SOUTH BALTIC FARMS
AN ESSENTIAL PART OF RENEWABLE ENERGY SYSTEMS

Interreg
South Baltic

Co-funded by the European Union

2025

Project DELIVERABLE

2.2 Report on the potential of using renewable energy in the SBS region, including a joint green policy strategy

Solar Power Potential
Wind Power Potential
Biogas Potential
Joint Green Policy Strategy

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Preface

The project receives funding by the Interreg South Baltic Programme 2021-2027 under the project BIOSOLFarm - South Baltic Farms - an essential part of renewable systems, STHB.02.01-IP.01- 0003/23-00.

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List of Abbreviations:

Abbreviation	Full Term
BTDM	Billion Tonnes of Dry Matter
EU	European Union
GHG	Greenhouse Gas
GWh	Gigawatt-hour
kWh	Kilowatt-hour
Mtdm	Million Tonnes of Dry Matter
Mtoe	Million Tonnes of Oil Equivalent
PV	Photovoltaic
RES	Renewable Energy Systems
SBS	South Baltic Sea

Introduction

The need for coordinated global efforts to mitigate climate change is well recognized, particularly in the wake of the Paris Agreement, which aims to limit global temperature rise to well below 2°C above pre-industrial levels [1]. Given that approximately 80% of greenhouse gas (GHG) emissions originate from the energy sector, a transition to renewable energy (RE) is essential [2]. The European Union (EU) has taken significant steps toward achieving this goal, as exemplified by the establishment of the European Energy Union and the adoption of a resilient energy strategy [3].

According to the Intergovernmental Panel on Climate Change (IPCC), renewable energy sources are expected to supply between 70% and 85% of global electricity by 2050 to achieve the 1.5 degrees target [4]. Recent technological advancements and cost reductions have significantly accelerated the global shift toward renewables. Between 2010 and 2019, the costs of key clean energy technologies plummeted. The costs for solar energy dropped by 85% and for wind energy by 55%, driving substantial deployment increases across multiple regions [5]. This trend continued in 2023, when global wind and photovoltaic (PV) capacity additions soared to nearly 540 gigawatts,

Renewable energy sources are expected to supply between **70% and 85%** of global electricity by **2050**

marking a 75% increase from 2022 [6]. That same year,
non-bioenergy renewables accounted for nearly 30% of global electricity generation, with wind and solar alone contributing 13.2% [6].

A particularly promising area for regional energy cooperation is the South Baltic Sea Region (SBSR), where strong economic and environmental ties exist between countries. The Baltic Sea Region (BSR) as a whole has already demonstrated success in energy cooperation, especially in the Nordic countries, where electricity trade and integration efforts have facilitated a more resilient and sustainable energy system [7]. However, a systematic analysis of the potential for a green energy transition in the

SBSR is still lacking. With an abundance of renewable energy resources—including biomass (Sweden, Finland, and Lithuania), hydropower (Norway, Sweden, andFinland), wind (Denmark, Sweden, and Norway), and solar (Denmark, Southern Sweden, Estonia, Latvia, and Lithuania)—the SBSR is well-positioned to accelerate the shift towards a 100% renewable energy system.

Despite these opportunities, several challenges remain. The maritime economy plays a crucial role in the SBSR, contributing significantly to employment and economic output. The so-called "Blue Economy" in the EU accounts for approximately 5.4 million jobs and generates nearly 500 billion EUR annually [8]. The SBSR, in particular, holds a leading position in maritime industries, but limited cooperation and promotion activities hinder the competitiveness and sustainable development of the region [9]. Additionally, the lack of international support mechanisms for small and medium-sized enterprises (SMEs) further impedes progress toward a green transition [9].

The **BSR Region** generated in 2015 an annual GDP of about 2.000 billion EUR, which is equivalent to **12.5%** of the EU-28 economy [10]

This report explores the potential for expanding renewable energy use in the SBSR and proposes a joint green policy strategy to enhance energy security, economic growth, and sustainability. A coordinated approach, leveraging regional strengths and increasing cross-border collaboration, could significantly contribute to reducing carbon emissions while fostering innovation in green technologies. Furthermore, the integration of energy storage solutions and sector interconnections will be crucial in ensuring a stable and flexible energy supply, particularly given the intermittency challenges associated with wind and solar energy.

By fostering stronger regional cooperation and implementing a joint green policy framework, the SBSR has the opportunity to become a model region for sustainable energy development, balancing economic growth with environmental responsibility.

Study Area & Scope

GERMANY

The study area encompasses independent cities such as Wismar, Rostock, Stralsund, and Greifswald, and counties like Nordwestmecklenburg, Bad Doberan, Nordvorpommern, Ostvorpommern, and Uecker-Randow. Mecklenburg-Western Pomerania is notable for its extensive agricultural land, having the largest average farm size in Germany. As of 2023, the average farm size in the region was 283 hectares, considerably larger than the national average of 65 hectares [10].

In 2023, there were a total of 4,750 farms in Mecklenburg-Western Pomerania. These farms were categorized into different size classes. Small farms (Class I) with less than 5 hectares made up 6.3% (299 farms), while Class II farms (5-10 hectares) comprised 12.1% (574 farms). Medium-sized farms (Class IV, 50-200 hectares) accounted for 21.2% (1,007 farms), and Class V farms (200-500 hectares) represented 17.3% (822 farms). Large farms (Class VI, 500-1,000 hectares) made up 11.3% (537 farms), and Class VII farms (>1,000 hectares) constituted 7.4% (352 farms) [11].

The primary crops cultivated in Mecklenburg-Western Pomerania in 2023 included cereals and oil crops, which together accounted for 70.1% of the arable land. Specifically, cereals covered 50.5%, while rapeseed, for which the state led nationally, occupied 19.1% of the arable land. Root crops were grown on 4.3% of the land, while vegetables and strawberries were of minor importance, covering just 0.3%. Plants for green harvesting, including fodder and energy crops, were grown on 16.2% of the land [12].

The region generated significant amounts of crop residues, including cereal straw, rapeseed straw, grain maize straw, and root crop residues. Germany's sustainable straw potential ranges between 8 and 13 million tons of fresh matter (tFM) annually, with Mecklenburg-Western Pomerania contributing notably to this figure. The cereal straw growth in the region was 2,839 t FM, with potential straw yields varying based on different methods of humus balancing [13].

In 2016, Mecklenburg-Western Pomerania had substantial livestock populations, including 547,414 cattle, 782,396 pigs, and 9,814,583 chickens. The region produced significant quantities of solid manure from various livestock, including cattle, pigs, horses, sheep, and poultry [14].

The region has been utilizing waste for biogas production and other purposes. The number of biogas plants and the use of rapeseed press cake for energy generation highlight the efforts toward efficient waste management and utilization [12].

The primary energy sources used in German farms are fuels and electricity. About 40% of total energy consumption in agriculture is attributable to fuels, with approximately 30% coming from fossil fuels such as heating oil and gas. Among the energy consumption from fossil fuels, 30% is used for heating stables, while 70% is required for greenhouses [15].

A significant portion of energy consumed on farms is derived from renewable sources. Photovoltaic (PV) systems are widely used in agriculture, as many farm buildings have suitable roof surfaces for solar panel installation. The efficiency of these systems depends on factors such as location and orientation, with average yields in Germany ranging between 900 and 1,100 kWh of electricity per kWp of installed capacity per year. Economically, self-supply with PV electricity is beneficial, as current electricity generation costs are lower than electricity purchase prices. Small wind turbines, however, are only profitable under optimal conditions. Due to low feed-in tariffs, feeding electricity into the grid does not typically cover costs. In good locations with high average wind speeds and minimal obstructions in front of turbines, the levelized cost of electricity (LCOE) can be lower than the purchase price, making self-generated electricity economically viable. Additionally, combined heat and power (CHP) plants play a key role in agricultural energy use. These systems generate both electricity and heat on demand, balancing fluctuations from solar and wind sources. CHP units are becoming increasingly important as non-fossil power generation expands, offering a more cost-effective and simpler alternative to electricity storage [15,16].

The development of renewable electricity generation in Mecklenburg-Western Pomerania in the first half of 2021 included biomass contributing 390.9 GWh (with a net expansion of 7.6 GWh), solar radiation energy at 2,688.8 GWh (net expansion of 247.1 GWh), wind energy from land sources at 3,514.6 GWh (net expansion of 27.5 GWh), offshore wind energy at 48.3 GWh, and landfill gas at 8.1 GWh [17].

Mecklenburg-Vorpommern is the first federal state in Germany that can already cover **100 percent** of its energy needs from renewable sources. [20]

Energy consumption in dairy farms varies according to farm size. The smallest dairy farms, averaging 44 cows per farm, are primarily found in Bavaria. Medium-sized farms, which typically keep around 70 dairy cows, have slightly higher energy demands. Large farms are more common in Mecklenburg-Western Pomerania, where farms average 284 hectares in size—significantly above the 2010 national average of 59 hectares. The largest dairy farms in Germany are found in this region, averaging 244 dairy cows per farm. As the number of livestock per farm increases, the overall number of farms decreases, with only 6% of farms keeping more than 200 dairy cows [18,19].

Major energy-consuming activities on farms include fuel usage (accounting for approximately 40% of total energy consumption) and electricity use for operations such as hay drying, hot water treatment, barn ventilation and air conditioning, milking equipment, and milk cooling. Fossil fuels contribute about 30% to energy consumption, particularly for heating purposes, with 30% of that used for stable heating and 70% for greenhouses [15].

Peak energy demand periods vary depending on the type of agricultural operation and the energy-consuming installations in use. Factors such as ventilation, feeding, feed preparation, infrared lamps, lighting, cleaning, and heating equipment all play a role in energy demand. Ventilation is a particularly high-energy consumer, with its usage increasing in hot weather, leading to greater energy consumption. Other activities like feed preparation, feeding, and cleaning also contribute significantly to energy demand, which is dependent on daily operational needs [19].

The major contributors to peak energy demand are closely related to farm types. Livestock farms generally have higher energy requirements than crop-based farms, except for fruit-growing operations, which are relatively less common in northern Germany. Dairy farms, pig production, and finishing farms also require high energy consumption, particularly for piglet rearing. Notably, electricity consumption per dairy cow decreases as the number of animals increases due to economies of scale in energy use [19].

LITHUANIA

The studied region in Lithuania covers the western part of the country, including Klaipėda County (5,209 km²), which borders Latvia to the north, the Baltic Sea to the west, Tauragė County (4,411 km²) to the south, and Telšiai County (4,349 km²) to the east. Tauragė County is bordered by Klaipėda County to the north, the Russian exclave of Kaliningrad to the west, Šilalė District to the south, and Jurbarkas District to the east. Telšiai County borders Latvia to the north, Klaipėda County to the west, and Šiauliai County to the south [20].

In Lithuania, farms are classified based on their economic size: the smallest category includes farms over 1 hectare, while the largest category includes agricultural enterprises exceeding 500 hectares [21]. The average farm size has increased from 13.8 hectares in 2010 to 22.2 hectares in 2020 [21]. The total number of farms in Klaipėda, Telšiai, and Tauragė counties is 12,778, 10,028, and 12,966, respectively. However, the number of medium and large farms in these regions is not specified [21].

Crop production accounted for 68% of total agricultural output in 2023, with cereals making up 34.9%, rapeseed 12.1%, fodder crops 7.4%, and vegetables 3.9%. Livestock production contributed 32% to total agricultural output, with livestock and poultry accounting for 14.5%, milk yields for 12.9%, and milk production for 12.9% [22].

Regarding crop residue utilization, approximately 20% of straw remains in the fields, another 20% is used for feed and bedding, and about 60% of the total crop potential can be used for energy production. The estimated energy potential from crop residues in Klaipėda County is 65,770 tons, in Telšiai County 44,297 tons, and in Tauragė County 31,033.8 tons [20].

Livestock manure is another important resource for energy production. The total biogas potential from livestock and poultry manure in Klaipėda District Municipality is 1,191,935 m³, while in Telšiai District Municipality, it is 1,641,118.56 m³. Data for Tauragė County is not available [20].

