power grid (sometimes there is a big problem with that), supply and reception of utilities, including heat sales, insurance during the construction period and investment project financing (Igliński et al. 2015).

Hydropower engineering in the Warmińsko-Mazurskie Voivodeship

In the Warmińsko-Mazurskie Voivodeship, at the end of 2019, a total of 76 hydropower plants with a total capacity of 15.115 MW were in operation (Installations of RE 2019).



Fig. 5 SHP "Niewodnik I" (Igliński et al. 2020b)



Fig. 6 SHP "Niewodnik II" (Igliński et al. 2020b)

For example, the “Niewodnik I” power plant (Fig. 5) has been operating since 1989 on the ruins of the former water mill from the mid-sixteenth century, the current hydrotechnical system was shaped at the beginning of the twentieth century, two propeller turbines with a diameter of 395 and 700 mm were installed in the power plant, water falls from a height of 2.40 m. The “Niewodnik

II” Power Plant (Fig. 6) was established in 1994 and is a power plant with the largest water level difference in the Warmińsko-Mazurskie Voivodeship—9.00 m (Igliński et al. 2020b).

Potential of hydropower engineering in the Warmińsko-Mazurskie Voivodeship

It was assumed that small hydropower plants (SHP) will be built on already existing dammings (e.g. barriers, weirs, etc.). In the Warmińsko-Mazurskie Voivodeship, the number of existing dammings is:

- 230 dammings where a small hydro power plant of less than 5 kW can be placed,
- 58 dammings where a small hydro power plant of 5–10 kW can be placed,
- 49 dammings where a small hydro power plant of 10–20 kW can be placed,
- 87 dammings where a small hydro power plant of 20–50 kW can be placed,
- 43 dammings where a small hydro power plant of 50–100 kW can be placed,
- 33 dammings where a small hydro power plant of 100–500 kW can be placed,
- 2 dammings where a small hydro power plant of more than 500 kW can be placed (Fig. 7) (Igliński et al. 2020b).

The total theoretical electrical capacity of all the dammings is 16.3 MW, which means that the potential using existing dammings is small. In order to increase this potential, water should undergo auxiliary damming.

SWOT analysis of hydropower in the Warmińsko-Mazurskie Voivodeship

Table 2 presents the SWOT analysis of hydropower in Warmińsko-Mazurskie Voivodeship.

Strengths

Already in 1896, the first hydro power plant in Poland—Struga na Słupi (Pomorskie Voivodeship)—was officially opened (Igliński 2019b). Since then, hundreds of hydro power plants in Poland have been opened; some have been in operation for over 100 years. It should certainly be stated that hydropower is a well-mastered technology, all the more so because it is currently supported by, among others, the Association for the Development of Small Hydropower Plants (Association 2020) and Small Hydropower Plants (Small Hydropower Plants 2020).

Fig. 7 Location of the existing dammings and the capacity of the hydropower plants that can be built in the Warmińsko-Mazurskie Voivodeship (own study)

