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Symbiosis of Renewable Energy and Green Hydrogen at the Regional Level: The Example of the Kujawsko-Pomorskie Voivodeship in Poland

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Abstract

Both the energy sector transition processes and the industry transformation processes should in the future be based on the use of green hydrogen (GH) obtained using renewable energy sources (RES). It is the symbiosis of RES and GH that will allow for a sustainable energy transformation of the entire economy. The calculated amount of RES in the Kujawsko-Pomorskie Voivodeship (Poland) is 18 TWh—this would provide 4.2 billion m^3 (under normal conditions) (0.38 million tons) of GH. The amount of GH produced from RES surpluses in the voivodeship is about 30% of the current production of GH from fossil fuels in Poland. The calculated GH would power 2.64 million cars. The Kujawsko-Pomorskie Voivodeship has numerous salt caverns where GH can be stored. The most important barrier in the context of GH production remains the effective construction of a hydrogen economy chain, which requires a simultaneous costly transformation of the supply and demand sides. In order to implement GH technology, it is necessary to reduce the costs associated with its production, storage and transmission.

Keywords: renewable energy; hydrogen; green hydrogen; Kujawsko-Pomorskie Vovivodeship

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1. Introduction

Energy is probably the main technology that determines the rapid development of any country today, as every economic process requires energy, heat, and cooling. However, never before have the economy and social life been so dependent on it. Providing affordable and clean energy is essential for the proper functioning of the global economy, individual households, and, consequently, for the quality of life. On the other hand, conventional energy production from fossil fuels is the largest source of pollutant and greenhouse gas emissions, primarily CO_2. This dangerous anthropogenic burden on the biosphere leads to an imbalance in the course of global natural processes. Without immediate action, climate change will become increasingly severe worldwide, particularly in poor countries in Africa and Asia [1]. This would mean increased migration, including to Europe (and Poland) (climate migration) [2].

Renewable energy sources (RES) are energy obtained from renewable natural resources. RES come in various forms and are generated directly or indirectly by sun energy, heat from the Earth's interior (geothermal energy), and tides [3–5].

In 2024, the largest RES capacity was installed in China (445 GW), followed by Europe (92 GW) and Asia and Oceania (excluding India and China) (73 GW). Significant capacity increases were recorded in India (36 GW) and Brazil (18 GW) (Figure 1) [6].

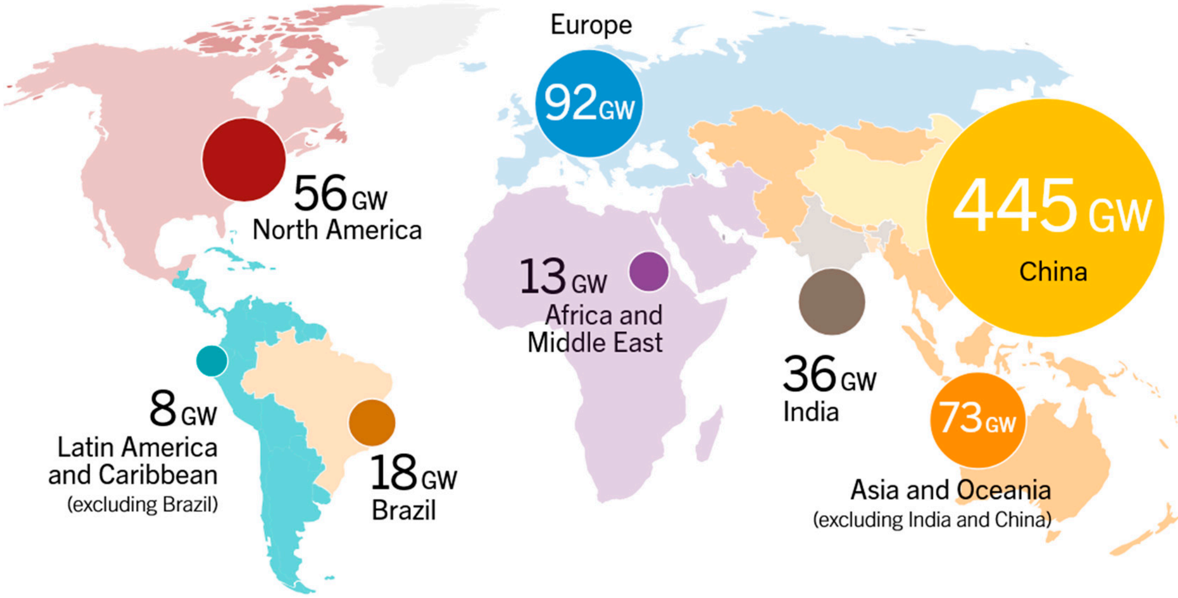

Figure 1. Growth in renewable energy capacity [GW] in the world in 2024 (adapted from [6]).

The energy transition involves the development of new technologies, and therefore the creation of new, well-paid jobs. The countries with the highest employment in the RES sector in 2024 are China, Brazil, the USA, India, Japan and Germany. Of all the RES market sectors, the largest employment was recorded in companies related to photovoltaics (PV), which employ around 5.0 million people (2.5 million in 2014). The second largest sector is biofuels, which employs 2.5 million people. The third is the hydropower sector [7].

One of the most important tasks facing the authorities of the Kujawsko-Pomorskie Voivodeship is to carry out the energy transition in the next decade. In their energy policy, the authorities of the voivodeship assume a departure from the use of energy sources based on fossil fuels and replacing them with energy obtained from RES. For the first time, local government authorities have strongly emphasized this goal in the adopted development strategies of the region. In the longer term, the goal is to achieve zero emissions and energy self-sufficiency in the voivodeship. This is an ambitious task, if we take into account the current indicator of the share of RES in electricity production in the Kujawsko-Pomorskie Voivodeship, which has reached a level of around 50% in recent years. One of the priorities of the voivodeship by 2030 is the total production of electricity from RES. In the opinion of the local government authorities, the region has predispositions for the large-scale development of small installations based on solar and geothermal energy. The regional authorities want to maintain the local character of RES development through the implementation of distributed energy systems based on housing cooperatives. In their opinion, further development of RES will bring measurable environmental benefits and will increase the level of energy security of the Kujawsko-Pomorskie Voivodeship. Providing an adequate amount of RES at the local level will also cover energy needs at the national level [8].

The process of transiting the energy sector and industry towards the use of RES requires the use of green hydrogen (GH), which allows us to "stabilize" the system, because some sources (wind energy and PV) of RES are unstable. In periods of overproduction of energy from RES, it can be used to produce pure GH, which in periods of energy shortage from RES could be used in the energy sector or industry. It should be emphasized that hydrogen is a fuel that can play a key role in the process of decarbonization of industry, energy, heating and transport [9]. Hydrogen technologies will be developed in heavy transport, including buses and public transport. In industry, the main recipients of H_2 will remain those that currently consume mainly grey H_2, produced from fossil fuels, and which will have to decarbonize. This means the refining, chemical and steel sectors, as well as industries where electrification is expensive or impossible to carry out.

The aim of the study is to present the possibilities of symbiosis of renewable energy and green hydrogen at the regional level. The symbiosis process is understood as a broad approach: not only the technical approach of converting RES energy into hydrogen, but also the potential consequences for the development of the economy and societies. In Poland there is lack of integrated RES-GH assessments at the voivodeship level. As part of the implementation of the goal, the current state of the RES mix in the Kujawsko-Pomorskie Voivodeship and the energy potential and development prospects will be presented. Then, the issue of the possibility of producing GH from RES will be discussed. The positive effects of symbiosis in the form of the possibility of using GH in the energy sector, heating, transport and industry will be indicated and discussed. This means that the symbiosis of RES and GH (Figure 2) is one of the most important elements contributing to the energy transition processes.

Figure 2. Symbiosis of renewable energy and green hydrogen (own elaboration).

Expanding the renewable energy system is a key pillar of ensuring energy security. It also aligns perfectly with the trend of decentralizing energy production. It is a path toward climate and environmental protection, which is also a priority in Polish and EU policies.

2. Literature Overview

There are as yet few articles on the "symbiosis" of RES and GH. This is a new topic, only just being analyzed by engineers and scientists.

Panchenko et al. [10] described the advantages of implementing agrivoltaics (APV) and GH in the modern world. The authors presented relevant examples of the use of PV converters in agriculture and GH production. They also presented innovative agricultural machinery and autonomous robots used in APV systems that could use GH as a fuel.

Eljack and Kazi [11] described a symbiosis approach aimed at optimizing the interaction between various industries and urban planning by examining several multifunctional hydrogen applications that, with appropriate planning, could be effectively implemented.

Butturi and Gamberini [12] explored the topic of creating synergies between rural areas and industrial clusters where hydrogen will be used. Hydrogen will enable sustainable cluster development and the implementation of low-emission mobility.