In Lithuanian agriculture, livestock manure is the primary source of biogas production. Large farms, particularly those with thousands of pigs, hundreds of cattle, or tens of thousands of poultry, have the highest potential. Wood and forest waste also serve as significant sources of biomass for energy production. Logging residues from forestry operations, sawdust, wood chips, and agricultural waste from orchards contribute to biomass utilization. These resources are used in various energy production systems, including biogas plants, to maximize their energy potential [20].

In 2021, modern renewables made **up** **33.22%** of Lithuania' s final energy consumption — a **93%** increase since 2000 [23]

Lithuanian farms are adopting several sustainability and environmental initiatives to promote renewable energy generation. Many farms have installed biogas production systems to convert livestock manure and organic waste into biogas for electricity and heat. Solar panels are increasingly used on farm buildings to harness solar energy, reducing electricity costs and feeding excess power back into the grid. Some farms have also set up small-scale wind turbines in regions with favorable wind conditions. Biomass heating systems, using wood chips, pellets, and agricultural residues, provide an alternative to conventional fuels. [23].

Sustainable forestry practices, such as selective logging and reforestation, are being implemented to ensure a continuous supply of biomass. Agroforestry practices, combining agriculture and forestry, help improve biodiversity and provide additional biomass resources. Some farms are also cultivating energy crops like miscanthus and switchgrass specifically for bioenergy production. Comprehensive waste management strategies ensure that agricultural residues and organic waste are efficiently utilized for energy production, reducing landfill waste [20].
Farm management structures and stakeholder involvement vary depending on individual entities.

The primary energy sources used in Lithuanian farms include biofuels, natural gas, and LPG gas [24]. A significant share of the energy consumed in agriculture is derived from renewable sources. The share of renewable energy in total electricity consumption varies by region: Klaipėda reported a 20.2% share in 2020 [20], Telšiai recorded 59.27% [25], and

Tauragė reached 76.7% [26].

Lithuanian farms are increasingly adopting renewable energy systems to enhance sustainability and reduce dependence on fossil fuels. Many farms operate biogas plants that convert livestock manure and organic waste into biogas through anaerobic digestion, producing both electricity and heat. Large dairy and pig farms are typical adopters. Solar panels are installed on farm buildings to generate electricity, reducing grid dependency and lowering costs. Some farms also participate in net metering, selling excess electricity back to the grid. Additionally, small-scale wind turbines are set up in windy regions to supplement other renewable energy sources. Biomass boilers burning wood chips, pellets, and agricultural residues are commonly used for heating, replacing conventional fuels. Some farms engage in sustainable forestry to maintain a continuous supply of biomass while preserving forest health. Others cultivate high-yield energy crops like miscanthus and switchgrass for bioenergy production. Furthermore, agricultural residues and organic waste are increasingly being used for energy generation, minimizing landfill waste. The Lithuanian government supports these initiatives through subsidies, grants, and favorable feed-in tariffs, encouraging investment in renewable energy [27,28].

Energy consumption varies by farm size. Small farms consume approximately 50-100 MWh per month, medium-sized farms use 150-200 MWh, and large farms require between 300-500 MWh per month [29]. The major energy-consuming activities on farms include irrigation systems, machinery operation, heating and cooling, lighting, ventilation, feed processing, milking and dairy processing, refrigeration, processing, and packaging [22].

The peak energy demand period in Lithuanian agriculture spans from March to November, which corresponds to the active agricultural season [28]. Several factors contribute to peak energy demand. In spring (March to May), energy consumption rises due to planting activities, requiring extensive use of machinery and irrigation systems. During summer (June to August), high energy demand continues due to irrigation, machinery use, and increased cooling needs for livestock and stored produce. In autumn (September to November), harvesting activities further drive up energy use, particularly for machinery, processing, and storage [28].

Poland

The Pomeranian Voivodeship, covering an area of 18,310.34 km², is the northernmost voivodeship in Poland. It is bordered by West Pomeranian Voivodeship to the west, Greater Poland and Kuyavian-Pomeranian Voivodeships to the south, Warmian-Masurian Voivodeship to the east, and the Baltic Sea to the north [30].
Farms in the region can be categorized into small, medium, and large farms. Large farms are extensive, intensive, and commercial institutions that operate in a mechanized manner. Medium-sized farms are often

transformed from small farms, typically inherited within families, and are increasingly developed for commercial viability. Small farms, however, are disappearing as agricultural production solely for personal use has become unprofitable due to market pressures favoring larger farms [31].

The average farm size in the Pomeranian Voivodeship in 2023 was 20.35 ha [32]. According to 2020 data, the structure of agricultural land size was as follows: up to 1 ha (22.4%), 1-2 ha (11.3%), 2-5 ha (14.3%), 5-10 ha (11.6%), 10-20 ha (9.9%), 20-50 ha (8.2%), and over 50 ha (4.7%) [32]. Regional variations exist, with smaller farms dominating in Kashubia and larger farms more common in Żuławy [33].

Small farms, defined as those with less than 15 ha, comprised 71.9% of farms in the region in 2020. Within this category, 36.4% had up to 5 ha, and 35.5% were between 5 and 15 ha. Interestingly, the number of small farms has slightly increased since 2010, with the most significant growth occurring among the smallest farms (under 5 ha) [30].

Medium-sized farms, defined based on land area and production value, accounted for 17.7% of farms (15-30 ha) and 6.4% (30-50 ha) in 2020, totaling 9,201 farms. Based on production value, 23.7% of farms (9,082 farms) were classified as medium-sized in 2021 [30].

Large farms, those with 50 ha or more, represented 9.2% of farms in the Pomeranian Voivodeship, totaling 4,011 farms. These farms had an average size of 151.2 ha and employed an average of 7.2 people. The breakdown by land area category was: 50-100 ha (48.5%), 100-200 ha (28.8%), and over 200 ha (22.7%) [30].

The region's agricultural sector is diversified in both crop production and livestock farming. The primary livestock includes cattle, pigs, and poultry. Among cultivated crops, cereals dominate, including wheat, barley, triticale, corn, rye, oats, and buckwheat. Additionally, potatoes, sugar beets, oilseed rape, vegetables, and fruits are cultivated, with wheat and sugar beets thriving in fertile soils such as those found in Żuławy Wiślane [34].

Crop residue generation varies by crop type: potatoes produce approximately 10% residue, cereals and rapeseed 20-25%. Cereals generate 3-5 tons of dry matter per hectare, rapeseed 10-12 tons, and corn 5-6 tons in silage farming and 10-15 tons in grain farming. Straw from cereals, rapeseed, and legumes is also considered crop residue [35].

Livestock residue is a significant byproduct in the region, with annual manure production estimates as follows: cattle (1,500,000 t/year), pigs (1,125,000 t/year), and chickens (325,000 t/year), totaling approximately 2,950,000 t/year [36].

Waste management in the region includes both on-farm and off-farm practices. On-farm methods include composting, anaerobic digestion, and proper manure storage and land application. Off-farm waste management involves processing facilities, waste-to-energy plants, and landfilling, though the latter is considered a last resort due to environmental concerns. Government regulations, economic factors, environmental impact, and technological advancements all influence waste management strategies [37–39].

Renewable energy generation in the Pomeranian Voivodeship is an emerging trend. Several farms have adopted biogas, solar, wind, and geothermal energy solutions. Notable examples include the Biogazownia Kołczygłowy and Biogazownia Brusk for biogas production, agritourism farms such as "Pod Lipami" and PPHU "EKOM" using solar energy, and wind farms like "Kociewie" (45 MW) and "Żarnowo" (25 MW). Geothermal projects, including those in Kościerzyna and Lębork, contribute to sustainable energy efforts in the region [40,41].

The farm management structure in the Pomeranian Voivodeship consists of small, medium, and large farms with varying degrees of stakeholder involvement. Farmers and their families manage daily operations, while government agencies like the Polish Ministry of Agriculture and Rural Development provide policies, subsidies, and advisory services. Regional authorities, industry associations, financial institutions, input suppliers, processors, retailers, and environmental NGOs also play crucial roles in shaping agricultural practices in the region [42].

In recent years, Poland has been reducing its **reliance on coal**, increasing its wind and solar power capacity

Energy consumption in farms within the Pomeranian Voivodeship is influenced by multiple factors, including farm size, production type, and seasonality. The primary source of energy used by most farms in the region is grid electricity due to its accessibility and versatility. It powers essential farm operations such as lighting, ventilation, milking parlors, and grain drying. However, some farms utilize secondary energy sources such as biogas and solar energy to offset grid electricity dependence. Farms with biogas plants benefit from converting agricultural waste into energy, while solar panels are increasingly installed to support irrigation and lighting needs. Other energy sources like diesel and propane are used in specific cases, such as for farm machinery and backup generators, though they are not the primary sources due to cost and environmental concerns [39,41].

A significant portion of energy consumed in agriculture comes from renewable sources, with national estimates suggesting that 10-15% of total energy consumption in Polish farms is derived from renewables. Solar photovoltaic (PV) installations allow some farms to cover up to 30% of their electricity needs, while biogas plants can contribute 50-100% of a farm's energy requirements, depending on the scale of production. Biomass, including wood chips and straw, is also commonly used for heating purposes [43–47]. Renewable energy systems in farms typically include solar panels, wind turbines, water energy, and biomass-based heating solutions [37].

The energy consumption of farms varies by size. Small-sized farms in the Pomeranian Voivodeship consume approximately 750-1400 kWh per month. This includes electricity for lighting, heating, cooling, machinery operation, and water pumping. Crop farms generally consume less energy than livestock farms, which require more power for heating and ventilation. Energy-efficient technologies can help reduce consumption significantly [37]. Medium-sized farms have higher energy demands due to increased mechanization and production needs. While definitive consumption figures are difficult to ascertain, these farms require more power for irrigation, cooling, and specialized machinery [37]. Large farms consume around 10,000 kWh per month, as they operate extensive livestock facilities, advanced irrigation systems, and processing units [38].

Agricultural energy use is divided into domestic and operational purposes. Domestic uses include lighting, heating living spaces, and powering household appliances, whereas operational energy is used for farm buildings, machinery, produce drying, cooling, and ventilation systems [37]. The peak energy demand periods for farms occur during the winter months (December–February), driven by the need for heating livestock buildings, greenhouses, and farm offices. Ventilation also requires more power to maintain air quality while preserving warmth. Larger farms, particularly those engaged in intensive livestock farming, experience the highest energy peaks during this period. The severity of peak demand is influenced by farm size, insulation efficiency, and the presence of renewable energy systems like biogas, which can reduce grid dependency [38,48].

The major contributors to peak energy demand include heating systems, ventilation, and, to a lesser extent, lighting and machinery use. Heating accounts for a significant portion of the increased winter energy demand, especially in livestock buildings and greenhouses. Ventilation is another major factor, as proper airflow is necessary for maintaining animal health and preventing moisture buildup. Poorly insulated farm structures exacerbate energy consumption by increasing heating requirements, whereas farms with energy-efficient systems can mitigate peak demand more effectively [49,50].