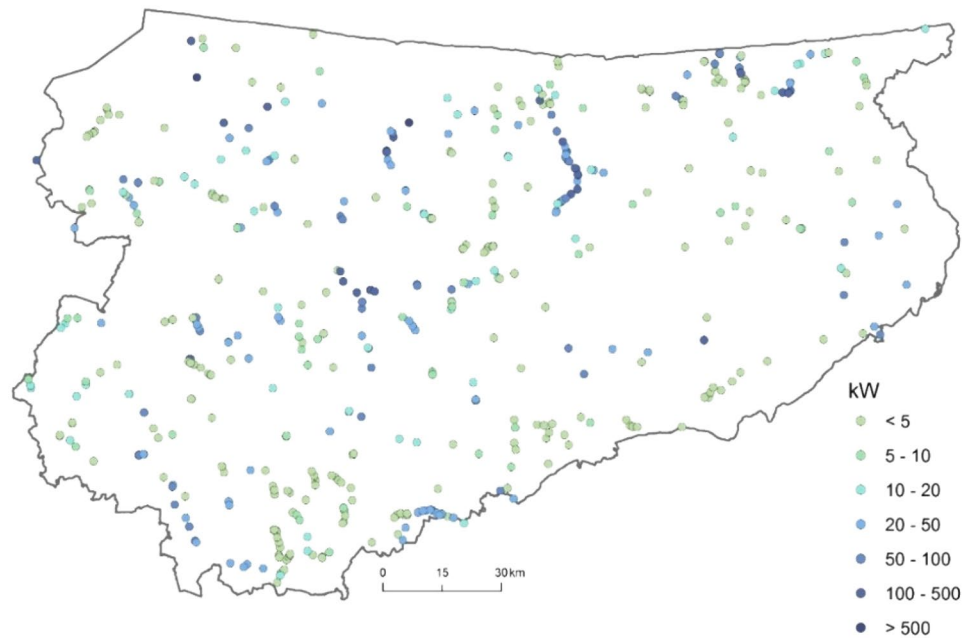


Table 2 SWOT analysis of hydropower in the Warmińsko-Mazurskie Voivodeship

Strengths	Weaknesses
Experience in operating SHPs	Necessity for damming or building water units in front of power stations
Stable electricity production	Necessity to construct the fish ladder
Increasing surface and groundwater retention	Resistance of environmental groups
Water purification	Complicated and time-consuming investment preparation procedures
SHPs can be constructed in many places, even on small watercourses	Operation of SHP depends on the water level in the river
Opportunities	Threats
Construction of SHP on former/present dammings	Low interest of the investors
Providing water reservoirs	Unclear legal provisions
Improving the hydrological balance of the region	Progressive climate change
New directions of SHP development	

Hydropower plants, especially reservoirs, are among stable energy sources. Even in times of drought, they produce electricity (Igliński 2019b).

One of the strong points includes the fact that SHP are part of a system for regulating water relations, improving soil moisture and groundwater levels. They therefore contribute to a small water retention through numerous subsoil and retention reservoirs (Igliński 2019b).

SHP not only ensures water retention in the environment, but also improves water quality, since mechanical treatment and oxygenation of the water improve the ability of rivers to self-purify biologically (Igliński 2019b).

SHP can be built even on small watercourses, supplying energy to nearby farms in the Warmińsko-Mazurskie Voivodeship (Igliński 2019b).

Weaknesses

Weaknesses include the fact that the construction of large, reservoir power plants involves the need to partition rivers. This involves the flooding of a large area, which in turn implies social protests and the need for resettlement of people (Igliński 2019b). Each hydropower plant must have at least a fish ladder, which increases investment costs.

The construction of large hydropower plants in particular is associated with resistance from environmental groups. They argue, among other things, that partitioning rivers has a negative impact on fish populations, and in particular on bi-environmental fish, i.e. fish migrating to the Baltic: eel, salmon and sea trout. Weirs, dams and water levels cause physical, chemical and biological processes to take place in the water on an accumulated section of the river, which

change the living conditions of the fish, which entails transformations in the species structure of the ichthyofauna. Salmonid fish lands are turning into areas of carp fish. Rheophilous river species such as brown trout, grayling, barbel, nase, chub, dace, rapfen and ofre are replaced, by fish typical of slow flowing or still water—e.g. bream, roach, taproot, perch and others (Igliński 2019b).

An investor who plans to build SHP must be armed with patience. The construction of a power plant involves obtaining many permits, which often takes months (or even years).

Another weakness is the fact that the operation of run-of-river hydropower plants, as well as those with a small reservoir, is very much dependent on the state of water in the river. A prolonged drought causes the level of water to gradually fall, which results in a decrease in the power of the power plants and lower electricity production (Igliński 2019b).

Opportunities

In order to be able to use the full potential of SHP in the Warmińsko-Mazurskie Voivodeship, power plants should be built on the former/present floors, and there are quite a few of them. Even before World War II, there were several hundred water installations operating in Warmińsko-Mazurskie Voivodeship, so it is realistic to restore them in the form of SHP (Igliński 2019b).

The construction of reservoirs at a hydropower plant should be associated with making it available to the local community for tourism and recreation (which may reduce the social resistance to its construction). The reservoir should be designed so that it is suitable for water sports and fishing (Igliński et al. 2020a, b).

The opportunity for the development of SHP is the use of waste water. Such power plants are classified as small hydropower plants operating on a flow-through basis. The greatest possibilities for the use of water energy are in the power industry in cooling systems of thermal power plants or in sewage treatment plants. The flow of the utility water stream is slightly dependent on weather conditions (Igliński 2019b).

Threats

Bureaucracy, high investment costs and uncertain profits mean that there are relatively few investors in SHP. These are enthusiasts, who often have SHP from their grandfather-great-grandfather.

Owners of hydropower plants (Igliński 2019b) and RE experts (Igliński 2019a) believe that the development of hydroelectric power will continue to be hampered by too many, unclear and changing laws. The validity of some

documents is too short, so they are not always able to collect and submit all the documents in good time.

Another threat is the ongoing climate change. These are characterised by long periods of rainfall-free periods, which have a huge impact on the operation of SHP and electricity production. Heavy rainfall and strong winds (spikes), on the other hand, can destroy the infrastructure of hydropower plants (Igliński et al. 2020b).