Sorrenti et al. [13] used the Skive GreenLab (the first industrial plant of its kind in the world) for the symbiosis of RES and GH. They observed a reduction in production costs and significantly lower CO_2 emissions than conventional installations.

Afferry et al. [14] analyzed a case study: the symbiosis of solar energy and a palm oil factory. They proposed greenhouse gas mitigation. These actions are consistent with the commitment to combat climate change and achieve the Sustainable Development Goals set out in the global agenda.

Reda et al. [15] analyzed the potential for hydrogen as a key element of the energy mix. Currently, almost all global hydrogen production relies on steam reforming of methane, which generates significant greenhouse gas emissions and disqualifies grey hydrogen as a clean energy source. The solution lies in the symbiosis of RES and GHG through hydrogen electrolysis. Hydrogen infrastructure, storage and transport systems, charging stations, and hydrogen transport also need to be developed.

Arun et al. [16] proposed a hybrid electrolysis and combustion Smart Grid system. This system allows for seamless integration of hydrogen production, transport, and storage, which in turn ensures grid stability. Hydrogen production efficiency of 98.5% was achieved, while combustion efficiency was 98.1%.

GH production appears to be an effective and more sustainable alternative to conventional methods, although it still faces various barriers to its wider application. These problems can be solved by implementing so-called industrial symbiosis (IS). The aim of the review [17] was to apply the IS concept to GH production. A broad bibliometric review of publications indexed in the Scopus database was conducted, selecting the most important literature. The results indicate that the topic represents a new area of interest, and there was also a low concentration of data within a single author or country. It was also concluded that the analyzed topic is at a developmental stage.

The renewable energy potential was also calculated for other voivodeships in Poland: Pomorskie [18], Warmińsko-Mazurskie [5], Wielkopolskie [19], Zachodnioporskie Voivodeship [20]. It is worth noting that the regional RES potential covers the energy needs of each voivodeship, which could also produce GH. Furthermore, since individual regions in Poland have surpluses of RES from which GH could be produced, Poland as a whole has sufficient RES potential to produce both energy and GH.

3. Renewable Energy in the Kujawsko-Pomorskie Voivodeship—Current State and Energy Potential

It was calculated how much energy from RES could be obtained in the Kujawsko-Pomorskie Voivodeship. This energy could later be used to produce GH.

3.1. The Use of Biomass for Energy Purposes in the Kujawsko-Pomorskie Voivodeship

In the Kujawsko-Pomorskie Voivodeship, the total capacity of biomass-based installations is 177.225 MW. In the voivodeship, there are entities that produce biomass and use it for energy purposes. Biomass is also used in collective heating systems. They are of various scales, usually small, operating for the needs of companies, housing cooperatives, public utility buildings, etc. They mainly use local biomass [21].

The largest plantation of energy plants is located near Grudziądz and has an area of 315 ha. Biomass is produced for OPEC-BIO in Grudziądz. The owner previously grew strawberries, but had problems with seasonal workers, so he introduced the cultivation of miscanthus.

In the Kujawsko-Pomorskie Voivodeship there are also gas production facilities at landfills, including in Bydgoszcz, Toruń, Grudziądz, Rypno and Machnacz. Agricultural biogas plants are located in Mełno, Starorypin Prywatne, Liszków, Wąpielsko, Radojewice, and Jeżewo [21].

In our calculations, 40% of waste wood from forests and forest industry during felling and processing in the wood industry could be used for energy purposes with 80% efficiency [22]:

$$E_w = 0.4 \cdot 0.8 \cdot A_w \cdot C_f \quad (1)$$

where: E_w—annual energy from waste wood generated during deforestation and wood processing in the woodworking industry [PJ/year],

A_w—the amount of wood harvested annually in forests (mln m^3/year),

C_f—calorific value of wood from forests (7 GJ/m^3).

The estimated amount of energy that could be obtained annually from waste wood in the Kujawsko-Pomorskie Voivodeship is 4.91 PJ/year.

According to data from the Central Statistical Office, the area of orchards in the Kujawsko-Pomorskie Voivodeship was 8.11 thousand ha [23]. Waste wood comes from grubbing-up and fruit tree maintenance. The amount of biomass generated from grubbing-up averages 80 Mg/ha of wood in old plantations and 60 Mg/ha in new low-stem plantations. In total, this amounts to an average of 3.5 Mg/(ha·year). In turn, the amount of biomass generated annually as a result of maintenance work averages 7 Mg/(ha·year):

$$E_o = 0.3 \cdot 0.8 \cdot (A_c + A_m) \cdot A_o \cdot C_o \quad (2)$$

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

A_c—the amount of wood obtained annually as a result of clearing a hectare of orchard (3.5 Mg/(ha·year)),

A_m—the amount of wood obtained annually as a result of maintenance work on a hectare of orchard (7 Mg/(ha·year),

A_o—orchard area [mln ha],

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

The calculated amount of energy form orchards in the Kujawsko-Pomorskie Voivodeship is 0.23 PJ/year.

The decline in the number of farm animals in Poland and the introduction of litter-free farming contributed to the creation of straw surpluses in agriculture. The amount of energy that could be obtained annually from surplus straw in the Kujawsko-Pomorskie Voivodeship is 8.57 PJ/year.

The Kujawsko-Pomorskie Voivodeship has a significant area of meadows and pastures; according to the data of the Central Statistical Office, it is 152.1 and 25.8 thousand ha, respectively [24]. Due to the reduction in livestock numbers and changes in animal feeding systems, most meadows and pastures in the voivodeship are not used now. In this study, it was assumed that hay obtained from meadows and pastures would be used as fuel.

Formula 3 shows the annual amount of energy that could be obtained from hay from unused meadows and pastures:

$$E_h = 0.15 \cdot 0.8 \cdot (m_m \cdot P_m + m_p \cdot A_p) \cdot C_h \quad (3)$$

where: E_h—energy from hay from meadows and pastures [PJ/rok],

m_m, m_p—mass of hay harvested annually from one hectare of meadows and pastures (4.9 Mg/(ha·year) and 3.6 Mg/(ha·year), respectively),

A_m, A_p—area of meadows and pastures [mln ha],

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

The potential of energy that could be obtained annually from hay in the Kujawsko-Pomorskie Voivodeship is 1.88 PJ/year.

The Kujawsko-Pomorskie Voivodeship has significant areas of fallow land and wasteland; according to data from the Central Statistical Office, these amounted to 4.7 thousand ha and 2.5 thousand ha, respectively [24]. They can be used to produce energy crops: grasses, cereals, trees or shrubs. In the study, it was assumed that it will be the basket willow *Salix viminalis*, i.e., a native species [22]. It was also assumed that 50% of fallow land, 20% of wasteland and 5% of agricultural land could be allocated to the cultivation of basket willow for energy purposes:

$$E_w = 0.8 \cdot Y_w \cdot (0.5 \cdot A_f + 0.2 \cdot A_w + 0.05 \cdot A_a) \cdot C_b \quad (4)$$

where: E_w–annual energy from basket willow grown on fallow and wasteland [TJ/year],

Y_w—annual yield of basket willow per hectare (8 Mg/(ha·year)),

A_f, A_w, A_a–area of fallow, wasteland and agricultural land [thousand ha],

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

The obtained energy from the biomass grown on fallow, wasteland and agricultural land in the Kujawsko-Pomorskie Voivodeship is 23.52 PJ/year.

The number of cattle, pigs and poultry in the Kujawsko-Pomorskie Voivodeship is 510 thousand, 845 thousand and 9.5 million, respectively. Biogas can be obtained from waste manure, and from biogas, electricity and heat can be obtained in cogeneration with 20% efficiency, with 60% methane content (taking into account large conversion units). Calculations of biogas obtained from bird droppings and slurry were made in accordance with Equation (5):

$$E_b = 0.2 \cdot 0.6 \cdot N \cdot M \cdot Y_b \cdot C_m \quad (5)$$

where: E_b—annual energy from biogas obtained from animal manure or bird droppings [TJ/year]

N—number of cattle, pigs and poultry, respectively [million livestock units],

M—annual mass of slurry from a large conversion unit [Mg/year],

Y_b–biogas yield from slurry [m^3/Mg],

C_m—calorific value of methane (35.73 MJ/m^3).

The calculated amount of energy that could be obtained from farm animal excrements in the Kujawsko-Pomorskie Voivodeship is 2.43 PJ/year.

In available sources we can find [25] that approximately 1,971,000 Mg/year of municipal waste is generated annually in the Kujawsko-Pomorskie Voivodeship, of which approximately half is the biodegradable fraction. The technical potential of biogas from municipal waste can be estimated at 20% of the theoretical potential. Biogas yield from the biodegradable fraction of municipal waste is 100 m^3/Mg. The obtained amount of energy from municipal waste in the Kujawsko-Pomorskie Voivodeship is 0.30 PJ/year.