Solar Power Potential

GERMANY

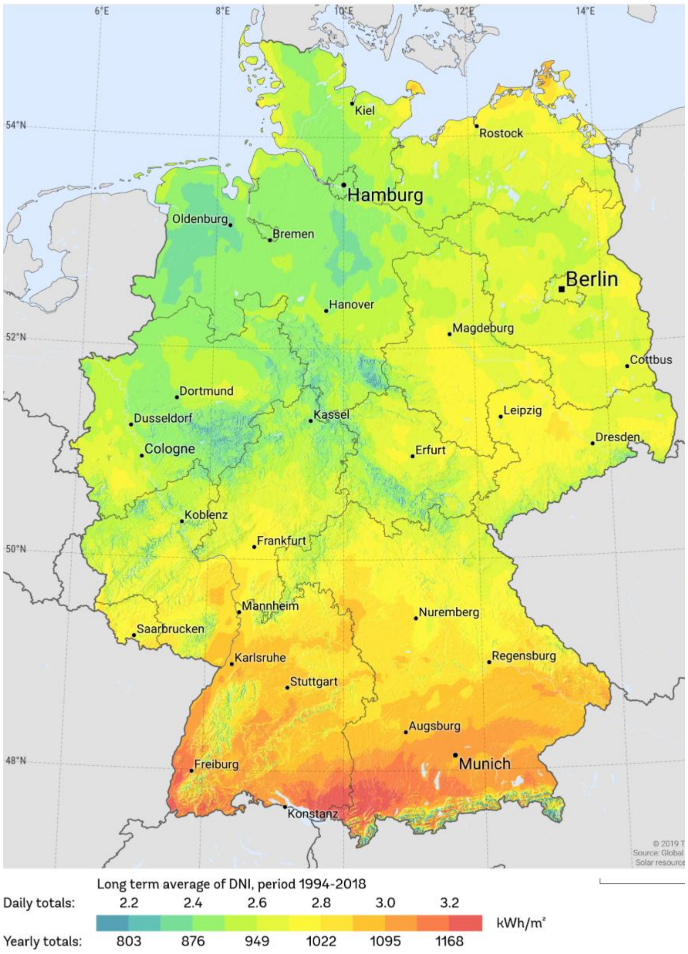

Figure 1: Long term average Direct Normal Irradiation (DNI) (kWh/m²) in Germany [51]

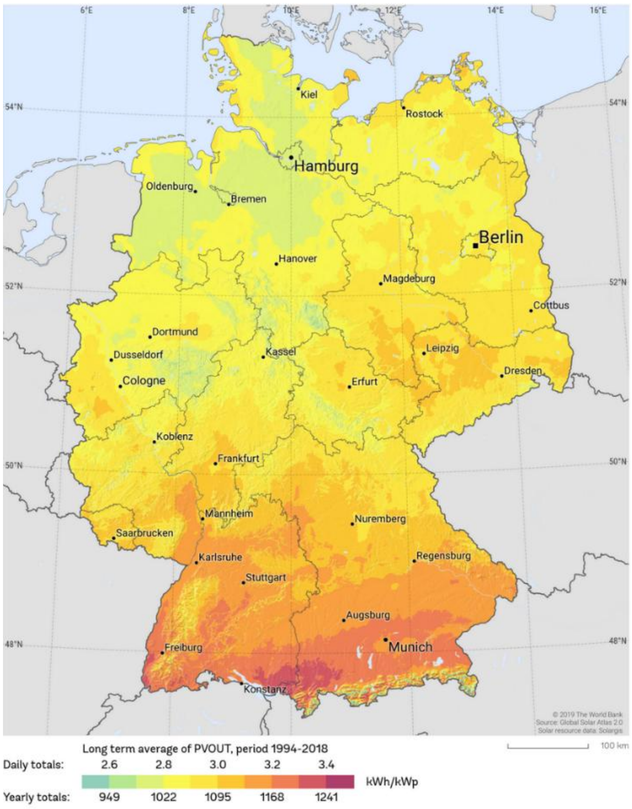

Figure 2: Long term average photovoltaic output (kWh/kWp) in Germany [51]

Mecklenburg-Vorpommern has a moderate solar potential, with an annual average of 1,647 hours of sunlight. Seasonal variations are significant, with the highest solar availability in June (236 hours) and the lowest in December (37 hours) [52]. The region receives an annual solar radiation of approximately 1,000 to 1,050 kWh/m² [53], making it suitable for photovoltaic (PV) installations. Currently, the installed PV capacity in Mecklenburg-Vorpommern stands at around 1,400 MW, contributing to approximately 14% of the total electricity generation from renewable energy sources [54].

Looking ahead, Mecklenburg-Vorpommern aims to expand its solar capacity to support its climate neutrality goals by 2035. To meet this objective, the region needs to reach a total solar capacity of approximately 22,750 MW, with an annual expansion target of 1,500 MW [45].

Germany as a whole has made substantial progress in solar energy deployment, with a cumulative installed PV capacity of around 81 GWp as of 2023 [55]. Farmland plays a crucial role in this development, accounting for 15.9% of the total PV installations, which corresponds to approximately 12,870 MWp [56]. The electricity generated from PV systems on farms is estimated at 9.52 TWh [56], considering the total solar electricity production in Germany reached 59.9 TWh in 2023. Of this amount, 53.5 TWh was fed into the public grid, while 6.4 TWh was used for self-consumption [57] .

Germany has significant potential for expanding solar energy installations, with a vast amount of available rooftop and ground space. The estimated total rooftop area suitable for solar panel installation is approximately 670 square kilometers. This includes built-up settlement areas but excludes roads and railways. If fully utilized, this space alone could provide a technical potential of 59 GWp. Moreover, Germany has around 40 million buildings, and the combined technical potential of rooftops and facades is estimated at 1,000 GWp. However, currently, less than 10% of the rooftop potential and less than 0.1% of the facade potential is being used for photovoltaic (PV) installations [58].

Beyond rooftops, large areas of land are also theoretically available for ground-mounted PV systems. In total, around 13 million hectares—roughly 37% of Germany' s land area—could be used for solar installations. Of this, 4.3 million hectares are particularly suitable for agrivoltaic systems, which integrate solar energy production with agricultural activities [59].

To support solar energy expansion, Germany has been rapidly increasing its battery storage capacity. In the first half of 2023, 1.7 GW of new storage was added, bringing the total installed battery storage capacity to 5.6 GW, with 8.3 GWh of energy storage. By the end of 2023, this capacity was projected to increase to 10–11 GWh [60].

Photovoltaic (PV) technology remains the preferred choice for solar installations in Germany, given its efficiency and widespread adoption. For agricultural purposes, electricity prices vary, but in the second half of 2023, the average electricity cost for non-household consumers was €0.189 per kWh [61].

Government incentives are further driving the adoption of solar energy. Households and businesses installing solar storage systems under 30 kW can receive subsidies covering up to 30% of their battery costs [62]. Additionally, the 19% VAT on PV systems has been eliminated, making solar installations more cost-effective [63]. A feed-in tariff of 8.20 cents per kWh is guaranteed for 20 years, encouraging investment in solar power generation. Moreover, in May 2024, additional solar funding opportunities will be available, providing further financial benefits for those who install PV systems [63].

In total, around **13 million hectares**—roughly 37% of Germany's land area—could be used for solar installations

The adoption of solar energy requires careful consideration of environmental and infrastructural aspects. Environmental sustainability is a key factor, especially for ground-mounted PV systems, which must be integrated into the landscape. Measures to ensure this include limiting PV module use to a maximum of 60% of the available area, implementing a care concept to promote biodiversity, ensuring accessibility for animal species, and incorporating biotope elements. Additionally, operations must be conducted in a soil-friendly manner to minimize environmental impact [64].

Another important factor is land use. Special feed-in tariffs encourage the dual use of arable land by combining PV modules with agricultural activities [65]. Furthermore, the maximum bid volume for tenders for ground-mounted PV plants has been permanently increased from 20 MW to 50 MW to enhance the efficiency of such projects [64].

Grid connection is crucial for integrating solar energy. Net metering is a promising solution for efficiently feeding surplus electricity into the grid. While systematic maintenance of PV installations is not legally required, it is strongly recommended. On average, operational costs account for 1–2% of the initial investment [66]. An annual inspection by specialists, along with a full system check every four years according to DIN EN 62446-1 VDE 0126-23-1:2019-04, ensures long-term performance. Regular cleaning may also enhance efficiency [67].

The integration of smart technologies significantly improves solar system performance. Artificial intelligence (AI) enables more accurate solar energy forecasting through deep learning models, particularly by combining an LSTM neural network with an autoencoder to analyze temporal and spatial features [68]. Smart grid technologies play a key role in renewable energy integration by providing advanced metering infrastructure, automated grid management, and flexible demand response systems [69]. Additionally, IoT-powered solar installations enable real-time monitoring and fault detection [70], while intelligent energy monitoring systems optimize the efficiency of renewable energy utilization [71].

The operational lifespan of solar photovoltaic (PV) panels in Germany is estimated to be around 30 years. As solar adoption increases, effective end-of-life (EOL) waste management becomes crucial [72]. Germany has established a comprehensive regulatory framework to manage e-waste, including PV panels, following the extended producer responsibility principle. Under this system, producers finance waste management and delegate the recycling and disposal of PV panels to specialized waste management sectors. Advanced recycling facilities have been developed, allowing for the efficient recovery of major PV panel components. This framework aligns with the national implementation of the EU Waste Electrical and Electronic Equipment (WEEE) Directive, ensuring sustainable solar waste management [72].

To support the growth of solar energy, Germany offers specialized training programs for professionals in the field. The Renewables Academy (RENAC) AG provides both online and in-person courses covering various aspects of renewable energy, including PV system design and protection mechanisms [73]. The Green Solar Academy Network (GSAN) focuses on vocational training, particularly for rural solar PV applications [74]. The SMA Solar Academy offers global training in complex PV systems, covering installation, maintenance, and system design [75]. Additionally, TÜV SÜD provides certification programs addressing regulatory trends, quality, and safety requirements for solar projects [76].

Despite Germany' s leadership in solar energy, several regulatory barriers still hinder wider adoption. Challenges include grid connection and integration issues, reductions in feed-in tariffs, complex administrative and permitting processes, high grid access fees, and restrictive land-use and zoning regulations. Additionally, market design and access constraints pose difficulties for project developers. In response, Germany has introduced policy reforms, grid modernization initiatives, and renewable energy auctions to enhance market efficiency and integration [72].

LITHUANIA

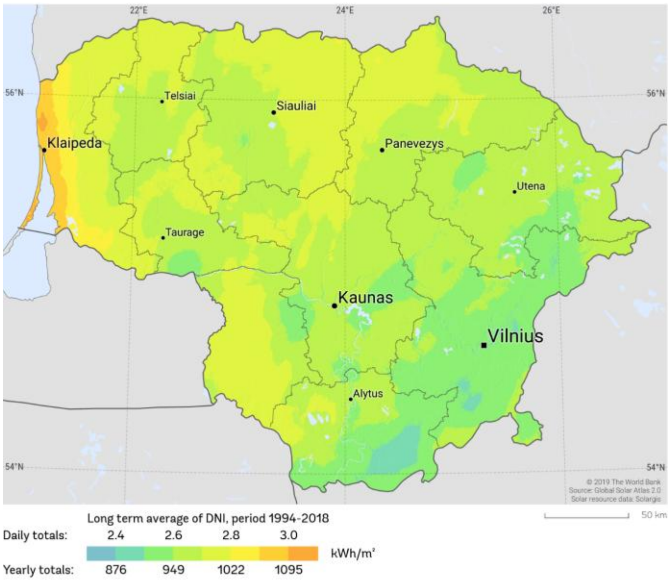

Figure 3: Long term average Direct Normal Irradiation (DNI) (kWh/m²) in Lithuania [51]

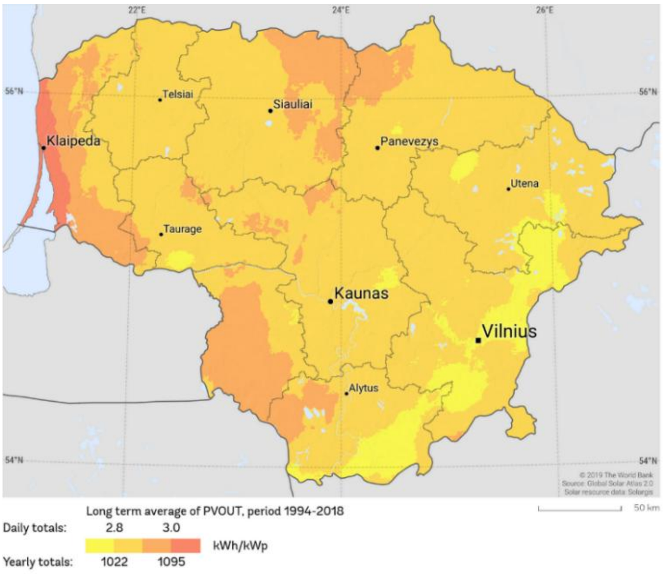

Figure 4: Long term average photovoltaic output (kWh/kWp) in Lithuania [51]

Lithuania experiences an average of 1,850 to 1,950 sunlight hours per year, depending on the region. Klaipėda records 1,940 hours, Telšiai 1,850 – 1,900 hours, and Tauragė 1,900 - 1,950 hours of sunshine annually [25,26,77]. Seasonal variations are notable, with December and January having the least sunlight, at 9 and 14 hours, respectively. Spring sees an increase, peaking in May with 347 hours, while summer remains consistently high, with June reaching 312 hours. Autumn sunlight is highest in September (257 hours) but declines through October (86 hours) and November (38 hours) [78].