Wind energy in the Warmińsko-Mazurskie Voivodeship

The oldest type of windmill found in Poland is the trestle windmill—“koźlak” (Fig. 8). Koźlaki survived without structural changes until the twentieth century and constituted the most numerous group of windmills (Igliński et al. 2016).

Wind energy (aeroenergy) is developing quite well—at the end of 2019, there were 43 turbines/windfarms operating in the Voivodeship with a total capacity of 356.985 MW (Installations of RES 2019).

The technical potential of aeroenergy in the Warmińsko-Mazurskie Voivodeship was calculated. It was assumed that 140-m turbines will be erected, i.e. their height together with the propeller will be 215 m. As already mentioned, according to “Distance Act” (Distance Act 2016), the turbine must stand at a distance of at least 10 times the height (i.e. in this case at least 2150 m) from residential buildings and from selected forms of nature protection (national parks, landscape parks, reserves and Natura 2000 areas) and forest promotion complexes (Distance Act 2016).

Taking into account all the limiting criteria for the buffer of 2150 m, the area of the area available is 245 km², i.e. 1.0% of the territory of Warmińsko-Mazurskie Voivodeship (Fig. 9).



Fig. 8 Koźlak windmill in Olsztynek (Igliński et al. 2020b)



Fig. 9 Area available for aeroenergy development for buffer 2150 m (own study)

Methodology for calculating the technical potential of wind energy in the Warmińsko-Mazurskie Voivodeship.

The kinetic energy of air movement E_k (J) of mass m (kg) moving at a speed of v (m/s) is determined by a formula known from classical mechanics:

$$E_k = \frac{1}{2} \cdot m \cdot v^2 \tag{12}$$

While the power P_w of air flowing in time is:

$$P_w = \frac{E_k}{t} \tag{13}$$

Taking into account that the mass of air of density ρ flowing in time t through the surface S (e.g. the surface drawn by the rotor blades, i.e. the so-called wind wheel) equals:

$$m = \rho \cdot S \cdot v \cdot t \tag{14}$$

this is replaced by the expression for the power of air flowing through the wind wheel:

$$P_w = \frac{1}{2} \cdot \rho \cdot S \cdot v^3 \tag{15}$$

Air density depends on current weather parameters, i.e. temperature and pressure. The average air density shall normally be used for the calculation $\rho = 1.25 \text{ kg/m}^3$. Equation (16) represents the kinetic energy of the wind flowing through a unit area perpendicular to the wind direction in time t (Igliński et al. 2020b):

$$P_w = 0,625v^3 \tag{16}$$

In order to calculate how much energy can be obtained from wind turbines, hourly data on wind speeds were obtained from Institute of Meteorology and Water Management. They were allocated to the groups: 0 m/s, 1 m/s, 2 m/s, 3 m/s etc. It is assumed that the energy use of the wind starts at 3 m/s, while the full power of the turbine reaches at 10 m/s. At a speed of 25 m/s and more the turbine is switched off and no electricity is produced. Data from meteorological stations in Elbląg, Mikołajki and Kętrzyn were taken for analysis. It was assumed that the turbines will be placed on 50% of the available area (Igliński et al. 2020b).

The technical potential of aeroenergy in Warmińsko-Mazurskie Voivodeship is 7.3 PJ (2.05 TWh).

SWOT analysis of aeroenergy in the Warmińsko-Mazurskie Voivodeship.

Table 3 presents the SWOT analysis of aeroenergy in Warmińsko-Mazurskie Voivodeship.

Table 3 SWOT analysis of aeroenergy in the Warmińsko-Mazurskie Voivodeship

Strengths	Weaknesses
Good wind conditions, especially in the northern part of the region	“Distance Act”
High interest from investors	Large area of the province covered by NATURA 2000 areas and other forms of protection
Well mastered technology	Complicated, lengthy investment preparation procedures
Financial support, including green certificates and auctions	The lack of acceptance of certain social groups for large wind energy
	Limited possibilities to connect to the energy networks
	Impact to humans and birds
	Interference with the landscape of large wind power plants
Opportunities	Threats
Development of the Polish aeroenergy industry	Climate changes
Entry into the market of local producers and distributors of small wind power plants	Lack of a clear energy policy
Interest of local investors in small wind energy	