In the Kujawsko-Pomorskie Voivodeship, 102.6 million m^3 of municipal sewage is treated annually [26]. It was assumed that 50% of the sewage flowing into the treatment plant would produce sludge (representing 1% of the incoming sewage), and 15 m^3 of biogas could be obtained from 1 m^3 of sludge. In the Kujawsko-Pomorskie Voivodeship, 7.8 million m^3 of biogas could be obtained, i.e., 0.13 PJ/year of energy.

3.2. Hydropower in the Kujawsko-Pomorskie Voivodeship

According to the estimates of the Kujawsko-Pomorskie Spatial and Regional Planning Office in Włocławek, the potential power of the rivers in the Kujawsko-Pomorskie Voivodeship is 367.90 MW, with the possibility of generating electricity worth 3222.89 GWh [27].

Based on data from the National Water Management Board [22] on the levelling drops and flows (more precisely, gullets) of water on individual impoundments, the theoretical electrical power of small hydropower plants that could be obtained on these impoundments was calculated:

$$P = 8.34 \cdot H \cdot \Theta \quad (6)$$

where: P—power plant capacity [MW],

H—height of water fall [m],

Θ—turbine flow, i.e., the volume of water flowing through the turbine per unit of time [m^3/s].

The total theoretical electrical power of small hydroelectric power plants in the impoundment province is 128.4 MW (Figure 3), which means that the energy production could amount to an average of about 800 GWh per year.

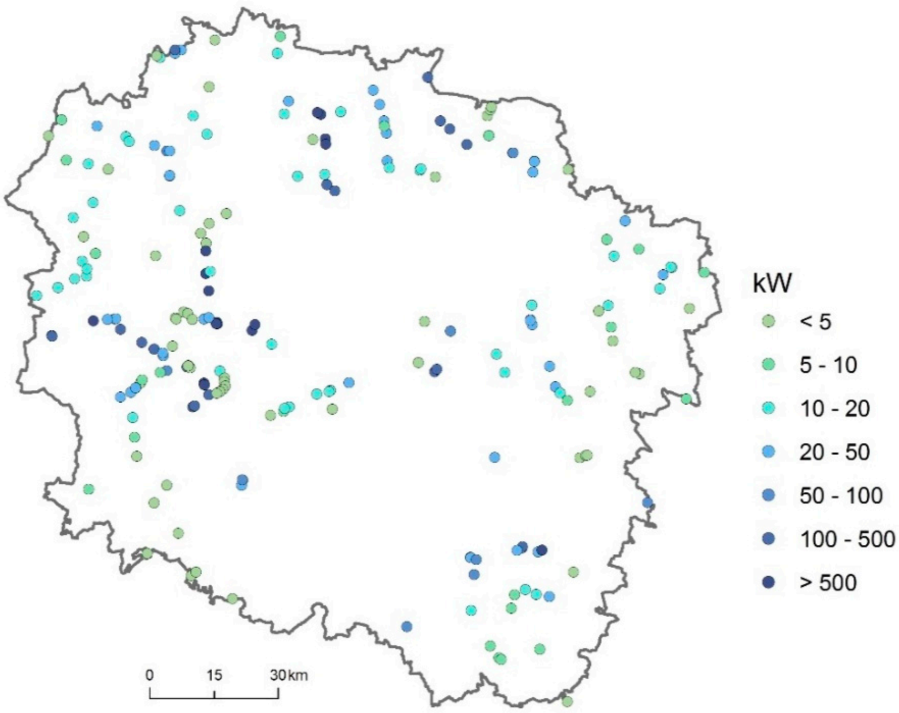

Figure 3. Location of existing impoundments and the capacity of small hydropower plants in the Kujawsko-Pomorskie Voivodeship (own elaboration).

3.3. Wind Energy in the Kujawsko-Pomorskie Voivodeship

The Kujawsko-Pomorskie Voivodeship has favorable conditions for the development of wind energy. Most of the voivodeship is located in the III wind resource zone, characterized by an average annual wind speed of 3.5–4 m/s. The southern part of the Voivodeship has even better wind resources with an average speed of 4–6 m/s. Currently, there are approximately 320 wind turbines operating there with a total capacity of 300 MW [21].

The technical potential of wind energy in the Kujawsko-Pomorskie Voivodeship was calculated. The turbine height, including the blade, was assumed to be 215 m. According to the new Distance Act [18], the turbine must be located at a distance of at least 10 times its height from national parks (i.e., 2150 m), 500 m from nature reserves and 700 m from residential buildings (Figure 4). The buffer zone for the remaining restrictions was based on an Act of Law [28].

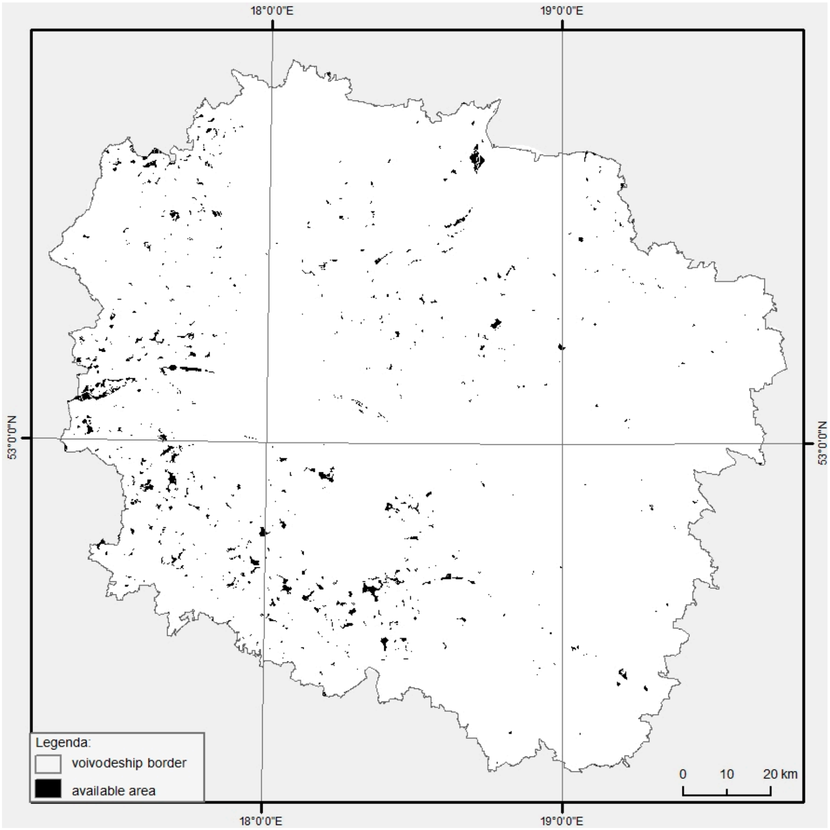

Figure 4. Area available for wind energy in the Kujawsko-Pomorskie Voivodeship (own elaboration).

Taking into account previous calculations, the area available for wind energy in the Kujawsko-Pomorskie Voivodeship is 3784 km^2. Calculations of wind potential were made in accordance with the methodology presented in [22]. Equation (7) represents the kinetic energy of the wind flowing through a unit area perpendicular to the wind direction at time *t*:

$$P_w = 0.625v^3 \quad (7)$$

where: P_w—capacity [MW],

v—wind speed [m/s].

The available amount of energy from wind is 12.25 PJ (3.43 TWh).

3.4. Solar Energy in the Kujawsko-Pomorskie Voivodeship

In the Kujawsko-Pomorskie Voivodeship, we have almost 100,000 energy prosumers, mainly having PV installations. The most popular are rooftop installations or those directly on the ground [29].

On one of the post-industrial water reservoirs in the Kujawsko-Pomorskie Voivodeship, the first commercial PV power plant in our country with a capacity of 500 kW was built, in which PV panels were placed on floating platforms. Such PV power plants have been built around the world for several years, but the installation that was carried out in Poland is probably the first project in the world in which the assembly of the structure and panels was carried out while the reservoir was covered with ice [30].

The PV potential in the Kujawsko-Pomorskie Voivodeship was calculated assuming that photovoltaic installations "do not take up" space. It was assumed that PV panels will be placed on roofs, on wastelands and by roads. The potential of APV in the voivodeship was also calculated [31].

APV is based on PV installations that are placed next to or above crops/pastures/meadows. The energy that could be obtained in the Kujawsko-Pomorskie Voivodeship was calculated assuming that 5% of arable fields and 10% of meadows and pastures will be used for APV [22]:

$$E_a = 0.15 \cdot A_u \cdot D \cdot I \tag{8}$$

where: E_a—electricity that can be obtained annually from agrovoltaics [TWh/rok],

A_u–usable area [km^2],

D—sunshine duration [s/year],

I—insolation [W/m^2].