Assessments of solar potential have identified significant opportunities for solar collector-generated heat. In Klaipėda, the centralized heating system supplied 43,730 MWh of heat energy in 2020, with 9,000 MWh (774 TOE) being the estimated solar potential. Generating this amount would require 19,150 m² (1.9 ha) of solar collector fields [20]. Similarly, Telšiai's centralized heating system supplied 45,389.28 MWh in 2021, with 9,077.86 MWh (780.70 TOE) estimated as the solar potential [25]. Tauragė has an annual solar heat energy potential of 148,560 MWh (12,773.9 TOE), including 18,371 MWh (1,579.6 TOE) from municipal installations [26].

Lithuania has approximately 3,000 photovoltaic (PV) installations ranging from 50-1000 kW in farms, with 44 large-scale PV farms exceeding 1000 kW. The total installed PV capacity on farms is estimated at 50 MW, generating 4,689.7 MWh in Klaipėda, 3,599.75 MWh in Telšiai, and 4,006 MWh in Tauragė [79]. There is substantial available space for further solar expansion. Klaipėda has 1,518,990 m², Telšiai 568,175 m², and Tauragė 327,514 m² of available rooftop space for solar installations. Additionally, large ground areas are available, with 4,157 ha in Klaipėda, 5,452.71 ha in Telšiai, and 1,794 ha in Tauragė [80,81].

In terms of electricity storage, excess energy is typically sent to the grid, where it is stored and can be retrieved at a later time based on the producer's chosen tariff structure [82].

Lithuania's solar market includes both self-funded and subsidized projects. PV systems under 100 kW are not regulated. Subsidized projects, such as those funded by the APVA fund, must comply with EU standards. Solar modules must be new, unused, and meet ecological labeling requirements. A 10-year product warranty and a 25-year 80% efficiency warranty are required for solar modules, while inverters must have a 5-year warranty [83].

The average cost of electricity for agricultural purposes in Lithuania is 60.2 € per MWh [84]. Government incentives are available to support solar projects. Several types of support measures are available through the Environmental Project Management Agency (APVA) in Lithuania. These include financial incentives for the installation of new solar power plants by private individuals on residential properties, as well as support for increasing the capacity of existing solar installations. These programs aim to accelerate the adoption of renewable energy at the household level and contribute to the country' s broader sustainability and energy independence goals [77].

From an environmental perspective, building permits and green certificates are required. A key criterion for subsidies is the CO2 reduction efficiency per Euro spent, prioritizing projects that achieve greater CO2 savings [85].

Lithuania allows 100% of generated solar energy to be connected to the grid. However, recent regulatory changes propose a shift from net metering to net billing for businesses, requiring them to sell excess electricity on the market and repurchase it later, potentially exposing them to market price fluctuations [86].

The development of **solar power** in Lithuania is still **lagging** behind other RES such as wind power

Solar installations require systematic maintenance to ensure efficiency and longevity, with costs ranging from €199 to €299 per kW [87]. The integration of smart grid technologies plays a crucial role in optimizing solar power generation. These technologies help efficiently manage energy distribution and integrate different sources, particularly benefiting rural and remote areas by improving access to energy and reducing dependence on large infrastructure [88].

Lithuania is steadily advancing in the deployment of smart grid technologies. As part of a nationwide modernization effort, over 300,000 smart meters (Advanced Metering Infrastructure – AMI) have already been installed, with full national coverage expected by 2026, led by the energy distributor ESO [89]. In more remote regions, such as Molėtai and Ignalina, microgrid projects are beginning to emerge, supported through the National Energy and Climate Plan (NECP) and EU funding mechanisms [90]. New photovoltaic (PV) systems are now required to include smart inverters and are increasingly paired with energy storage solutions. Battery storage is being piloted on farms through support from the Environmental Project Management Agency (APVA), helping to enhance self-sufficiency and grid stability [91]. These smart farm pilots also utilize Energy Management Systems (EMS) to monitor and optimize energy use in real-time. The integration of advanced battery technologies, ranging from lithium-ion to emerging lithium-glass, enables more efficient storage and distribution of solar energy, ensuring greater reliability during periods of low generation or peak demand [91].

In parallel, Poland is also investing in the development of a smart grid infrastructure capable of accommodating the variable nature of renewable energy sources such as solar. This includes the rollout of advanced metering infrastructure and intelligent grid management systems that incorporate artificial intelligence (AI) and Internet of Things (IoT) technologies to optimize performance and enhance energy resilience [92].

In terms of lifespan, manufacturers state that solar PV modules maintain 85-90% of their efficiency after 25 years. Depending on the brand, these modules come with a guarantee of up to 25 years, while power inverters typically have a warranty of up to 10 years [93]. However, the end-of-life waste management of PV panels remains a regulatory challenge. At the EU level, PV panels are classified under the Waste Electrical and Electronic Equipment (WEEE) Directive, which governs their disposal and recycling. Solar cell manufacturers must comply with legal recycling requirements to ensure that solar panels do not become an environmental burden, leading to the development of dedicated recycling technologies [94]. Education and training are essential for professionals working in solar energy. Regional training opportunities include private courses, vocational training, and specialized schools where electricians can requalify for solar energy projects [80]. Additionally, solar power and other renewable energy sources are actively promoted and encouraged by state governments and local authorities, ensuring awareness of relevant regulations at local, regional, and national levels [94]. However, certain regulatory barriers still exist, particularly concerning territorial security considerations, which may influence the adoption of solar power in specific regions [25].

POLAND

Poland receives an average annual solar irradiance ranging between 900-1000 kWh/m², making it a viable location for solar energy generation [95]. The distribution of solar radiation is uneven throughout the year, with approximately 77% of the total solar energy received between mid-April and early October. The highest levels of sunlight occur in the summer months, when daylight can exceed 16 hours per day, and in spring, with day lengths of 12-15 hours. The peak insolation is observed in May, June, and July, whereas in autumn, daylight duration drops below 12 hours, and in winter, it is limited to just 7-8 hours [96].

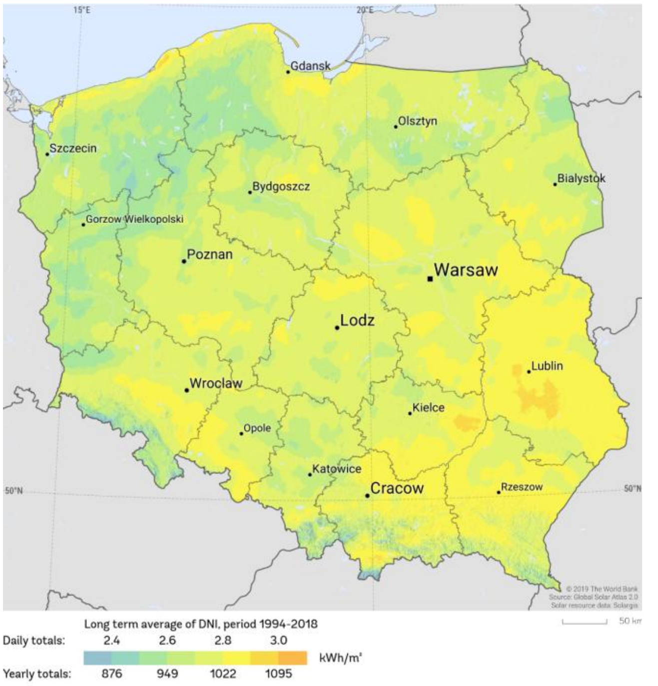

Figure 5: Long term average Direct Normal Irradiation (DNI) (kWh/m²) in Poland [51]

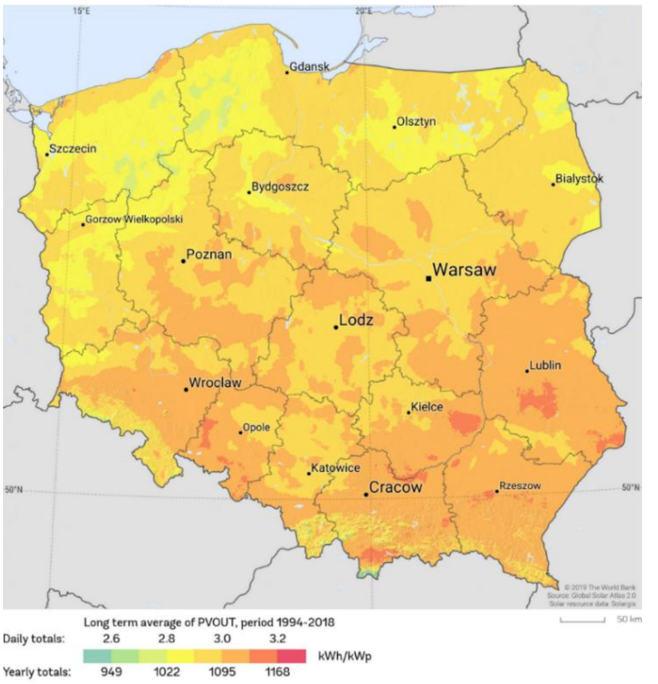

Figure 6: Long term average photovoltaic output (kWh/kWp) in Poland [51]

Poland's technical photovoltaic potential is estimated at 153.484 PJ (42.634 TWh), which could cover approximately 26.04% of the country's electricity demand [97]. As of June 2023, in the Pomeranian Voivodeship alone, there are 132 PV installations within the 50-1000 kW range and seven installations exceeding 1,000 kW. Nationally, there are 3080 smaller and 148 such large-scale PV systems [97,98]. There is currently no precise data on how many of these installations are located on farms or the total electricity they generate [99]. Despite this, agrivoltaic (Agri-PV) solutions, which integrate solar energy production with agricultural activities, are gaining traction in the region. These systems optimize land use by allowing for simultaneous farming and energy production, potentially enhancing farm income and sustainability.

In terms of available space for further solar development, Poland has significant potential. The estimated total rooftop area suitable for solar panels is around 118,563 square meters [100]. Additionally, various ground sites have been identified for potential PV installations, including 3.169 MW on wastelands, 0.836 MW on closed municipal waste landfills, 1.037 MW on landfills planned for closure, 4.350 MW along highways and expressways, and 75.160 MW near railway lines [100].

In Poland, energy storage is increasingly recognized as a crucial component for integrating renewable energy sources and ensuring grid stability. The preferred storage methods include both battery energy storage systems (BESS) and pumped hydro storage. Battery storage is gaining momentum, with companies like PGE investing in large-scale projects, such as a 200MW/820MWh battery facility integrated with the Żarnowiec pumped hydro plant to stabilize power from nearby wind farms. Pumped hydro remains a key solution due to its ability to provide large-scale energy storage, with plans to further expand the Żarnowiec facility in combination with battery technology. Recent regulatory changes have also facilitated the development of energy storage, making both battery and pumped hydro solutions more attractive to investors [101,102].

When it comes to solar technology, photovoltaic (PV) panels are the dominant choice in Poland. The country' s new solar capacity installed in 2020 was entirely based on silicon PV technology, underscoring its preference over other solar solutions like concentrating solar power (CSP) [103].

Financially, the cost of electricity for agricultural purposes is approximately 0.6980 zł/kWh or 0.17 EUR/kWh [104]. To encourage solar investments, the government has introduced various incentive programs, including Mój Prąd and Energia dla Wsi. These initiatives provide grants and financial support for micro-installations and renewable energy projects in rural areas, promoting solar adoption across different sectors [105–107].