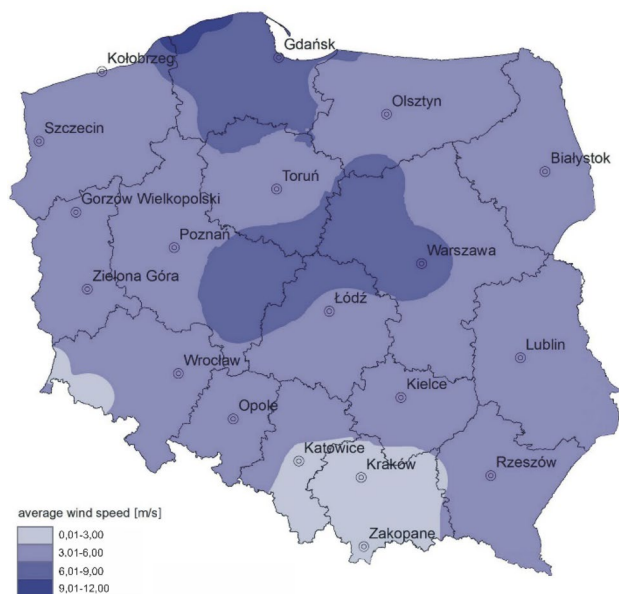


Fig. 10 Wind speed at a height of 140 m (own study)

Strengths

The strengths of aeroenergy include the fact that Warmińsko-Mazurskie Voivodeship has good wind conditions, especially in its southern part (Fig. 10), and thus a high theoretical potential of wind energy.

Wind energy, even in view of the “Distance Act”, enjoys great interest among investors. It also results from the considerable profits from the investment, following the example of other owners of power plants or wind farms and the desire to protect the environment. (Igliński et al. 2020b).

Wind energy producers in the Warmińsko-Mazurskie Voivodeship are extensive experienced—for over two decades wind power plants have been operating there (Igliński et al. 2020b).

Wind turbines launched by the end of June 2016 can count on financial support in the form of green certificates. The new Act (Act 2015) introduces auctions in place of the existing certificates (Act 2015).

Weaknesses

Introduced in 2016. “Distance Act” (Distance Act 2016) has practically brought to a standstill the development of aeroenergy in Warmińsko-Mazurskie Voivodeship.

In order to obtain a construction permit for a wind turbine, it is necessary to obtain an environmental decision which may require an environmental impact assessment procedure. Having a valid decision on environmental conditions, the investor may apply for issuing a decision on development conditions or, if a local development plan is in force

in the area covered by the application, almost may immediately ask for a construction permit (Igliński et al. 2016).

A significant area of the Warmińsko-Mazurskie Voivodeship is covered by Natura 2000 and other forms of nature protection, which implies that no wind turbines may be built in these areas (as well as in adjacent areas) (Igliński et al. 2016).

The construction of wind turbine is often associated with resistance from environmental groups, emphasising the negative impact of turbines on people, fauna and landscape (Igliński et al. 2016).

Investors wishing to develop aeroenergy in the Warmińsko-Mazurskie Voivodeship have increasing problems with connecting installations to the power grid. This is due to the poor condition of the power grid, as well as too many connection permits issued so far, many of which are only “virtual” (declared on paper) (Igliński et al. 2016).

Wind turbines have a negative impact on humans and fauna, especially birds and bats. In the Warmińsko-Mazurskie Voivodeship, this is the case with poorly established older wind turbines. The very close proximity of wind turbines, and in particular the noise and infrasound emitted by them, can cause a symptom complex that begins with the start-up. They are sometimes referred to as “wind turbine syndrome”.

Wind turbine as high object (more and more often than 100 m), with a colour contrasting with the background of the sky and the earth’s surface with its various forms of use, in addition to being mobile, influence the landscape. The majority of cases in when the wind power plants are believed to have significantly damaged the landscape values of the area are related to location mistakes made in the initial phase of aeroenergy development in Poland. This often results in the accumulation in a relatively small area of many power plants of different types and heights, distributed irregularly, which creates a subjective sense of spatial “chaos” (Igliński et al. 2016).

Opportunities

As a result of the slow development of wind energy in Poland (as well as in the Warmińsko-Mazurskie Voivodeship) which is hampered by administrative barriers, it has not developed into the production of complete wind turbines. Instead, there is a relatively significant production and distribution of small wind turbines with high development potential (Igliński et al. 2020b).

It is predicted that in the coming years, small domestic wind turbines with a capacity of several kW will become increasingly popular. They will work with photovoltaic panels, heat pump and battery, making such a building zero- or plus-energy. Excess electricity will be consumed to power an electric car or sold to the grid. In this way a prosumer

society will develop, which will be a producer and consumer of energy (Igliński et al. 2020b).