In the Kujawsko-Pomorskie Voivodeship, APV on arable fields would allow for the production of 9.4 TWh of electricity per year.

It was assumed that PV would cover 10% of the roof surface in the Kujawsko-Pomorskie Voivodeship. The obtained annual amount of energy is 0.243 TWh/year.

The Kujawsko-Pomorskie Voivodeship has a significant area of wasteland, the surface of which amounts to 2.5 thousand ha [25]. It was assumed that it is technically possible to reclaim 10% of the area of wasteland for "energy purposes" and build PV installations on them. In the Kujawsko-Pomorskie Voivodeship, it is possible to produce 0.09 TWh/year of energy from PV on wasteland.

The total mileage of public roads with a hard surface in the Kujawsko-Pomorskie Voivodeship is 33,674 km [25]. It was assumed that it is technically possible to install 10 m wide PV panels on 10% of the length of the roads. The calculated amount of electricity that could be obtained is 5.15 TWh/year. The electricity produced could be used to power traffic lights, roadside bars, restaurants, etc.

It was assumed that 10% of roofs in the Kujawsko-Pomorskie Voivodeship would be covered with solar collectors. The amount of electric energy that could be obtained with the efficiency of solar collectors at 80% is calculated as follows:

$$E_c = 0.8 \cdot A_r \cdot D \cdot I, \tag{9}$$

where: E_c—heat that can be obtained annually from rooftop collectors [J/rok],

A_r—roof area [m^2],

D—sunshine duration [s/rok],

I—insolation [W/m^2].

The obtained annual amount of energy is 4.65 PJ.

3.5. Geothermal Energy in the Kujawsko-Pomorskie Voivodeship

In Toruń, there is a geothermal heating plant with a capacity of about 18 MW. Heat from the geothermal heating plant constitutes about 8% of heat in the heating system of Toruń. The ecological effect of Geotermia Toruń calculated with the estimated annual decrease in greenhouse gas emissions is 13.5 thousand tons of CO_2/year, while the production of heat energy is 81.5 GWh. Drillings were made in 8 locations, which can be used to obtain an estimated 500 GWh of heat [31].

Currently, there are 35–40 thousand heat pumps operating in the Kujawsko-Pomorskie Voivodeship, with a total capacity of 200–250 MW.

It was assumed that heat pumps in the Kujawsko-Pomorskie Voivodeship would be installed in kindergartens and schools. There were 1072 kindergartens and 1115 school facilities in the Kujawsko-Pomorskie Voivodeship [32].

Assuming an operating time of 2500 h per year and a heat pump COP (coefficient of performance) of 4.5, the annual amount of heat produced can be calculated:

$$E = P \cdot COP \cdot t \tag{10}$$

where: E—annual amount of heat produced [MJ/rok],

P—total power of heat pumps [MW],

COP—coefficient of performance,

t—average annual operating time of the heat pumps (2000 h/year) [11].

The potential of energy for heat pumps in kindergartens and schools is 1.132 PJ/year.

In the Kujawsko-Pomorskie Voivodeship, there were 1327 tourist accommodation facilities: hotels, motels and guesthouses [33]. The potential calculations were performed in accordance with the methodology presented in [22]. It is possible to obtain 0.905 PJ/year.

Analysis of the heat pump market leads to the conclusion that they are increasingly being installed in newly constructed buildings. It was assumed that in 5% of newly completed buildings within the next 10 years it would be technically feasible to install a heat pump with a heating capacity of 70 W/m^2. It was assumed that the pumps would operate for an average of 2500 h per year, which would increase the annual heat production in newly completed residential buildings by approximately 1.0 PJ each year.

3.6. Energy Self-Sufficiency in the Kujawsko-Pomorskie Voivodeship?

The question to be answered is whether the Kujawsko-Pomorskie Voivodeship could be 100% supplied with electricity and heat from RES. In 2023, 8.0 TWh of electricity and 42 PJ of heat were consumed in the Kujawsko-Pomorskie Voivodeship [34], while our calculations show that the technical potential is 23.75 TWh of electricity and 33.45 PJ of heat (Table 1). So the answer is—yes, the voivodeship could even be an exporter of electricity. The surplus of electricity could be used to power heat pumps and electromobility and be exported to neighboring voivodeships. However, heat production should be increased—biomass boilers should be introduced on a larger scale, the market for heat pumps and solar collectors should be developed and, most importantly, buildings in the Kujawsko-Pomorskie Voivodeship should be thermally modernized—thermomodernization will reduce heat consumption by 2–3 times.

Table 1. Total renewable energy potential in the Kujawsko-Pomorskie Voivodeship.

Type of RES	Electricity [TWh]	Heat [PJ]
Solid biomass	4.08	24.44
Biogas	0.30	1.43
Hydropower	0.80	
Wind energy	3.43	
Sun energy	14.64	4.65
Geothermal	0.50	
Heat pumps		3.04
Sum	**23.75**	**33.45**

4. Symbiosis of Green Hydrogen with Renewable Energy and Industry

GH is used in every branch of the energy and manufacturing industry. It can be used as a fuel in transport, replacing petroleum products, such as gasoline. The energy industry is focusing on H_2, both as a fuel and for storage of electrical energy. As a fuel, it would replace, for example, natural gas, used for heat production [35]. As a form of electrical energy storage, it is the answer to the future of the RES industry and reduces instability through the re-electrification process (Figure 5) [36].

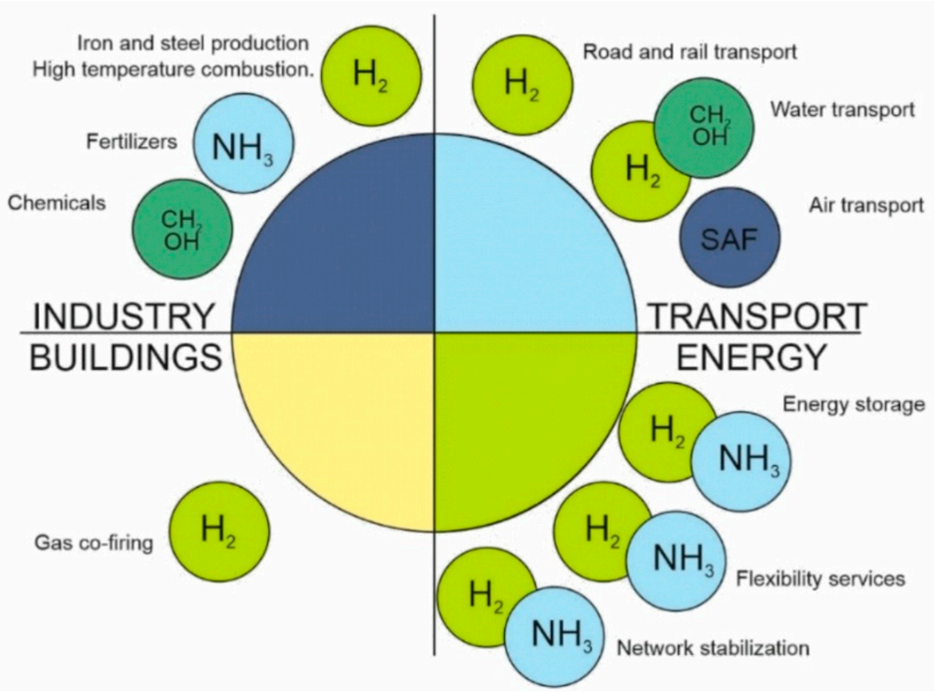

Figure 5. Application of green hydrogen (adapted from [36]).

Heavy industry is one of the most difficult areas in the process of decarbonizing the economy. In the absence of alternative options, achieving climate goals without the use of GH in some industries may prove impossible [37].

Hydrogen is used in the metal industry in processes such as metal alloying, where it is introduced into molten metals to improve properties such as strength and corrosion resistance. H_2 is used in welding, primarily in atomic welding. In this process, H_2 is split into atoms by an electric arc. These atoms combine to form a flame that melts metals. In jewelry, oxy-hydrogen torches are used in cutting and welding metals. Their use allows for very precise processing of silver, gold, or platinum [38].

Flat glass is a type of glass often used for glass windows and doors. During its production, H_2 and N_2 are used to prevent oxidation and defects [39].

H_2 is used, among other things, to convert unsaturated fats into saturated oils and fats, including hydrogenated vegetable oils such as margarine [40].

In electronics production, H_2 is an effective reducing and etching agent. It is used to create semiconductors, LEDs, displays, PV segments, and other electronic devices [41].