From an environmental perspective, photovoltaic projects in Poland may require an environmental decision as part of the administrative process. This regulation ensures that solar installations comply with local environmental standards before construction begins [108,109]. Additionally, land use is a critical factor for ground-mounted solar farms, as they require significant space. To minimize competition with agricultural land, it is recommended to utilize degraded areas, brownfields, or marginal lands that are less suitable for farming or other essential activities [110].

Regarding grid connection, the process is regulated under Polish Energy Law. For projects connected to grids with voltages below 1 kV, the Distribution System Operator (DSO) must issue connection conditions within 30 days from the application date. For projects with voltages above 1 kV, this period extends to 150 days, provided the applicant has made a prepayment [111,112].

Poland' s solar market has historically relied on net metering to encourage distributed generation. However, in April 2022, the country transitioned from net metering to a net billing system for PV micro-installations up to 50 kW. This shift aims to better regulate the influx of renewable energy into the grid and promote self-consumption at the point of generation rather than excessive feed-in [46,113].

In 2021, Poland's total photovoltaic capacity reached approximately **5.7 GW**, while the estimated technical potential for photovoltaics in the country is 153.484 PJ, equivalent to **42.634 TWh** [77]

The maintenance and operational costs of solar installations in Poland vary depending on system size. For small-scale systems, such as a 1.5 kW installation, annual operating costs—including future repairs—can be as high as 10-15% of the system' s value, making maintenance a significant expense [114].

Smart technologies are playing an increasingly important role in optimizing solar power generation. Advanced battery storage solutions, including lithium-ion and emerging lithium-glass technologies, are enhancing energy storage efficiency by allowing surplus solar energy to be stored and utilized during periods of low production or peak demand. Poland' s energy strategy is also focused on integrating a smart grid infrastructure, which includes advanced metering infrastructure (AMI) and AI-driven grid management systems to improve the reliability and performance of renewable energy sources like solar [115–117].

The operational lifespan of photovoltaic (PV) systems in Poland is generally expected to be between 25 and 30 years under typical climatic conditions, ensuring a long-term return on investment [100]. However, end-of-life waste management remains a challenge. Under the EU' s Waste Electrical and Electronic Equipment (WEEE) Directive, PV panels are classified as electronic waste, meaning that manufacturers must register with the BDO (Register of Entities Introducing Products, Packaged Products, and Managing Waste) and prepay for recycling costs based on the weight of the equipment. While these measures are in place, the specifics of future waste collection processes remain unclear, with national regulations still lacking detailed guidelines [118].

Training and education for solar industry professionals in Poland are supported by multiple organizations [106]. The Network of European Funds Information Points in the Pomorskie Voivodeship provides training on funding opportunities and project implementation in the renewable energy sector [119]. Additionally, the Energy Center offers specialized training on the design, installation, and maintenance of PV systems, ensuring that participants are well-versed in relevant standards and optimization techniques [120]. Solar Building Poland, accredited by the Office of Technical Inspection, provides hands-on training with state-of-the-art tools for aspiring PV installers [121].

From a regulatory standpoint, the development of solar energy in Poland is governed by the Renewable Energy Sources Act (RES Act), which establishes support mechanisms such as auction systems and feed-in tariffs. Recent amendments in December 2024 have further streamlined investment processes, offering improved conditions for prosumers and aligning national policies with EU directives. Local regulations also play a role, as spatial planning authorities designate areas for solar installations, and certain projects may require building permits and Environmental Impact Assessments (EIAs). Moreover, tax incentives, including exemptions for holding structures involved in solar projects, provide financial benefits for investors [100].

Despite these regulatory frameworks, there are significant barriers to solar adoption in Poland. One of the primary challenges is grid congestion, as the existing infrastructure struggles to accommodate the increasing influx of renewable energy. This results in delays and additional costs for grid upgrades, impacting the feasibility of larger projects. Furthermore, frequent changes to renewable energy policies, including modifications to net metering and feed-in tariff structures, create an unstable investment environment, making long-term financial planning difficult for investors [122].

Wind Power Potential

GERMANY

The region under study exhibits a varying wind profile throughout the year, with wind speeds averaging above 20 km/h during the winter months and around 10-15 km/h in the summer [125]. This seasonal fluctuation results in lower wind speeds between May and September, potentially influencing energy generation during these months. Despite these variations, the region is generally considered suitable for wind turbine installations, as it meets the necessary wind speed criteria for effective energy production.

As of April 2024, approximately 246 smaller wind turbines (50-1000 kW) remain operational in the SBS region. These turbines were predominantly installed in the 1990s and early 2000s, and many are currently being decommissioned or repowered. It is important to note that smaller wind installations below 10m in height are not required to be registered, meaning their exact numbers remain unknown [126].

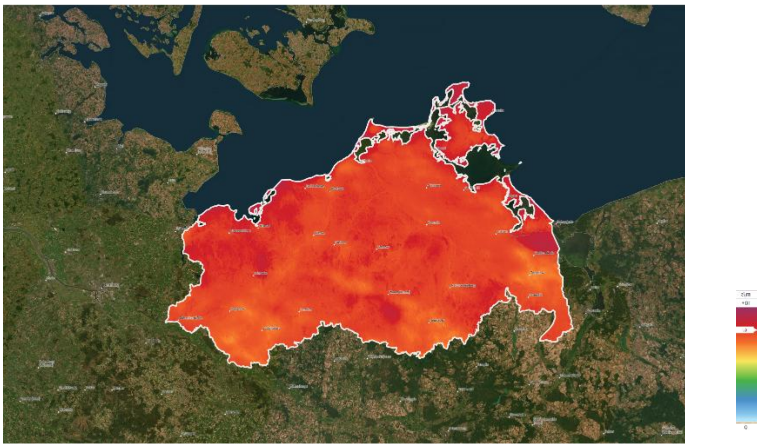

Figure 7: Long term mean wind speed (m/s) at 100m in Mecklenburg-Vorpommern (Germany) [123,124]

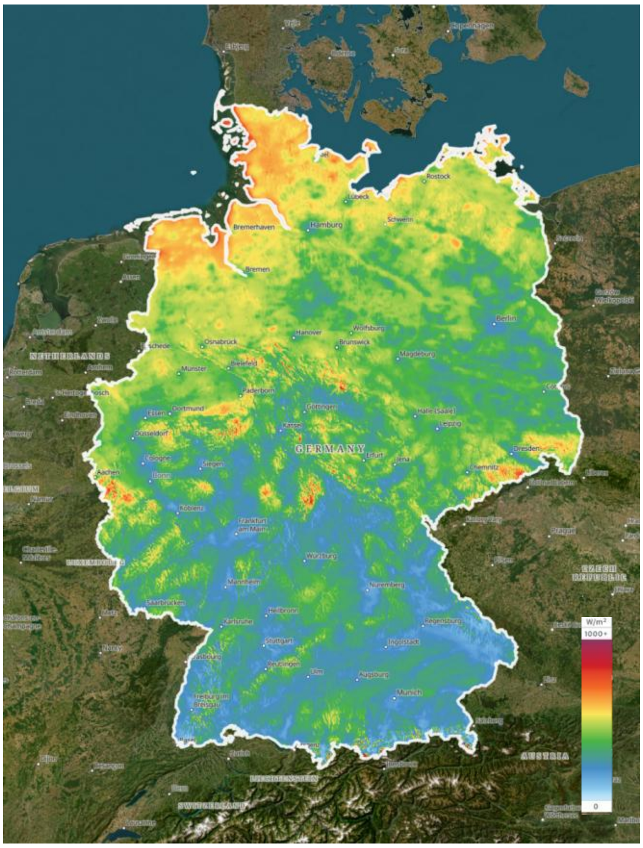

Figure 8: Mean wind power density at 100m (W/m²) in Germany [123,124]

Larger wind turbines (>1000 kW) have seen a different trajectory, with around 1,015 currently in operation. The peak of wind energy installations was reached in 2020, when nearly 2,000 turbines were recorded. However, due to the gradual phasing out of older and less efficient turbines, this number has been declining. Offshore wind farms account for 232 of these installations, contributing a total capacity of 1,096 MW [127]. The total wind energy capacity installed on farmland in the SBS region is estimated at 1,302 MW, although there is no direct registry for installations exclusively on agricultural land. Typically, farmers either lease their land to energy companies for up to 30 years or establish wind parks independently or in partnerships [128].

The potential for wind energy expansion is influenced by zoning regulations and land availability. Under federal regulations, at least 2.1% of the land area must be designated for wind energy by 2032, which equates to approximately 269.7 km². However, if all exclusion criteria are applied, wind power may be feasible on up to 4% of the region' s area, or 513.8 km². These exclusions include nature reserves, important forests, and drinking water protection areas. Additionally, minimum distance regulations require turbines to be placed at least 1,000 meters from towns and 800 meters from individual residences [129].

The preferred turbine technology in the region is the horizontal-axis wind turbine. Over the years, there has been a shift toward larger and taller turbines, with newer installations often exceeding hub heights of 170 meters. Older installations from the 1990s, which typically have hub heights around 70 meters, are gradually being replaced with more efficient and powerful models [130].

All wind turbines must be connected to the grid, as the "Bundesnetzagentur" oversees the sale of electricity generated by renewable energy sources. The feasibility of grid connection is generally high, though it requires strategic planning to ensure adequate regional distribution of wind energy sites. The aim is to allocate 2.1% of the land area evenly across different regions for wind energy expansion [131].

Mecklenburg-Western Pomerania aims to significantly increase the amount of wind farms by the end of 2032. By then, 2.1 percent of the state's land area is to become designated as suitable areas for wind energy, compared to the current 0.8 percent.

The cost of installing wind power varies, with an estimated range of 770 to 1,030 euros per kW. However, additional expenses such as accessibility improvements, grid connection, foundation work, environmental reports, and ecological compensation measures significantly increase the total installation cost, often by approximately 125-135% above the system price [132].

To support wind power development, the Federal Ministry for Economic Affairs and Climate Protection (BMWK) provides financial incentives, particularly for local citizen energy companies. Funding is available for preliminary planning, feasibility studies, legal consultations, and land-use adjustments, covering up to 70% of eligible costs, with a cap of €200,000. However, if a project receives subsidies under the Renewable Energy Sources Act (EEG 2023), these grants must be repaid [133].

There are also two primary remuneration models under EEG regulations: the market premium and the feed-in tariff. The market premium is calculated monthly and supplements the price achieved on the electricity market. For onshore wind turbines, the applicable value is determined through bidding processes. Smaller systems under 750 kW, however, are subject to fixed reference values based on previous auction results. Alternatively, the feed-in tariff model allows system operators to sell all generated electricity to transmission system operators at a legally guaranteed rate [134]. Investments in wind power generally yield an annual return of 4-8%, depending on factors such as turbine capacity, wind conditions, and maintenance costs. While profitability varies by project, wind energy remains a stable and promising sector for long-term investment [135].

Wind turbines in the region follow a systematic maintenance cycle, with scheduled servicing occurring twice a year. Maintenance costs represent a significant portion of operational expenses, accounting for up to 40% of total operating costs. These expenses range between 10.5 and 14.7 €/MWh, making long-term financial planning crucial for project viability [136]. Most wind power plants in the region are equipped with remote control and supervision systems, allowing for efficient monitoring and operation. The integration of smart technologies has enhanced system performance by optimizing maintenance schedules, predicting failures, and ensuring real-time data analysis for improved energy output [137].

The estimated operational lifespan of wind turbines in the region is approximately 20 years, after which repowering or decommissioning may be required [132].

The current status of end-of-life waste management for wind turbines remains a challenge, with limited regulations in place to ensure sustainable disposal and recycling. Efforts are being made to enhance waste management strategies, particularly for turbine blades and other non-recyclable components [132].

As of February 2023, all environmental considerations related to wind energy projects have been consolidated under land-use impacts. This regulatory adjustment aims to streamline the approval process while ensuring that environmental concerns are effectively addressed [138].

Wind turbine installations are subject to strict land-use regulations. A minimum settlement distance of 1,000 meters is required from areas designated under §§ 30 and 34 BauGB, which include residential, recreational, tourism, and health-related functions. Additionally, a buffer of 800 meters must be maintained from individual houses and splinter settlements. Other restrictions include protected nature and landscape areas, forest conservation zones, designated water protection areas, and infrastructure-sensitive zones such as military properties, airports, and weather radar stations. These regulations ensure that wind energy expansion does not interfere with critical ecological and infrastructural functions [138].