Threats

Progressive climate change is leading to an increasing incidence of violent weather phenomena such as hurricanes, hailstorms and trumpets. These phenomena can have a negative impact on the operation or even destroy turbines and the power grid (Igliński et al. 2020b).

The last months have brought new information on the vision of the future of the energy sector in Poland. Much has been said about nuclear power, about new coal-fired power stations, and then the position is changed by 180°, and it is said that the nuclear power station will not be built, and the power station in Ostrołęka will be the last coal (or perhaps gas) power station in Poland. The lack of clear plans for the future of the energy sector in Poland (as well as in the Warmińsko-Mazurskie Voivodeship) has a negative impact on every sector, including the areoenergy sector (Igliński et al. 2020b).

Solar energy in Warmińsko-Mazurskie Voivodeship

At the end of 2019, a total of 73 photovoltaic (PV) power plants with a total capacity of 43.208 MW were in operation in the Warmińsko-Mazurskie Voivodeship (Installations of RE 2019). Much more (thousands) of solar collectors were in operation.

Technical potential of PV in Warmińsko-Mazurskie Voivodeship.

PV on roofs

As the combustion of solid biomass and biogas covers the heat demand of the Voivodeship, it was assumed that PV panels would be installed. It was assumed that photovoltaic will cover 10% of roofs in the Warmińsko-Mazurskie Voivodeship. It was calculated how much electricity can be obtained with the efficiency of PV panels 15%, using the formula (Igliński et al. 2020b):

$$E_r = 0.1 \cdot 0.15 \cdot S_r \cdot S \cdot I \quad (17)$$

where: E_r —annual energy to be obtained from PV on roofs [J/year],

S_r —surface of roofs (62.3 km²) (m²),

S —sunshine (h/year), converted into (s/year),

I —insolation (W/m²).

The obtained annual potential is 695 TJ, which is 0.193 TWh.

Waste land

The Warmińsko-Mazurskie Voivodeship has a significant wasteland area of 67.7 thousand ha (Central Statistical Office 2019a). It has been assumed that it is technically possible for 10% of the wasteland area to be recultivated in the “energy” direction and to place solar power plants on it. The sunshine and insolation of individual areas of Poland was taken into account (data were obtained from Institute of Meteorology and Water Management), and then it was calculated how much electricity can be obtained with the efficiency of photovoltaic panels 15%, using the formula (Igliński et al. 2020b):

$$E_w = 0.10 \cdot 0.15 \cdot S_w \cdot S \cdot I \quad (18)$$

where: E_w —Annual energy to be obtained from photovoltaics on waste land (J/year),

S_w —Surface of waste land (m²),

S —Sunshine (h/year), converted into (s/year),

I —Insolation (W/m²).

It will be possible to produce 3 385 TJ of energy, or 0.94 TWh in the Voivodeship.

PV on roads

The total length of hard paved public roads in the Warmińsko-Mazurskie Voivodeship is 13,843 kms (Igliński et al. 2020b). It has been assumed that it is technically possible to build 10 m wide PV panels on 5% of the road length. It was calculated how much electricity can be obtained with the efficiency of PV panels 15%, using the formula:

$$E_m = 0.05 \cdot 0.15 \cdot L \cdot S \cdot I \quad (19)$$

where: E_m —annual energy from PV at motorways and expressways (J/year),

L —length of motorways and expressways (m),

S —sunshine (h/rok), converted into (s/year),

I —insolation (W/m²).

The calculated amount of obtainable electricity is 3.86 PJ (1.072 TWh). The electricity produced can be used to power traffic lights, roadside bars, restaurants etc.

The total technical potential of the PV in the Warmińsko-Mazurskie Voivodeship is 2.20 TWh.

Table 4 SWOT analysis of solar energy in Warmińsko-Mazurskie Voivodeship

Strengths	Weaknesses
Well developed network of installers and distributors of collectors and panels	High installation costs
Very high social acceptance	Seasonality of energy generation
Possibility of obtaining funding	
Possibility of use in places not connected to the power grid	
Low operating costs of the installation	
Low failure rate of the solar system and low maintenance needs	
Can be combined with other installations	
Opportunities	Threats
Very high interest of investors in PV	Progressing climate change
Expected major technological progress in PV cells	
Development of perovskite	
Dropping prices of photo cells	
Increasing efficiency of photo cells	

SWOT analysis of solar energy in Warmińsko-Mazurskie Voivodeship

Table 4 presents the SWOT analysis of solar energy in Warmińsko-Mazurskie Voivodeship.

Strengths

Every year in Poland (and in the Warmińsko-Mazurskie Voivodeship) there is a developed network of installers and distributors of solar collectors and PV panels. More and more offers cause prices to gradually decrease (Igliński et al. 2020b).