The chemical industry will continue to generate significant demand for H_2 in the context of ammonia production. Methanol will remain important in the context of formaldehyde production for the construction industry. H_2 is used to produce ammonia for agricultural fertilizers (Haber process) and methanol and cyclohexane, which are intermediates for the production of plastics and pharmaceuticals. In the refinery industry, it H_2 is used to separate high-chain hydrocarbons (hydrocracking) and to remove sulfur during oil refining (hydrodesulfurization). The advantage of ammonia over H_2 is its condensation temperature: ammonia condenses at −33 °C at ambient pressure, whereas H_2 requires as much as −253 °C. In addition, 1 cubic meter of ammonia contains 50% more energy than the same volume filled with H_2. Capturing energy from GH in the form of ammonia could be a breakthrough in affordability and solve the challenges related to the chemical properties of H_2 [42].

In the medical industry, H_2 is used to create hydrogen peroxide (H_2O_2), a commonly used antiseptic. More recently, H_2 has also been studied as a therapeutic gas in the treatment of a variety of diseases [43].

GH is the purest of all currently known hydrogens. This is mainly due to its production technology, which is relatively simple. Its purity reaches 99%. This allows it to be used in fuel cells of propulsion engines, which is a considerable advantage in the context of plans to transform the mobility and transport sectors [44].

The GH production process is actually the only process that does not emit pollutants. This is why it is considered the most reasonable alternative to conventional fuels. The two most common production methods are:

- biomass gasification,
- electrolysis powered by electricity from RES (Figure 6).

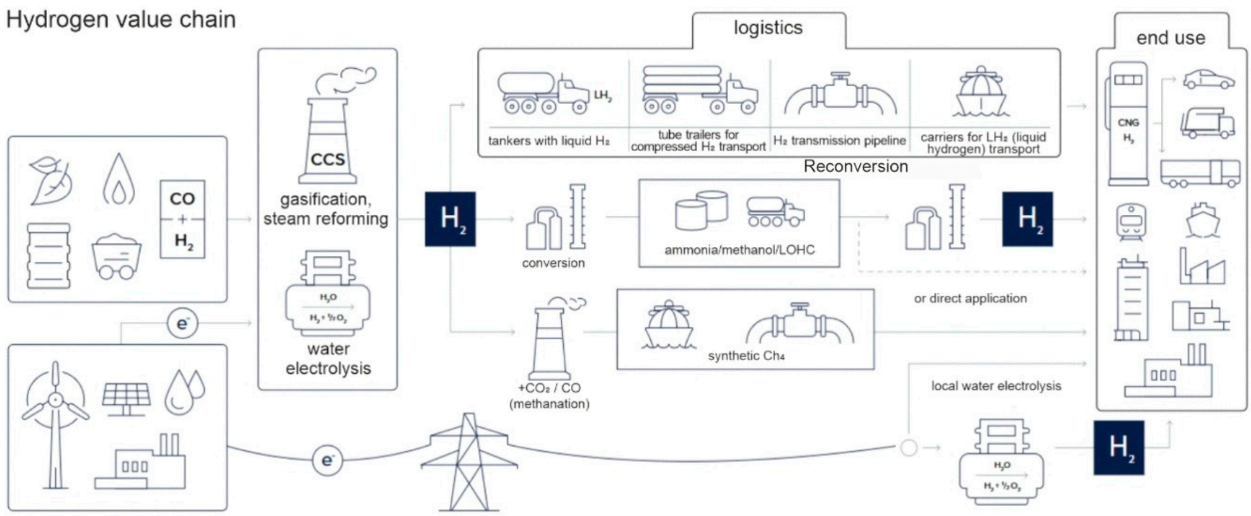

Figure 6. Green hydrogen value chain (adapted from [45]).

The first one is characterized not so much by zero carbon dioxide emissions but even negative ones. This is a quite promising method but very expensive—several times more expensive than the electrolysis process. It also requires huge amounts of biomass for production and also as a by-product, which is a significant problem [45].

RES are mainly referred to as PV and wind farms, mainly due to location and urban planning factors. Electricity from hydroelectric power plants is less frequently mentioned, because this defines the creation of H_2 production centers in the vicinity of hydrological facilities [46].

Green Hydrogen Production and Its Storage Costs

GH can be used to store surplus energy produced from RES, which would contribute to better energy supply management. However, the most important challenge in this direction remains the development of appropriate storage and transportation infrastructure for GH [47].

Electrolyzers play a key role in hydrogen production, but their cost is significant. Depending on the technology (e.g., alkaline electrolyzers, PEM, or SOEC), these costs can vary. Although PEM electrolyzers are highly efficient, have a wide range of work, and offer high operating flexibility, they require the use of expensive precious metals such as platinum or iridium, which increases their price. Alkaline electrolyzers, although cheaper, are less efficient, especially under variable operating conditions. It is estimated that electrolyzer costs could account for 30–40% of the total cost of GH production [48].

The costs associated with GH production also include expenses for building appropriate infrastructure, including hydrogen storage and transportation. Due to the weak development infrastructure in this sector, building infrastructure and adapting it to appropriate conditions requires additional costs. These costs can range from several to a dozen or so percent of the total production cost, depending on the conditions and investment size [49].

Example hydrogen prices are presented in Table 2 [50]. Currently, GH production is more expensive than conventional hydrogen Within a few years, thanks to factors such as falling electrolyzer prices and falling energy prices from renewable energy sources, GH will be cheaper than gray or blue hydrogen.

Table 2. Cost of hydrogen production [50].

A Type of Hydrogen	Current Cost [$/kg]	Projected Cost in 2030 [$/kg]
Green hydrogen	3.0–7.5	2.2
Grey hydrogen	1.0–3.5	Up to 5 (with CO_2 fees)
Blue hydrogen	2.0–4.0	2.5–3.5

Hydrogen prices can vary significantly depending on the region, the availability of energy sources, and the pace of technological development.

5. Green Hydrogen from Renewable Energy in the Kujawsko-Pomorskie Voivodeship

The GH innovation ecosystem in the Kujawsko-Pomorskie Voivodeship will be formed by representatives of the quadruple helix of key stakeholders—government and local government administration, representatives of enterprises located here, business environment institutions and clusters, and representatives of the science sector. The voivodeship has favorable factors for the development of the hydrogen value chain, including production using RES, storage technologies, distribution systems, and GH applications in various sectors of the economy.

The surplus electricity in the Kujawsko-Pomorskie Voivodeship (15.75 TWh/year) can be used to produce GH. The first such installation was launched in October 2023 in Solec Kujawski, when the GH plant was officially opened (Figure 7). During the opening, not only was the plant installation presented, but also the refueling station. The hydrogen station allows for the management of surplus energy produced by wind turbines located on the plant's premises. The energy is used to produce GH in the electrolysis process. For now, GH is used to refuel forklifts and passenger cars used in the sales department, and will eventually also be used in the production of aerated concrete [51].

Table 3 presents the potential areas of GH application in the Kujawsko-Pomorskie Voivodeship and neighboring voivodeships [52].

The actual energy consumption for the production of 1 m^3 of GH is 4.3 kWh, and the amount of energy from surplus RES in the Kujawsko-Pomorskie Voivodeship is 15.75 TWh—this would provide 3.7 billion m^3 (in normal conditions) (0.33 million tons) of GH. The amount of H_2 produced from surplus RES in the voivodeship is about 30% of the current H_2 production from fossil fuels in Poland.

Figure 7. Green hydrogen production plant in Solec Kujawski [51].

Table 3. Potential areas of green hydrogen application in the Kujawsko-Pomorskie Voivodeship and neighboring voivodeships (own elaboration based on [52]).

Application of Green Hydrogen	Application Description	Hydrogen Demand	Possibility of Producing Electricity from Waste Heat	Possibility of Producing Heat/Cooling
Oil refining	Removing sulfur and other contaminants from crude oil, as well as upgrading low-quality fuels into high-quality products	Big	Yes	Yes
Glass cleaning	Reduction of metal oxides and other impurities in glass production and to provide a protective atmosphere for melting and shaping glass	Medium	Small	For the plant's own needs
Semiconductor production	Cleaning silicon and other materials, as well as creating thin films and etching patterns on semiconductor devices	Small	Nie	Nie
Aviation applications	As a fuel for rockets and satellites, and as a propellant for jet engines and geographic positioning control systems	Medium	Yes	Yes
Fertilizer production	Production of ammonia, which is the main component of nitrogen fertilizers	Big	Yes	Yes
Welding, annealing and heat treatment of metals	As a shielding gas to prevent oxidation and improve the quality of welding, annealing and heat treatment processes of metals	Big	Yes	Yes
Transport	Hydrogen can be used as fuel in vehicles such as cars, buses, trucks, trains, ships and airplanes that use hydrogen fuel cells or internal combustion engines	Big	No	No

Table 3. *Cont.*

Application of Green Hydrogen	Application Description	Hydrogen Demand	Possibility of Producing Electricity from Waste Heat	Possibility of Producing Heat/Cooling
Buildings	Use for heating, cooling and power generation in buildings by mixing it with natural gas or by using it in fuel cells or boilers	Big	No	No
Energy generation	Hydrogen can be used to produce electricity in power plants or distributed generators using fuel cells, engines or turbines	Medium	No	Yes

5.1. Examples of the Use of Green Hydrogen Technology in the Economy of the Kujawsko-Pomorskie Voivodeship and Poland

Below are selected sectors of the economy where GH can be used.