Environmental mitigation measures are incorporated into land-use impact regulations. These include strategies for bird and bat protection, noise reduction technologies, and adaptive turbine operation to minimize environmental disturbances [138].

Currently, there are no region-specific training programs available for personnel involved in wind power projects. However, industry stakeholders often rely on general wind energy certification programs and technical training offered at the national level [139]. Public participation in wind energy projects is mandatory under the Citizens' and Municipal Participation Act, which came into effect on May 28, 2016. This law requires project developers to offer participation opportunities to residents within a 5 km radius of any new wind turbine installation that falls under the Federal Emission Control Act [140].

Regulatory challenges include high zoning requirements and lengthy approval processes managed by the ministry. These factors contribute to delays in wind energy project implementation, creating bottlenecks that hinder expansion efforts [140].

LITHUANIA

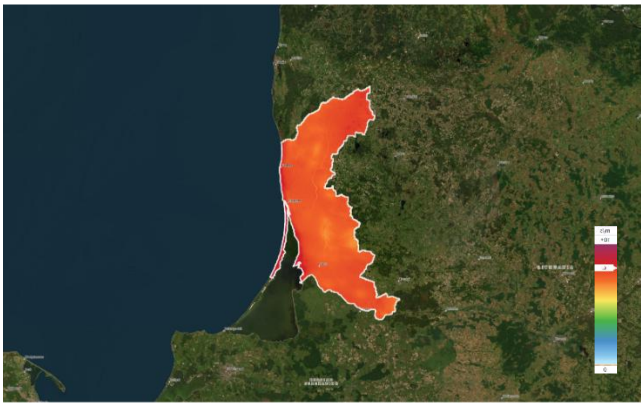

Figure 9: Long term mean wind speed (m/s) at 100m in Klaipedos (Lithuania) [123,124]

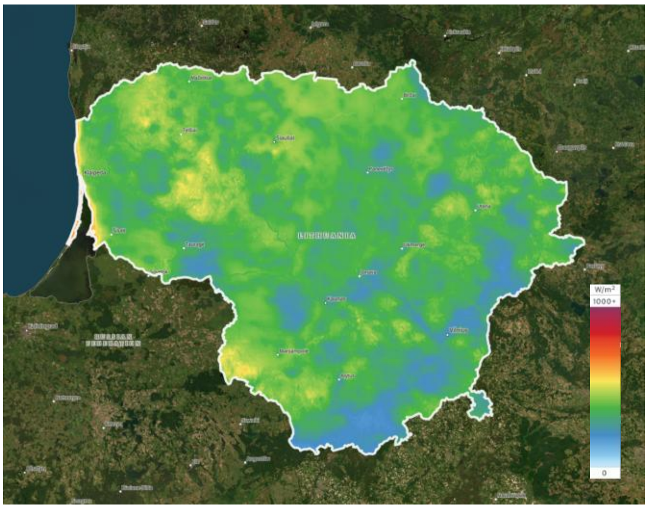

Figure 10: Mean wind power density at 100m (W/m²) in Lithuania [123,124]

The average annual wind speed in Lithuania varies across different regions, with an overall national average of 3.1 m/s. In specific locations such as Klaipėda, the wind speed reaches 5.5 m/s, in Telšiai it is 4.4 m/s, and in Tauragė it stands at 5 m/s [141]. When considering wind turbine installations, planners must adhere to the regulations established in the Order of the Commander of the Lithuanian Armed Forces No V-217 of February 2016, which specifies areas where wind power plants may be restricted due to national security concerns and other legal stipulations [142]. Seasonal variations also play a role in wind energy production, with the windiest months occurring between November and February (3.4-3.6 m/s), while the lowest wind speeds are recorded in July and August (2.4-2.5 m/s) [143].

While exact figures for wind turbines in the 50–1000 kW range are difficult to obtain, it is evident that Lithuania hosts a significant number of installations within this capacity bracket, contributing meaningfully to the country's renewable energy portfolio. Wind turbines in the 600–2000 kW range, along with smaller-scale turbines, are particularly common and continue to play a vital role in the expansion of Lithuania's wind energy sector [144].

As of 2024, Lithuania's total wind power capacity, including turbines exceeding 1000 kW, reached approximately 1,740 MW, marking a significant increase from 946 MW at the end of 2022. According to the Interreg Baltic Sea Region, wind power generation in Lithuania totaled 1,703.1 GWh in the first half of 2024 alone, highlighting the rapid growth and contribution of wind energy to the national power mix [142].

Lithuania has made significant progress in wind energy development, with a total wind turbine installation capacity of 946 MW [3]. Of this, 6 MW are situated on wind farms, with 803 MW connected to the transmission grid and 143 MW integrated into the distribution grid as of 2021 [143].

The total available land for wind turbine installations in Klaipėda is approximately 1,773.7 hectares, while Telšiai has 1,374.81 hectares. However, Tauragė has no available land for new installations due to existing regulations. The Tauragė region falls under the jurisdiction of the Exclusive Economic Zone and other regulations, requiring renewable energy producers to enter agreements with the Lithuanian Armed Forces regarding national security investment reimbursements and related costs [20,25,26].

Land-use considerations for wind farms include selecting areas with minimal vegetation and tall buildings to maximize wind exposure. Wind farms are predominantly developed in sparsely populated agricultural areas, maintaining a minimum distance of 440 meters from residential buildings as per regulations. Landscape identity and recreational potential are also taken into account, as highlighted by a 2006 study from Vilnius University. Cultural heritage sites are avoided to prevent visual and physical disruptions. Additionally, proximity to existing transmission lines (35kV to 330kV) is a key factor to ensure efficient grid connection and capacity management [145].

The preferred wind turbine technology in Lithuania is the Enercon E82 model, which has become a standard choice for installations. This model is selected based on its suitability for local wind conditions and energy efficiency [146].

The feasibility of grid connection varies by region. Klaipėda currently hosts 90 wind power plants with a combined capacity of 180 MW. Tauragė has 64 wind power plants generating 14.4 MW, while Telšiai operates 72 wind power plants with a total capacity of 143 MW [147].

For infrastructure requirements, horizontal-axis wind turbines are recommended for farms with distant neighbors due to their efficiency. For areas where neighbors are within a 100-meter radius, vertical-axis wind turbines are preferred because they generate less operational noise. Additionally, small wind turbines under 10 meters in height do not require building permits, making them more accessible for smaller-scale applications [20,25,26].

Several technical challenges affect wind power implementation in different regions. In Klaipėda, local governance has not prioritized renewable energy expansion, leading to a stagnation in new installations since 2012. Tauragė falls under the V-217 Armed Forces regulation, necessitating special permits for construction. In Telšiai, the combination of relatively low annual wind speeds and limited available land makes wind energy development less economically viable [148].

While specific solutions have not been identified, addressing these challenges would require policy incentives, regulatory adjustments, and infrastructure investments to facilitate wind energy expansion in these regions.

Lithuania has been actively investing in wind power as part of its renewable energy strategy. The budget for wind power installation is structured to support projects of up to 6 MW, though funding is provided specifically for up to 3 MW of installed capacity. The cost calculation is based on a fixed unit rate of €1608.65 per kW, ensuring a structured approach to financing wind farm installations [149].

To encourage investment in wind energy, financial incentives are available. In June 2023, the Lithuanian Energy Agency (LEA) announced a funding initiative that provided over €18 million to support Renewable Energy Communities, Citizens' Energy Communities, companies, and farmers in developing wind farms of up to 3 MW. This funding, backed by the European Union, aimed to enhance the country's renewable energy infrastructure [149]. As a result of these initiatives, Lithuania expects to add 30.1 MW of new electricity generation capacity from wind energy by May 2026 [149].

Operational and maintenance aspects of wind power projects remain a key consideration. Although no official data is available for maintenance costs in the region, advancements in technology are helping improve efficiency. For example, drones equipped with various cameras—visual, infrared, and even X-ray—are increasingly being used to inspect turbine components such as blades, towers, and nacelles. These inspections help detect potential issues caused by environmental exposure and high-speed rotation, ensuring the longevity and efficiency of wind farms [146].

As of **2024**, Lithuania's total **wind power** capacity, including turbines exceeding **1000 kW,** reached approximately 1,740 MW, marking a significant increase from 946 MW at the end of **2022 [142].**

The expected lifespan of wind turbines in Lithuania ranges between 25 and 40 years, depending on factors such as maintenance and environmental conditions [150]. The country has also made progress in wind turbine waste management, with researchers at Kaunas University of Technology and the Lithuanian Energy Institute exploring ways to recycle wind turbine blades. Their experiments have successfully broken-down fiberglass-reinforced plastics into reusable aromatic compounds and fibers, which can be repurposed for concrete, polymer composites, or fiber coatings [143].

Environmental considerations are an integral part of wind power development in Lithuania. While opponents of wind energy have long argued that turbine blade disposal poses sustainability challenges, efforts are being made to address this issue. Additionally, noise pollution remains a concern [151]. Environmental impact assessments are mandatory for wind power projects, evaluating the effects on land, water, air, biodiversity, and public health. Special attention is given to protected species and habitats to ensure minimal disruption [152]. To mitigate negative environmental impacts, Lithuania follows best practices in project implementation, including measures to avoid, minimize, or compensate for potential damage while complying with national and international environmental standards [153].

Education and training initiatives are also in place to support the wind energy sector. The Lithuanian Ministry of Energy and private companies offer scholarships to encourage students to pursue careers in energy and engineering. In 2022, the Ministry allocated €24,000 for scholarships, while companies such as Amber Grid, Litgrid, Tetas, and Ignitis collectively provided over €250,000 in financial support for engineering students, with individual scholarships ranging from €200 to €300 per month [154].

Lithuania is making significant strides in wind energy regulation, particularly in offshore wind development. The country has established a clear regulatory framework, involving key stakeholders to ensure a conducive environment for wind power expansion [155]. However, regulatory barriers still exist. Historically, Lithuania's renewable energy development was slow, with real progress occurring only after the adoption of the Law on Energy from Renewable Sources (LERS) in 2011. Since then, major legislative changes have facilitated a more competitive energy market and improved energy efficiency. Future plans for renewable energy and climate change policies are expected to further enhance Lithuania's wind energy sector [156].

POLAND

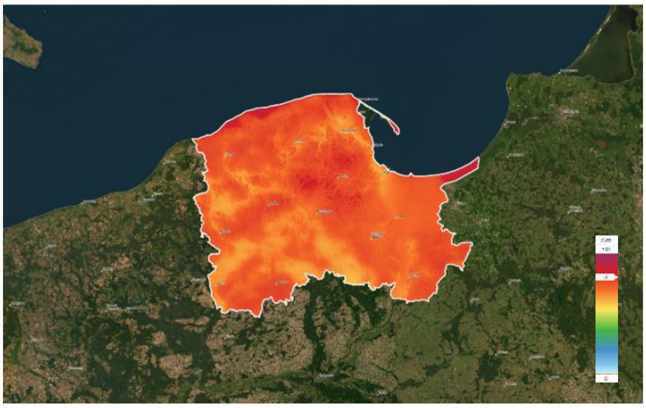

Figure 11: Long term mean wind speed (m/s) at 100m in Pomorskie (Poland) [123,124]

The Pomeranian Voivodeship, located on the Baltic Sea, stands out as one of Poland's most promising regions for wind energy development. The average annual wind speed in this region ranges from 4 to 4.5 m/s, although slight variations can occur based on specific locations and yearly weather conditions. This makes it a particularly attractive area for wind energy investments [157].

Several factors contribute to the region’ s suitability for wind turbine installations. The high wind speeds, favorable geographical conditions, well-developed infrastructure, and strong government and EU support create an ideal environment for wind energy projects. As a result, the Pomeranian Voivodeship is considered one of the best locations in Poland for wind turbine deployment [158]. Wind patterns in the region exhibit clear seasonal variations, mainly due to its proximity to the Baltic Sea. Stronger winds, particularly from the west and northwest, dominate in autumn and winter, often intensifying due to passing atmospheric lows. In contrast, summer months experience weaker winds, although local breezes can develop due to temperature differences between land and sea. These seasonal patterns significantly influence wind energy production and must be considered in project planning [159].