The construction of a solar system can be subsidised with EU or national funds. Priority programme “My Current”

(My Current 2020) is a unique instrument in Poland to date, dedicated to supporting the development of prosumer power generation, and specifically to support the PV microinstallations segment. The implementation of the programme is a strong impulse for further development of the prosumer power industry and significantly contributes to the fulfilment of Poland’s international obligations in the field of renewable energy development. Up to now, the effects of the „My Current programme”—73 000 grant applications—have amounted to 408 MW of installed capacity (My Current 2020).

The strong points of PV include the fact that the installation of PV panels together with an energy storage facility provides electricity in places where access to the power grid is difficult, e.g. on the islands in Warmińsko-Mazurskie Voivodeship (Igliński et al. 2020b).

Fig. 11 Photo of the PV installation on the roof of Pisz heating plant (Igliński et al. 2020b)



The low operating costs and low maintenance needs of solar installations are also strong points (Igliński et al. 2020b). Figure 11 shows a PV installation on the roof of Pisz heating plant.

Combining solar installations with other RE installations, e.g. with heat pumps or hydroenergy (Velloso et al. 2019; Zhu et al. 2020), is becoming increasingly popular. A PV installation provides electricity for the heat pump, which in turn supplies central heating and domestic hot water. Excess electricity may power an electric car or be sold to the electricity grid (Igliński et al. 2020b).

Weaknesses

Solar installations are still quite expensive, which is why few private individuals decide to use them without funding. The price of the PV system for Olsztyn is from about 18 thousand PLN (1 PLN=0.26 USD) for 3.33 kW panels and about 38 thousand PLN for 9.99 kW panels (Igliński et al. 2020b). Despite the annual price drop, the price of the solar system is still quite high, which means a long payback period. The collectors are cheaper, the whole set can be bought for less than 10 thousand PLN (Igliński et al. 2020b).

The weak points include the fact that the climatic conditions of the Warmińsko-Mazurskie Voivodeship result in large disparities in the amount of solar energy reaching us during the year. Most of the total annual amount of sunshine falls in the six months of the spring–summer season, from the beginning of April to the end of September, with the time of solar operation in summer being extended to 16 h a day, while in winter it is reduced to 8 h a day (Igliński et al. 2020b).

Opportunities

In Poland, as well as in the Warmińsko-Mazurskie Voivodeship, a boom for collectors and especially PV is observed. Collectors and panels are assembled by private persons, public companies, companies. This boom is expected to continue and only by the end of 2020 the total PV capacity in Poland will exceed 3 GW (Igliński et al. 2020b).

All over the world, many scientific centres are working to improve existing materials or develop new materials for solar installations. Perhaps the perovskites will soon revolutionise PV. The advantages of these minerals are indeed many, and the most important among them are: high light absorbing capacity, flexibility, transparency and lightness. The cells can be used to cover a wide range of materials—from thin PET films, through tiles and walls, to clothes and electronics. In this way, each of these objects would become

a mini power plant producing clean energy (Igliński et al. 2020b).

Since 1977, the price of a photocell, per unit of electric power, has fallen nominally by about 250 times—from USD 76 to almost 30–35 cents per watt; it is worth noting at this point that the real fall in this price was even greater, because over 40 years the value of money, including American money, has fallen significantly (Igliński et al. 2020b).

The opportunities include the fact that the fall in the price of PV cells has been accompanied in the last three decades by a several-fold increase in their efficiency, which nowadays is in the order of 10–30% (depending on the type), and in the case of the most efficient ones (four-connector cells with a so-called concentrator) it is close to 50%. (Igliński et al. 2020b).

Threats

Progressive climate change is a threat to solar energy in the Warmińsko-Mazurskie Voivodeship. Hailstorms or whirlwinds can damage the solar power installation. Long-lasting heat adversely affects the operation of solar collectors or panels.

Heating pumps in Warmińsko-Mazurskie Voivodeship

There are no good conditions for the development of deep-sea geothermal energy in the Warmińsko-Mazurskie Voivodeship. However, it is possible to successfully roll up heat pump technologies. It was assumed that they will be installed in public facilities.

Potential of heating pumps.

Heating pumps in schools and pre-schools

In the school year 2018/2019, there were 2,134 school and preschool establishments in the Voivodeship (Schools 2019). It has been assumed that on average every 10th institution with an area of 1500 m² of building will be heated, while the heating power of the heat pump will amount to 70 W/m². The total power of the heat pump P constitutes the product of the area and 70 W/m² unit power. Assuming an operating time of 2000 h per year and a COP (Coefficient Of Performance) 3.8, the annual heat output can be calculated (Igliński et al. 2020b):

$$E_h = P \cdot COP \cdot t \quad (20)$$

where:

E_h —Annual energy generated from heat [MJ/year],

P —Total power of heating pumps [MW],
 COP —Coefficient Of Performance,
 t —average annual operating time of the heat pump (2000 h/year = 7 200 000 s/year).