5.1.1. Transport

Assuming that a passenger car burns 0.8 kg H_2/100 km, the GH produced from surplus RES would allow for a distance of 41.6 billion km. The average annual mileage of a passenger car in Poland is 18,000 km [53], i.e., the calculated GH would allow for the powering of 2.31 million cars. This is more than all of the cars in the Kujawsko-Pomorskie Voivodeship (1.12 million cars) and constitutes 13% of all passenger cars in Poland.

5.1.2. Chemical and Petrochemical Industry

The estimated annual consumption of H_2 in the chemical and petrochemical sector in Poland currently amounts to 7.4 billion m^3 [54], which means that the GH produced from the RES surpluses of just one province would cover 50% of Poland's H_2 needs.

In the oil industry, H_2 is used primarily in three important processes. These are:

- reforming—the purpose of which is to increase the octane number,
- hydrotreating—reducing the content of nitrogen, sulfur and oxygen compounds and getting rid of unsaturated compounds that reduce fuel stability,
- hydrocracking—which involves processing heavy fractions of crude oil, such as lubricants or heavy oils into gasoline.

5.1.3. Fat Industry

Poland produces about 340,000 tons of margarine per year [54], and one of the largest fat plants in Europe is in the Kujawsko-Pomorskie Voivodeship—in Kruszwica. H_2 is used in the fat hardening process, and in particular in the production of margarine. About 41 million m^3 of H_2 is used in Poland for margarine production annually. This is about 9.0% of GH produced from surplus RES in the Kujawsko-Pomorskie Voivodeship.

6. Underground Storage of Green Hydrogen in the Kujawsko-Pomorskie Voivodeship

H_2 storage provides significantly higher energy storage density compared to compressed air storage technology and traditional pumped storage power plants. The rock salt location is the most cost-effective (relative to extracted deposits, aquifers and depleted workings) [55].

Gas storage in salt caverns and storage takes place in caverns (chambers) made in the salt deposit. In order to make caverns, the deposit should meet specific geological conditions, including the appropriate form, size and depth of deposition, and the salt should have the appropriate chemical composition. The technology of exploitation of underground GH storage in salt deposits is complex and specific, and the operation of the above-ground installation must be properly correlated with the geophysical conditions of the underground chambers. Cavern storage provides large storage capacities while occupying small areas of land; salt caverns are very available, and gas can be injected into and withdrawn from them many times a year [56,57].

Rock salt found in Poland belongs mainly to two salt formations, which were formed in the late Permian (Zechstein) in the period of approx. 257–252 million years ago and in the Neogene (Miocene) approx. 13 million years ago. Zechstein salts currently cover over 2/3 of the area of Poland. They are located at depths of several hundred meters in northern Poland and in the Fore-Sudetic zone, where they form so-called seam deposits, and up to 7 km in the central part of the Polish Lowlands, where they occur in the form of salt domes, pillows, columns and ridges—these are so-called diapir deposits [58]. In Figure 8, salt deposits in Poland and in the Kujawsko-Pomorskie Voivodeship are marked in black and grey (black contour of the voivodeship).

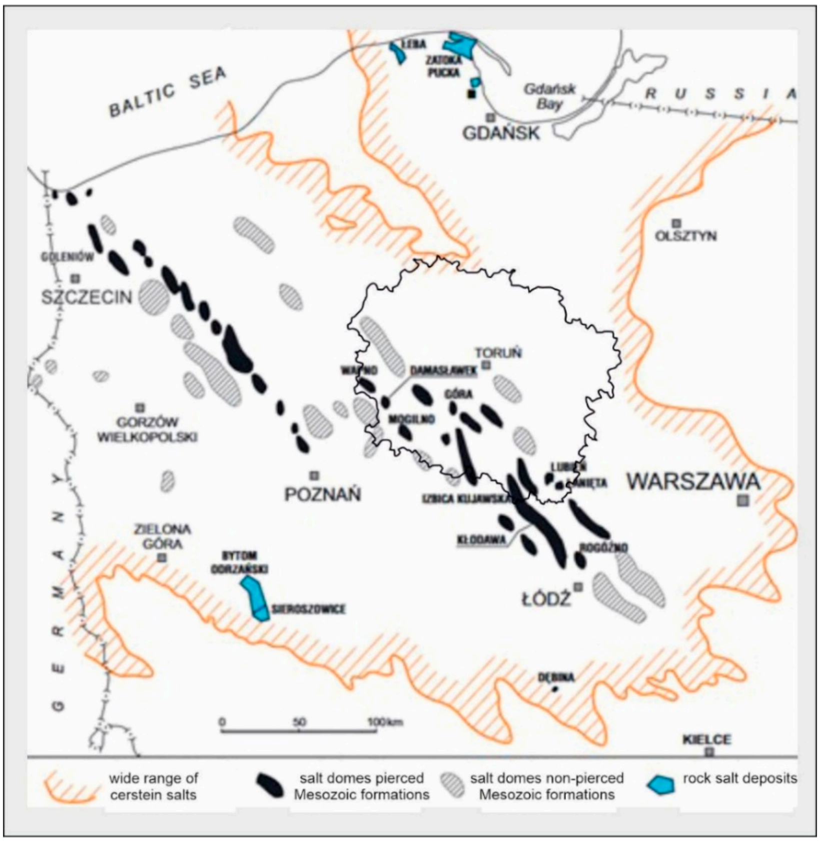

Figure 8. Underground hydrocarbons storages in Poland: actual investments and prospects (adapted from [58]).

In Poland, two salt cavern complexes are currently used to store natural gas: KPMG Mogilno with an active capacity of 585.4 million m^3. The Mogilno cavern is to be expanded to 800 million m^3 by 2027.

The rock salt deposit "Mogilno I", exploited by boreholes since 1986 by Inowrocławskie Kopalnie Soli "Solino" S.A., has been better and better recognized for years, using various research methods. In recent years, the range of the deposit and its internal structure have been specified using modern borehole georadar measurements. All previous geological studies have been verified and presented in the form of a 3D model of the deposit, which is the basis for updating the geological documentation of the deposit, while improving the safety of exploitation and the environment [58,59].

Table 4 presents the characteristics of locations in the Kujawsko-Pomorskie Voivodeship and in the bordering voivodeships where GH could be stored. The best conditions for GH storage are in the south of the voivodeship—in Lubień and Łanięta [58,59].

Table 4. Suitability of salt deposits for GH storage in the Kujawsko-Pomorskie Voivodeship and the bordering voivodeships [58,59].

Salat Deposit	Deposit Management	Possible Storage, Volume" in Deposit	Water for Leaching	Brine Output
Damasławek	Medium	For each deposit up to several tens of caverns of 300–500 $\times 10^3$ m^3	Easily accessible	Difficult to access
Kłodawa cz. płd	Medium			
Kłodawa cz. płn	Medium			
Lubień	Good			
Łanięta	Good			
Rogoźno	Medium			
Izbica Kujawska	Weak			
Dębina-Bełchatów	Weak			

7. Discussion

The Kujawsko-Pomorskie Voivodeship should continue to develop RES, which is environmentally friendly, provides additional jobs, and is becoming increasingly cheaper each year. Energy can be obtained from many sources in a given location—solar installations or wind turbines can be installed on energy plantations solid biomass. Due to the high temporal variability of energy supplied by sources such as wind, water, or the sun, additional energy batteries are used in hybrid systems. These batteries allow for the storage of surplus energy from sources during periods of reduced consumption and the return of stored energy to the customer during periods of increased demand. Micro-installations based on biogas and biomass combustion may be a specialty of the Kujawsko-Pomorskie Voivodeship. This takes into account the fragmented structure of agriculture, especially in the southeastern part of the voivodeship (Kujawy). This region also has producers of home wind turbines, producing energy for the needs of a farm or a single home.

Both the energy sector transition processes and the industry transition processes should in the future be based on the use of GH obtained using energy from RES. It should be emphasized that GH is the answer to all questions regarding the future and stability of the energy market. It should be remembered that the hydrogen strategy process has already begun. This is not a futuristic plan that does not contribute anything special to the market. Each of the countries that have joined the H_2 population is actively working in this direction and is allocating huge amounts of money for research and construction of the industrial base needed for the production and distribution of H_2.