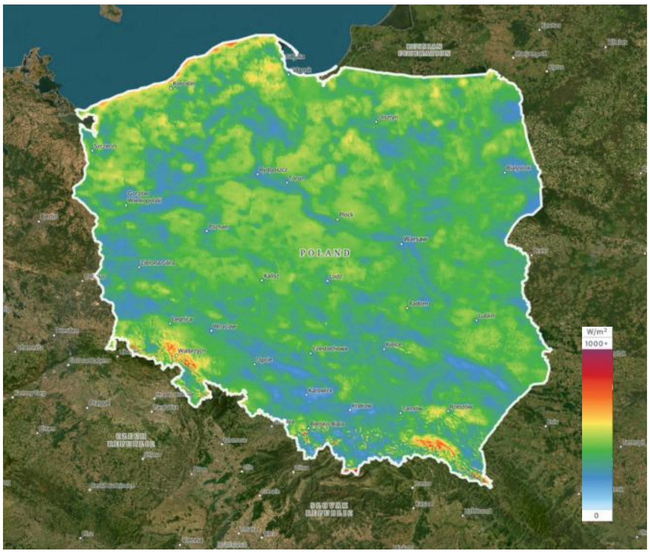

Figure 12: Mean wind power density at 100m (W/m²) in Poland [123,124]

The Pomeranian Voivodeship hosts a significant number of wind turbines, particularly in the 50-1000 kW range. Across Poland, approximately 1,400 wind turbines of various capacities are in operation, and the Pomeranian region ranks among the leaders in such installations. Many of these projects are supported by renewable energy auctions and EU funding, with installations concentrated in coastal and rural areas where spatial conditions are favorable [160].
For larger-scale projects, wind turbines exceeding 1000 kW are primarily found in Polands major wind energy hubs, such as West Pomerania and Greater Poland. While the Pomeranian Voivodeship plays a key role in wind energy generation, it does not match the scale of these leading regions. Large wind farms are often developed by major energy companies such as PGE, Tauron, and Energa, which control a significant share of Poland' s wind power capacity [161].

As of the end of 2023, Poland had an installed wind energy capacity of approximately 9.4 GW (9400 MW). Northern regions, including Pomerania, contribute significantly to this total due to their advantageous wind conditions. The region's largest wind farm, the Potęgowo Wind Farm, has a capacity of 219 MW, further highlighting its importance in the national energy mix. In total, wind farms in the Pomeranian Voivodeship generate around 1326 MW of electricity [162].

Land availability is a crucial factor for wind energy expansion. Recent legislative changes have increased the potential area for wind turbine installations in Poland. A key amendment reducing the required distance between wind turbines and residential buildings from 700 meters to 500 meters has expanded the available land for wind energy by 74%. This change increases the total area available for wind turbine installations in Poland from 10,500 km² to 18,300 km², or from 3.4% to 5.8% of the country' s total land area. Such policy adjustments create new opportunities for wind energy projects in the Pomeranian region [163].

Zoning regulations play an essential role in wind farm development. Poland' s Wind

Farm Investment Act, which establishes rules for wind farm locations, requires turbines to be a certain distance from residential areas, nature conservation sites, and high-voltage power grids. Onshore wind turbines are considered permanent structures requiring building permits and occupancy approval, while smaller rooftop turbines below 3 meters in height can be installed without additional formalities. These regulations guide wind energy development and ensure compliance with environmental and safety standards [164].

In the Pomeranian Voivodeship, horizontal-axis wind turbines are the preferred technology, as they perform best in open landscapes with stable wind speeds [165]. The height of wind turbines in Poland varies based on their location and design, with onshore models typically ranging from 100 to 150 meters, and some reaching up to 200 meters. Taller turbines benefit from stronger, more consistent winds at higher altitudes, leading to improved efficiency. Medium-sized wind turbines (2-3 MW) can generate approximately 5-6 GWh annually under optimal conditions, while offshore models can reach capacities of up to 15 MW per unit. Poland is gradually integrating smart technologies into wind energy systems, enhancing real-time monitoring and efficiency optimization [166].

Connecting wind power projects to the grid is a key consideration for investors. The process involves obtaining connection conditions, followed by signing a connection agreement with grid operators. These steps ensure that wind farms can be effectively integrated into the national electricity grid. Infrastructure requirements also vary depending on the turbine's location. For example, wind turbines installed on buildings may not require additional permits if their height does not exceed 3 meters. In cases where turbines are installed on private land and have a capacity of up to 40 kW, no building permits or inclusion in local development plans are necessary, simplifying the approval process [167,168].

Despite the advantages of wind energy in the Pomeranian Voivodeship, several technical challenges remain. The "Distance Act," which requires wind turbines to be situated at least ten times their height away from residential buildings, limits available land for new installations. Additionally, integrating wind farms into the grid requires balancing energy production with demand, managing voltage stability, and addressing fluctuations in wind conditions. Effective maintenance is also crucial, as turbines must withstand extreme weather conditions, requiring advanced monitoring and repair systems. Furthermore, public resistance to wind farms, due to concerns about aesthetics, noise, and environmental impact, continues to be a challenge [169].

To address these issues, several strategies can be implemented. Streamlining administrative processes and expediting project approvals can help overcome bureaucratic delays. The integration of energy storage solutions, such as battery systems and hydrogen technologies, can improve grid stability by managing energy fluctuations. Advanced data analytics and real-time monitoring systems

Pomerania Voivodeship has **786 MW** of wind capacity, with a theoretical potential of **12 GW** (48–56 TWh) and a technical offshore potential reaching 7.4 GW by 2030 [131]

can optimize maintenance and detect potential failures before they occur. Additionally, continued research into new turbine materials and blade designs will enhance efficiency and resilience against changing weather conditions. Strengthening partnerships between wind energy companies, technology providers, and local industries can also support the successful execution of wind projects. By adopting these measures, the Pomeranian Voivodeship can continue to expand its wind energy sector and contribute to Poland' s renewable energy transition [170].

The budget required for wind power installation varies depending on capacity and efficiency. A small 3 kW home wind turbine typically costs around EUR 4,762, with each additional kilowatt adding approximately EUR 2,381. This means a 5 kW installation would cost at least EUR 9,500, while a 10 kW system ranges from EUR 19,000 to 24,000. Some manufacturers offer 2 kW wind turbines with battery storage for domestic hot water and heating systems at around EUR 2,300. Higher-efficiency models exist, such as a 5 kW wind farm capable of producing 7,300 kWh annually at 5 m/s wind speeds, priced at nearly EUR 20,238. A 3 kW version of similar efficiency costs around EUR 12,700 [171].

For large-scale wind projects, feasibility studies—including technical, financial, and environmental analyses—range between PLN 200,000 and 500,000. Administrative procedures, such as obtaining permits and conducting environmental impact assessments, can cost between PLN 500,000 and 1,000,000. The purchase of wind turbines averages between PLN 1.3 and 2.2 million per megawatt (MW) of installed capacity. Transport and assembly add another PLN 300,000 to 600,000 per MW, while infrastructure expenses—such as foundations (PLN 300,000-600,000 per MW), access roads (PLN 100,000-200,000 per MW), and grid connection (PLN 300,000-500,000 per MW)—further contribute to the total investment. Additionally, annual operational costs include maintenance (PLN 50,000-100,000 per MW) and monitoring (PLN 50,000-150,000). Financial costs such as loan interest and insurance range from 5-10% of total investment [171].

Various financial incentives exist to support wind energy investments. On a regional level, the Pomeranian Fund for Environmental Protection and Water Management (PFOSiGW) provides subsidies or preferential loans for farmers investing in renewable energy, including small wind farms. Similar initiatives exist under national programs, such as the National Fund for Environmental Protection and Water Management (NFOŚiGW), which runs the "Energy Plus" program, offering grants and loans for agricultural renewable energy projects [172]. At the European level, Poland utilizes EU Structural and Cohesion Funds to support renewable energy investments, particularly under the Operational Program Infrastructure and Environment (POIiŚ), which funds projects aimed at reducing CO_2 emissions and expanding renewable energy on farms. Local governments and municipalities also run specialized support programs. Additionally, commercial banks offer tailored loan products for wind energy investments [172].

The expected ROI for wind power projects in Poland depends on factors such as location, scale, and regulatory conditions. Favorable conditions exist due to stable revenues from energy sales contracts, particularly Power Purchase Agreements (PPAs) and renewable energy auctions. The rising cost of CO_2 emission allowances and ongoing decarbonization efforts further enhance profitability [173]. Wind power maintenance costs typically range between 24 and 60 EUR per kW. Routine servicing is essential to ensure optimal turbine performance and longevity [174].

Smart technology integration in Poland’ s wind energy sector is still developing but progressing steadily. Emerging technologies include advanced monitoring systems, artificial intelligence for wind forecasting, and real-time turbine optimization. These innovations aim to enhance energy efficiency and stabilize the power grid. Some wind farms are beginning to implement smart management systems that align production with demand more effectively.
Pilot projects are increasingly adopting these advanced solutions, which could lead to improved efficiency and stronger integration with other renewable sources, such as photovoltaics. In offshore wind energy, Power-to-X technology is gaining traction, enabling the conversion of excess wind power into green hydrogen for energy storage and alternative applications [175].

Wind turbines in the Pomeranian Voivodeship are generally expected to have a service life of approximately 25 to 30 years. For example, the Pomerania Wind Power Portfolio is anticipated to operate for three decades, providing renewable energy to the region. While the overall structure, including foundations and towers, is designed to last for this period, certain components such as blades, gearboxes, and generators may require maintenance or replacement earlier due to operational wear and tear [176,177].

The management of waste from decommissioned wind turbines in the region remains an evolving topic, with limited specific data available. Approximately 80-90% of wind turbine components, including metals and electrical systems, can be recycled using established processes. However, turbine blades, made from composite materials, present a significant recycling challenge. Traditional disposal methods include landfilling and incineration, but these are becoming less favorable due to environmental concerns and regulatory changes. Emerging solutions include advanced recycling techniques, such as shredding and repurposing fiberglass and resin into industrial products like cement and plastics. Additionally, repurposing initiatives have found creative uses for old turbine blades, incorporating them into structures like playgrounds, bike shelters, and footbridges [178,179].

Environmental considerations play a crucial role in wind power projects. An environmental impact assessment (EIA) is required for projects likely to have significant environmental effects. According to the Regulation of the Council of Ministers of September 10, 2019, wind energy installations must undergo an EIA if their total nominal power reaches or exceeds 100 MW, or if they are located in Poland' s maritime areas. Additional considerations include the potential impact on protected areas, requiring assessments of how projects might affect factors such as noise levels, air quality, groundwater, and wildlife. EIAs help determine ways to mitigate adverse effects, including noise reduction measures, protective strategies for birds and bats, and minimizing the stroboscopic effect caused by turbine blades [180,181].

Land use impact is another key factor in wind turbine installations. Poland's 2016 "Distance Act" mandates that wind turbines be located at least ten times their height from residential buildings and protected areas, significantly influencing land availability for wind projects. This regulation aims to reduce noise and visual disturbances for local communities. Moreover, environmental protection measures must consider the region's diverse ecosystems, including coastal zones and protected areas, to avoid disruptions to wildlife habitats. Other land use concerns include potential effects on soil quality, water resources, and the compatibility of wind turbines with agricultural activities. Effective community engagement and transparent communication with residents help address concerns related to aesthetics and possible health effects [182–184].

Several mitigation measures are planned to reduce the environmental impact of wind projects. The Pomerania Wind Farm, located in the communes of Dzierzgoń and Stary, has conducted environmental assessments to minimize harm to bird and bat populations. The Bięcino Wind Farm has implemented measures to reduce noise impact and intends to take corrective actions if breaches occur. Other mitigation efforts include placing turbines away from key wildlife habitats and migration routes, implementing ultrasonic deterrents for bats, painting one turbine blade a different color to enhance visibility for birds, and using modern turbine designs that incorporate noise-reducing features. Adjusting operational parameters, such as rotational speed during low wind conditions, and establishing buffer zones between turbines and residential areas are additional measures being explored [185,186].