The potential calculated for heating pumps in schools is 0.61 PJ.

Heating pumps at accommodation facilities

In 2018, there were 507 tourist accommodation facilities in Warmińsko-Mazurskie Voivodeship: hotels, motels, guest-houses (Hotels 2018). It was assumed that 10% of such facilities will have a heating pump, the average area of a single facility is 1000 m², and the heating power of the heat pump is 70 W/m². Assuming that the heating pumps operate for 2000 h per year, it has been calculated on the basis of formula (20) that the annual heat production in tourist accommodation facilities will be 0.10 PJ.

Heat pumps in cultural facilities

In 2018, a total of 507 cultural facilities operated in the Voivodeship (Central Statistical Office 2019c). It was assumed that 10% of such facilities will have a heat pump, the average area of a single facility is 500 m², and the heating power of the heating pump is 70 W/m². Assuming that the heat pumps operate for 1500 h per year, it has been calculated on the basis of formula (20) that the annual heat production in cultural facilities will be 0.04 PJ.

Heating pumps in churches

In 2017, there were 569 churches in the Warmińsko-Mazurskie Voivodeship (Central Statistical Office 2017). It was assumed that 10% of the churches will have a heating pump, the average area of a single church is 1200 m² and

the heat pump heating power is 70 W/m². Assuming that the heat pumps will operate for 1500 h a year, it has been calculated on the basis of formula (20) that the annual heat production in churches will be 0.10 PJ.

SWOT analysis of heating pumps in Warmińsko-Mazurskie Voivodeship

Table 5 presents the SWOT analysis of heat pumps in Warmińsko-Mazurskie Voivodeship.

Strengths

The heating pump does not emit gases directly, does not generate waste water or waste. If the heating pump is powered by RE, then there are no indirect emissions either (Igliński et al. 2010).

New heat pumps consume relatively little electricity thanks to their ever higher efficiency. If the entire installation is properly sized, the operating costs are low (Igliński et al. 2012).

The lower source of heating pumps can be selected according to needs and location possibilities. A characteristic feature of heating pumps is that the temperature of the lower source can be lower than the required temperature of the heating medium, which allows the use of low-temperature energy sources such as:

- Air (external or exhausted),
- Surface water,
- Soil,
- Underwater soil,
- Low-parameter geothermal waters,
- Sewage waste (Igliński et al. 2010).

Table 5 SWOT analysis of heating pumps in Warmińsko-Mazurskie Voivodeship

Strengths	Weaknesses
No harmful effects on the environment	High investment costs
Low exploitation costs	Low knowledge on heating pumps
Wide range of lower heat source	
Comfort of usage	
Low failure rate	
Very high rate social acceptance	
Opportunities	Threats
State and EU investment funding	High risk in drilling exploratory wellbores and the associated variable investment costs
Cooperation with other RE installations	Lack of effective promotional policy towards heating pumps

Heating pumps are convenient to use and almost faultless. The owner of the longest running heating pump (since 1996) stresses that it is still working without any failures (Igliński et al. 2010).

One of the strong points is that heating pumps, like solar installations, are very popular among the Poles. One can even say that having a heating pump has become fashionable (Igliński et al. 2010).

Weaknesses

The weak points of heating pumps are their high investment costs. It is worth being stressed that their cost is relatively low in newly constructed buildings with underfloor heating. The cost of installing a heating pump is several thousand. High costs make the return on the purchase of a heat pump quite long (Igliński et al. 2020b).

Weak points include the fact that older people in particular are very reserved in their approach to alternative energy sources, which is mainly due to their lack of knowledge. People are afraid that the heat pump will not work for them. However, it should be mentioned here that over the last decade (Igliński et al. 2010), knowledge about RE and heat pumps has been gradually increasing.

Opportunities

The installation of heating pumps is a great solution in the fight against low emissions, and therefore also against smog. This has been noticed by EU and national authorities, thanks to which there are already and will soon be funds or credits to be obtained for the installation of the heating pumps. For example in the “Clean Air Programme” (Clean Air Programme 2020), the highest possible levels of co-financing are to apply to investments in heat pumps (and photovoltaics), for which so far in the “Clean Air Programme” only financing could be obtained in the form of preferential loans—and not subsidies as in the case of other equipment (Clean Air Programme 2020).