The actual energy consumption for the production 1 m^3 of GH is 4.3 kWh, and the amount of energy from surplus RES in the Kujawsko-Pomorskie Voivodeship is 15.75 TWh—this would provide 3.7 billion m^3 (in normal conditions) (0.33 million tons). The amount of H_2 produced from RES in the voivodeship is about 30% of the current production of H_2 from fossil fuels in Poland. The calculated GH would power 2.64 million cars. This is more than all of the cars in the Kujawsko-Pomorskie Voivodeship (1.12 million cars) and constitutes 13% of all passenger cars in Poland.

The estimated annual consumption of H_2 in the chemical and petrochemical sector in Poland is currently 7.4 billion m^3, i.e., GH produced from RES in the Kujawsko-Pomorskie Voivodeship alone would cover 50% of Poland's needs for H_2.

Poland produces about 340 thousand tons of margarine per year, including one of the largest fat plants in Europe—in Kruszwica. H_2 is used in the fat hardening process, and in particular in the production of margarine. About 41 million m^3 of H_2 is used annually in

Poland for the production of margarine. This equates to about 9.0% of GH produced from RES in the Kujawsko-Pomorskie Voivodeship.

The most important barrier in the context of GH production remains the effective construction of a hydrogen economy chain, which requires a simultaneous costly transformation of the supply and demand sides. On the supply side, a significant reduction in the costs associated with production, transport and storage is required. The costs of devices, vehicles and infrastructure using H_2 must also decrease.

The analysis of the conditions for the development of the hydrogen economy in the Kujawsko-Pomorskie Voivodeship indicates a high potential in this area. The fundamental strategic goal of building a hydrogen economy should therefore be to build a lasting demand for H_2 while maintaining the continuity of its production in the region.

In the coming years, it will be necessary to conduct pilot implementations of hydrogen technologies in order to build competences and assess the real costs and benefits. After this stage, it will be possible to conduct an evaluation of the projects, which will allow for the development of a target hydrogen strategy for the region. The approach to its development should be iterative, and the initial assumptions should be constantly verified. The pace of technological development makes it necessary to constantly supplement knowledge and re-verify costs and benefits.

8. Conclusions

(a) The Kujawsko-Pomorskie Voivodeship has big renewable energy potential (23.75 TWh), greater than its electricity consumption (8.00 TWh),

(b) Surplus electricity in the voivodeship can be utilized for the development of electromobility and/or the production of GH. The amount of energy from surplus RES in the Kujawsko-Pomorskie Voivodeship is 15.75 TWh—this would provide 3.7 billion m^3 (in normal conditions) (0.33 million tons) of GH.

(c) GH has wide applications in the chemical and petrochemical industries, the food industry (e.g., margarine production), and transportation.

(d) The Kujawsko-Pomorskie Voivodeship has numerous salt caverns where GH can be stored. The best conditions for GH storage are in the south of the voivodeship—around Lubień and Łanięta.

(e) The symbiosis of RES and GH will allow for the economic use of surplus energy. This will benefit the environment and the economy. It should be emphasized that GH is the answer to all questions regarding the future and stability of the RES market.

Limitations of the Study:

- Limitations of the research sample: relatively small sample, difficulties in accessing specific data on RES in the voivodeship.
- Time constraints: RES potential is calculated for 2024 and may vary slightly in subsequent years.
- Formal constraints: The need to protect sensitive personal data, hence the shorter description of RES in the voivodeship.
- Cognitive/human constraints: Researcher's emotions, stereotyping, possible errors in data interpretation.

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Conflicts of Interest: Author Skrzatek was employed by Earth Story. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Assoumou-Ella, G.; Nkah-Ella, C. Climate change, governance, and macroeconomic stability: Empirical analysis in a panel of African countries. *Emerg. Mark. Rev.* **2024**, *61*, 101152. [CrossRef]
2. Fernández, S.; Arce, G.; Garcia-Alaminos, Á.; Cazcarro, I.; Arto, I. Climate change as a veiled driver of migration in Bangladesh and Ghana. *Sci. Total Environ.* **2024**, *922*, 171210. [CrossRef] [PubMed]
3. Igliński, B.; Buczkowski, R.; Kujawski, W.; Cichosz, M.; Piechota, G. Geoenergy in Poland. *Renew. Sustain. Energy Rev.* **2012**, *5*, 2534–2557. [CrossRef]
4. Jamez, J.; Christopher, W.; Lauren, R. A global cross-resource assessment of offshore renewable Energy. *Renew. Sustain. Energy Rev.* **2025**, *215*, 115563. [CrossRef]
5. Igliński, B.; Kiełkowska, U.; Piechota, G.; Skrzatek, M.; Cichosz, M.; Iwański, P. Can energy self-sufficiency be achieved? Case study of warmińsko-mazurskie voivodeship (Poland). *Clean Technol. Environ. Policy* **2021**, *23*, 2061–2081. [CrossRef]
6. REN21. *Renewables 2025 Global Status Report–Renewables in Energy Supply*; REN21: Paris, France, 2025.
7. IRENA. *Renewable Energy and Jobs: Annual Review 2024*; IRENA: Abu Dhabi, United Arab Emirates, 2024.
8. Development Strategy of the Kujawsko-Pomorskie Voivodeship until 2030-Acceleration Strategy 2030+, Toruń 2030. Available online: https://kujawsko-pomorskie.pl/wp-content/uploads/pliki/2025/planowanie/20250617_strategia/uz-7-24-18-945-z-4.pdf (accessed on 8 June 2025).
9. Algburi, S.; Munther, H.; Al-Dulaimi, O.; Fakhruldeen, H.F.; Sapaev, I.B.; Al Seedi, K.F.K.; Khalaf, D.H.; Jabbar, F.I.; Hassan, Q.; Khudjhair, A.; et al. Green hydrogen role in sustainable energy transformations: A review. *Results Eng.* **2025**, *26*, 105109. [CrossRef]
10. Panchenko, V.A.; Kovalev, A.A.; Chakraborty, S. Agrivoltaics and green hydrogen–Symbiosis of solar energy technologies for sustainable development of humanity. *Int. J. Hydrogen Energy* **2025**, *153*, 150225. [CrossRef]
11. Eljack, F.; Kazi, M.-K. Prospects and challenges of green hydrogen economy via multi-sector global symbiosis in Qatar. *Front. Sustain.* **2021**, *1*, 612762. [CrossRef]
12. Butturi, M.A.; Gamberini, R. The potential of hydrogen technologies for low-carbon mobility in the urban-industrial symbiosis approach. *Int. J. Energy Prod. Manag.* **2022**, *7*, 151–163. [CrossRef]
13. Sorrenti, I.; Zheng, Y.; Singlitico, A.; Shi, Y. Low-carbon and cost-efficient hydrogen optimization through a grid-connected electrolyzer: The case of GreenLab skive. *Renew. Sustain. Energy Rev.* **2023**, *171*, 113033. [CrossRef]
14. Affery, A.P.; Tan, J.X.; Ong, I.Y.B.; Lim, J.Y.; Yoo, C.; How, B.S.; Ling, G.G.T.; Food, D.C.Y. Optimal planning of inter-plant hydrogen integration (IPHI) in eco-industrial park with P-graph and game theory analyzes. *Process Saf. Environ. Prot.* **2021**, *155*, 197–218. [CrossRef]
15. Reda, B.; Elzamar, A.A.; AlFazzani, S.; Ezzat, S.M. Green hydrogen as a source of renewable energy: A step towards sustainability, an overview. *Environ. Dev. Sustain.* **2025**, *27*, 29213–29233. [CrossRef]
16. Arun, M.; Barik, D.; Dara, R.N.; Tudu, K.; Praveenkumar, S.; Kanti, P.K.; Ayanie, A.G. Integrated renewable energy supply architecture for advancing hydrogen symbiosis eco synergistic smart grid interactions with next generation combustion technologies. *Sci. Rep.* **2025**, *15*, 25619. [CrossRef] [PubMed]
17. Simões, J.C.T.; Vaz Júnior, S. Industrial symbiosis concept applied to green hydrogen production: A critical review based on bibliometric analysis. *Discov. Sustain.* **2024**, *5*, 504. [CrossRef]
18. Igliński, B.; Flisikowski, K.; Pietrzak, M.B. Renewable energy in the Pomerania Voivodeship–institutional, economic, environmental and physical aspects in light of EU energy transformation. *Energies* **2021**, *14*, 8221. [CrossRef]
19. Igliński, B.; Pietrzak, M.B.; Kiełkowska, U. How to meet the Green Deal objectives–Is it possible to obtain 100% RES at the regional level in the EU? *Energies* **2022**, *15*, 2296. [CrossRef]
20. Igliński, B.; Kiełkowska, U.; Pietrzak, M.B.; Skrzatek, M.; Kumar, G.; Piechota, G. The regional energy transformation in the context of renewable energy sources potential. *Renew. Energy* **2023**, *128*, 119246. [CrossRef]
21. Igliński, B.; Kujawski, W.; Buczkowski, R.; Cichosz, M. Renewable energy in Kujawsko-Pomorskie Voivodeship (Poland). *Renew. Sustain. Energy Rev.* **2010**, *14*, 1336–1341. [CrossRef]
22. Igliński, B. *Research on the Renewable Energy Sector in Poland: Technical Potential, Survey Research, SWOT Analysis, PEST Analysis*; Nicolaus Copernicus University: Toruń, Poland, 2019.