Table 6 Annual amounts of electricity and heat from RE in the Warmińsko-Mazurskie Voivodeship

	Energy volume (TWh/year)	Heat volume (PJ/year)
Bioenergy	2.54	14.99
Hydroenergy	0.14	
Aeroenergy	2.05	
Solar energy	2.20	
Heating pumps		0.85
Total	6.93	15.84

Opportunities include the fact that heating pumps can work with other RE installations, e.g. with photovoltaic panels.

Threats

Heating pumps provide a very good solution for air pollution (smog) in Poland. Nevertheless, there is still no effective promotional policy. Central and local authorities should introduce more programmes supporting further development of “shallow” geothermal energy in Poland (Igliński et al. 2020b).

Perspectives and summary

The paper describes the current state of RE in the Warmińsko-Mazurskie Voivodeship, estimation of the technical potential of RE sources and development prospects. The voivodeship has great development potential in terms of biomass, wind energy and solar energy. However, it is worth developing each sector of RE, as only the RE mix will ensure the region’s energy self-sufficiency.

The Warmińsko-Mazurskie Voivodeship has the appropriate RE potential to ensure its energy self-sufficiency. Table 6 presents the technical potential RE in the Warmińsko-Mazurskie Voivodeship. The energy mix should be developed, based mainly on bioenergy, aeroenergy and solar energy.

In 2018, 4 TWh of electricity and 12 PJ of heat were consumed in the Warmińsko-Mazurskie Voivodeship. The calculated technical potential indicates that the Voivodeship could store excess electricity in energy warehouses and electric cars. Answering the question “Can energy self-sufficiency be achieved?” it should be confirmed that it is possible. The Warmińsko-Mazurskie Voivodeship has such a large potential of the RE mix that it may become self-sustaining when it comes to electricity and heat. Similar preliminary calculations were previously carried out by the authors for the remaining 15 voivodeships in Poland. Almost every one has a surplus of the potential of the RE mix—and as a whole, Poland could base its energy and heating sectors on the RE mix.

The Warmińsko-Mazurskie Voivodeship could in the near future become an exporter of electricity/energy carriers such as hydrogen. “Green” hydrogen which will be generated by electrolysis can be exported to other Voivodeships or even countries (the Voivodeship borders with Russia and Lithuania).

The development of domestic RE installations, their assembly and conservation work is a huge impulse for the economic development of the Warmińsko-Mazurskie Voivodeship. And to start with, the development of RE is

a new, relatively well-paid job in rural regions with quite high unemployment. A RE power plant/installation is not only jobs, but also big financial benefits, as it pays various types of taxes, VAT, pays money to the Labour Fund and Guaranteed Employee Benefits Fund, tax on natural persons and legal entities, as well as various types of operating fees, supports local culture.

The sustainable use of RE in the Warmińsko-Mazurskie Voivodeship will make it possible to radically reduce emissions of harmful compounds, including dusts responsible for smog. RE also generates less waste than conventional fuels. Improved air quality will have a positive impact on the health of the inhabitants, as well as attracting more tourists. The Polish “Green Lungs” will really become green.

The development of RE favours a decentralised society, powered by a network of smaller and safer power plants and the strengthening of local communities. A significant part of energy production (biogas, biomass, solar, etc.) will be transferred to agricultural land, followed by economic benefits. Today, money to buy fuel and electricity flows out of the countryside in a wide stream, impoverishing it. The development of RE means that it is the inhabitants of rural areas who will be the beneficiaries—it is they who will supply waste to biogas plants, and solar farms, for example, will operate on their territory. It is they who will become successful being employed in new plants producing energy from RE sources. Farmers’ incomes will be diversified. Own energy production will also improve the quality of rural infrastructure and quality of life. Energy networks in rural areas are often in a terrible state and this situation is not improving—energy concerns do not want to invest there, because extensive infrastructure is expensive and there are few recipients.

Increasing the share of RE in the national energy economy increases the energy security of the state. It favors the diversification of the energy sector by reducing dependence on suppliers of fossil fuels. Thanks to the commonness of RE sources, this type of energy can take a dispersed form and solve the problems of areas suffering from an energy deficit and those with numerous interruptions in energy supply. The development of technologies processing RE carriers may, in the longer term, lead to lower energy production costs.

It should also be pointed out at this point that the increase in electricity obtained from RE, in addition to having a smaller negative impact on the natural environment than conventional energy sources, may translate into an improvement in national energy security. Thus, an actual increase in the share of electricity from RE may contribute to the gradual implementation of the idea of sustainable development in the social and economic being of a given country.

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