23. Central Statistical Office. *Statistical Yearbook of Agriculture*; Central Statistical Office: Warszawa, Poland, 2024.
24. Central Statistical Office. *Agricultural Statistical Yearbook*; Central Statistical Office: Warszawa, Poland, 2024.
25. Central Statistical Office. *Statistical Yearbook of Voivodeships*; Central Statistical Office: Warszawa, Poland, 2024.
26. Central Statistical Office. *Environmental Protection*; Central Statistical Office: Warszawa, Poland, 2024.
27. Kujawsko-Pomorskie Spatial and Regional Planning Office in Włocławek, Kujawsko-Pomorskie Voivodeship: Resources and Possibilities of Using Renewable Energy Sources, Włocławek. 2009. Available online: https://kzgw.gov.pl/index.php/pl (accessed on 8 June 2025).
28. Act of March 9, 2023 Amending the Act on Investments in Wind Farms and Certain Other Acts. Journal of Laws Item 553. Available online: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20230000553/O/D20230553.pdf (accessed on 8 June 2025).
29. Tomczyk, D.; Łapniewska, Z. Solar panels on every rootftop? Photovoltaics boom in Poland and the role of the European Union funds. *Energy Res. Soc. Sci.* **2025**, *125*, 104107. [CrossRef]
30. Amaducci, S.; Yin, X.; Colauzzi, M. Agrivoltaic systems to optimise land use for electric energy production. *Appl. Energy* **2018**, *220*, 545–561. [CrossRef]
31. Igliński, B.; Kiełkowska, U.; Pietrzak, M.B.; Skrzatek, M. *Renewable Energy in the Kujawsko-Pomorskie Voivodeship*; Nicolaus Copernicus University: Toruń, Poland, 2025. (In Polish)
32. Central Statistical Office. *Education and Upbringing in the 2022/2023 School Year*; Central Statistical Office: Gdańsk, Poland, 2023.
33. Central Statistical Office. *Tourism in 2023*; Central Statistical Office: Rzeszów, Poland, 2024.
34. Central Statistical Office. *Consumption of Fuels and Energy Carriers in 2023*; Central Statistical Office: Rzeszów, Poland, 2024.
35. Yue, M.; Lambert, H.; Pahon, E.; Roche, R.; Jemei, S.; Hissel, D. Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renew. Sustain. Energy Rev.* **2021**, *146*, 111180. [CrossRef]
36. Sarker, A.K.; Azad, A.K.; Rasul, M.G.; Doppalapudi, A.T. Prospect of green hydrogen generation from hybrid renewable energy sources: A review. *Energies* **2023**, *16*, 1556. [CrossRef]
37. Yao, Y.; Tan, L.; Chen, F.; Pan, A.; Ma, Q.; Zhao, J.; Kang, R. Hydrogen energy industry in China: The current status, safety problems, and pathways for future safe and healthy development. *Saf. Sci.* **2025**, *186*, 106808. [CrossRef]
38. Caiafa, C.; Kratena, K.; Arto, I. Macroeconomic and environmental impacts of two decarbonization options for the Durch steel industry: Green relocation versus green hydrogen imports. *Energy Policy* **2025**, *296*, 114726. [CrossRef]
39. Egerer, J.; Farhang-Damghani, N.; Grimm, V.; Runge, P. The industry transformation from fossil fuels to hydrogen will recognize value chains: Big picture and case studies for Germany. *Appl. Energy* **2024**, *358*, 122485. [CrossRef]
40. Akbar, U.; Mondol, M.S.; Abdi, G.; Dash, K.K.; Khan, S.A.; Dar, A.H. Hydrogen assisted technologies in food processing, preservation and safety: A comprehensive Review. *Food Control.* **2025**, *178*, 111535. [CrossRef]
41. Zhu, Y.; Keoleian, G.A.; Cooper, D.R. The role of hydrogen in decarbonizing U.S. industry: A review. *Renew. Sustain. Energy Rev.* **2025**, *214*, 115392. [CrossRef]
42. Wang, K.; Liu, F.; Liu, J. Techno-economic assessment of different clean hydrogen development pathways across industries in China. *Appl. Energy* **2025**, *382*, 125244. [CrossRef]
43. Yidiz, F.; LeBaron, T.W.; Alwazeer, D. A comprehensive review of molecular hydrogen as a novel nutrition therapy in relieving oxidative stress diseases: Mechanisms and perspectives. *Biochem. Biophys. Rep.* **2025**, *41*, 101933. [CrossRef] [PubMed]
44. Singh, V.; Aishwarya, V.M.; Sriprasarth, V.J.; Pranavi, M.; Singh, T. Green hydrogen value chain challenges and global readiness for a sustainable energy future. *iScience* **2025**, *28*, 112900. [CrossRef]
45. Sawhney, R.; Hearn, J.; Hibbett, R.; Kingston, K.; Parkinson, M.; Zacarias, M.; Majkut, J. Techno-economic assessment of green hydrogen production via an optimized solar and wind system. *Renew. Energy Focus* **2025**, *55*, 100726. [CrossRef]
46. Al Makky, A.; Kanjo, H.A.; Farag, M.M.; Hamid, A.-K.; Hussein, M.; Salameh, T. Techno-economic feasibility of green hydrogen production using hybrid solar-wind energy systems in Oman. *Int. J. Thermofluids* **2025**, *28*, 101302. [CrossRef]
47. Ghazal, M.; Osman, M.; Alhalabi, M.; Gad, A.; Yaghi, M.; Ramadan, M.; Alkhedher, M. Advancements and challenges in green hydrogen production, storage, transportation, and utilization for climate-resilient energy systems. *Results Eng.* **2026**, *29*, 108993. [CrossRef]
48. Lazo, J.; Barrios, V.; Watts, D. Dynamic dispatch optimization of green hydrogen electrolyzers under price volatility: A real option approach. *Renew. Sustain. Energy Rev.* **2026**, *226*, 116445. [CrossRef]
49. İzgeç, M.M.; Emre, T. Strategic siting and cost modeling for green hydrogen export from off-grid renewables: A multi-hub approach for Turkiye. *Int. J. Hydrogen Energy* **2026**, *210*, 153616. [CrossRef]
50. How Much Hydrogen per Liter of Water—A Complete Guide to Production and Profitability. Available online: https://elektrosiec.pl/blog/ile-wodoru-z-litra-wody-kompletny-przewodnik-po-produkcji-i-oplacalnosci (accessed on 25 January 2026).
51. Hydrogen Station in Solec Kujawski. Available online: http://gashd.eu/2023/10/13/stacja-wodorowa-w-solcu-kujawskim-tankowanie-wodoru-od-solbet (accessed on 25 January 2026).

52. Marshal's Office of the West Pomeranian Voivodeship. *Assessment of the Potential for the Development of Green Hydrogen Production Technology and Use in the Economy of West Pomerania*; Marshal's Office of the West Pomeranian Voivodeship: Szczecin, Poland, 2023. (In Polish)
53. Central Statistical Office. *Transport–Activity Results in 2024*; Central Statistical Office: Szczecin, Poland, 2025.
54. Central Statistical Office. *Statistical Yearbook of Industry*; Central Statistical Office: Warszawa, Poland, 2024.
55. Tarkowski, R.; Uliasz-Misiak, B. Towards underground hydrogen storage: A review of barriers. *Renew. Sustain. Energy Rev.* **2022**, *162*, 112451. [CrossRef]
56. Andersson, J.; Grönkvist, S. Large-scale storage of hydrogen. *Int. J. Hydrogen Energy* **2019**, *44*, 11901–11919. [CrossRef]
57. Karnkowski, P.H.; Czapowski, G. Underground hydrocarbons storages in Poland: Actual investments and prospects. *Przegląd Geol.* **2007**, *55*, 1068–1074.
58. Dadlez, R.; Marek, S.; Pokorski, J. *Geological Map of Poland Without Cenozoic formations 1: 1 000 000*; Ministry of the Environment and the Polish Geological Institute, Cartographic Publishing House of the Polish Ecological Agency: Warszawa, Poland, 2002. (In Polish)
59. Czapkowski, G.; Ślizowski, K. The state of knowledge about undeveloped salt domes in Poland: Optimism or a problem? In Proceedings of the Międzynarodowe Sympozjum Solne QUO VADIS SAL, Kłodawa, Poland, 11–12 October 2007. (In Polish)