The Pomeranian region offers various training programs for personnel involved in wind power projects. The Gdańsk University of Technology provides courses in environmental engineering and renewable energy, while the Pomeranian Center for Ecological Education conducts workshops on wind energy. The Global Wind Organization (GWO) offers specialized safety and technical training, such as Basic Safety Training (BST) and Basic Technical Training (BTT), through accredited regional centers. Additionally, the Polish Wind Energy Association has launched the "Get into the Wind Turbines and Work at the Highest Level!" program, investing over 1 million PLN in training technicians and installers for onshore wind projects. The Maritime School Complex in Darłowo has also introduced a free training program for wind turbine work certifications [187,188].

Awareness of local, regional, and national regulations is essential for wind power project implementation. Poland's "10H" rule initially required wind turbines to be at least ten times their height away from residential areas, but recent legislative efforts propose reducing this distance to 500 meters to expand land availability for wind projects. Key national regulations include the Act on Renewable Energy Sources (RES), which establishes support mechanisms such as feed-in tariffs and auction systems. The Energy Law Act outlines market regulations and grid connection conditions, while the Construction Law Act defines building permit requirements. Environmental regulations mandate environmental impact assessments and permits, while local spatial development plans determine the zoning regulations for wind farms [189,190].

Despite regulatory frameworks, several barriers hinder wind power development. Lengthy administrative processes for obtaining permits, varying local regulations, and complex environmental impact assessments contribute to delays. The presence of protected areas, such as Natura 2000 sites, imposes further restrictions. Spatial planning conflicts arising from the "10H" rule limit suitable land for wind farms, exacerbating land availability issues. Grid connection regulations also pose challenges, with high connection fees and technical restrictions discouraging investment. Furthermore, policy volatility, sudden regulatory changes, and unpredictable financial support mechanisms affect investor confidence. Local opposition and legal challenges further complicate the process, as community concerns about landscape impact, noise, and property values often lead to extended public consultations and legal disputes [191,192].

Biogas Potential

GERMANY

In Germany, biomass potential is derived from a variety of sources, including crop residues, manure, and dedicated energy crops. The assessment of these feedstocks plays a crucial role in optimizing biogas production efficiency while maintaining sustainable agricultural practices. The primary biomass energy crops cultivated in Germany include wheat, rye, barley (both winter and spring), oats, triticale, maize (including corn cob mix), plants for green harvesting, silage maize, sugar beet, potatoes, and winter oilseed rape. The most critical factor in energy maize cultivation is dry matter yield, with an optimal dry matter content of 30–35%. Yield variations

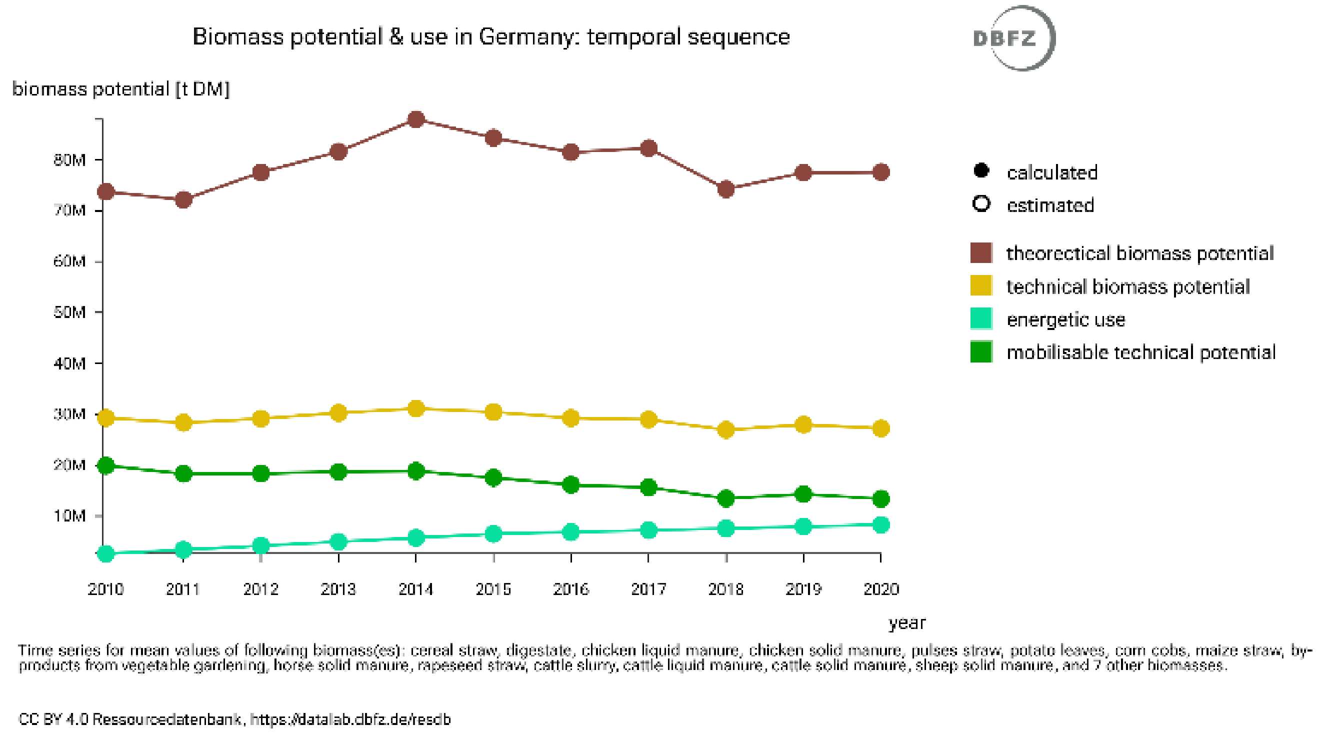

Figure 13: Biogas Potential and use in Germany derived from DBFZ[194]

depend on whether the crop is grown as a main or secondary crop [193].

The annual quantity of crop residues generated is significant. Germany's animal husbandry sector produces approximately 200 million tons of liquid and solid manure annually, of which around 15% is utilized in biogas plants. Additionally, the processing of approximately 21 million tons per year of energy crops generates around 16 million tons of fermentation residue. This results in a total potential of 45 million tons annually, with an average of approximately 10,000 tons produced per biogas plant [195].

The main sources of manure for biogas production come from cattle, pigs, and poultry. According to operator surveys from 2015–2017, cattle manure constitutes the largest share (65%), followed by pig manure (15%), and structured manure, including dry chicken manure (4%). Solid cattle manure accounts for 9%, while solid pig manure contributes a negligible amount [196].

In 2022, biomass produced **50.2 TWh** of electricity in Germany — **21%** of renewable power and 9% of total consumption [155]

Annually, Germany produces vast quantities of manure suitable for biogas production.

Cattle manure contributes an estimated 115.2 million tons of fresh mass (FM), while solid cattle manure ranges from 16.7 to 28.5 million tons. Pig manure production averages 30.7 million tons, with solid pig manure contributing an additional 1.4 million tons. In total, manure-based biomass potential stands at approximately 169.9 million tons per year [196].

It is estimated that between 2.5 and 4 million hectares of agricultural land will be available for renewable raw material production, with around 1.2 million hectares currently dedicated to biogas production. However, regulatory constraints have influenced feedstock availability. The 2012 amendment to the Renewable Energy Sources Act introduced limits on maize cultivation for biogas, encouraging the use of residual materials such as liquid manure, dung, and alternative energy crops [197].

The collection of feedstocks relies on well-developed storage infrastructure. Substrate storage facilities are designed to accommodate expected material volumes, balancing storage needs with contractual purchase agreements and delivery frequency. For hygienically sensitive substrates, strict separation is required, and odor control measures such as enclosed storage and biofilters are implemented [198].
Transport distances play a crucial role in economic feasibility. The average transport distance for feedstocks is approximately 13 kilometers, though distances of up to 50 kilometers are achieved for large biogas plant parks. For silage maize as a primary substrate, transport distances of up to 30 kilometers are still considered viable. In the case of manure, it is generally recommended that livestock locations be within 5–10 kilometers of the biogas plant [199].

Germany has a well-established biogas sector, with a total of 11,492 biogas plants operating at various capacities. The distribution of installed electrical system output is as follows [198]:

- <75 kWel – 1,341 plants
- 76–150 kWel – 667 plants
- 151–300 kWel – 2,657 plants
- 301–500 kWel – 2,234 plants
- 501–1,000 kWel – 3,137 plants
- 1,000 kWel – 1,456 plants

Biogas plants play a significant role in energy generation, producing electricity and methane for various applications. The continued operation of these facilities relies on supportive policy frameworks and the efficient utilization of agricultural residues, ensuring long-term sustainability in the sector [200].

Support levels, particularly feed-in tariffs for renewable electricity, have been reduced for new biogas production in Germany due to amendments to the EEG in 2014 and 2016. As a result, the number of new biogas plants has steadily declined. The introduction of the auction model in 2017, along with further reductions in the maximum tariffs available, has led to a significant drop in the commissioning of new plants. Most of Germanys biogas facilities were established between 2003 and 2012 under 20-year energy supply contracts. Consequently, a large share of these plants will see their guaranteed tariff periods expire between 2023 and 2032. Without economically viable follow-up frameworks, this is expected to trigger a substantial decrease in the number of operating biogas plants [201].

Digestate, a byproduct of biogas production, is managed primarily through its use as fertilizer in agriculture, forestry, and horticulture. The German Biowaste Ordinance (BioAbfV) regulates the application of compost and digestate, setting strict limits on heavy metal content to ensure safe recycling. Additionally, research is being conducted to optimize the pelleting process for digestate and landscape conservation hay, aiming to create high-quality solid fuels for decentralized heat generation, thereby increasing sustainability and reducing competition between material and energy use of biomass [202].

Several technical challenges exist in biogas plant operations, particularly concerning the contamination of substrates. Large amounts of impurities, such as sand, stones, and glass, enter the system, leading to sediment buildup in tanks, increased wear on pumps and pipes, decreased fermentation efficiency, and higher energy consumption for mixing. These issues result in lower gas yields and higher operational costs. One potential solution to this problem is the implementation of mobile slurry mixers, which prevent silting in slurry tanks and maintain optimal processing conditions [203,204].

The financial considerations for biogas plant installation vary based on system size and configuration. Investment costs range from approximately 2,000 to 3,000 €/kW for large-scale systems and between 5,000 to 7,000 €/kW for smaller plants. Factors such as engine type and the reuse of existing infrastructure influence the overall costs. Financial incentives exist under the EEG 2021 framework, which provides different remuneration options based on plant capacity, including fixed tariffs, market premiums, and auction-based pricing. Additional compliance requirements, such as flexibility mandates and substrate limitations, also impact financial planning. The transition from feed-in tariffs (FiT) to an auction model under EEG 2017 has further influenced market dynamics [205,206].

Operation and maintenance of biogas plants depend on system size and type. Maintenance cycles for Combined Heat and Power (CHP) units typically range from 500 to 2,000 operating hours for large systems, while smaller installations may require servicing every 10,000 hours. Stirling engines, due to their lower wear, require less frequent maintenance, typically after 5,000 to 8,000 operating hours. The costs and intervals of maintenance are highly dependent on engine type and operational conditions [207].

Smart technology integration in biogas plants is advancing to enhance efficiency and grid compatibility. Technologies such as power-to-heat conversion, micro gas grids, and latent heat storage are being explored to optimize energy use and ensure stable integration with variable renewable energy sources like wind power [208].

Education and training for biogas plant personnel are available through initiatives such as the Biogas Training Association, founded in 2014. The Fachverband Biogas e.V. has been working to standardize training programs across Germany for over a decade, offering both in-person and online training formats. Awareness of regional and national regulations is also facilitated through research institutions such as FNR and DBFZ, as well as industry associations like Fachverband Biogas [209].

Animal production has long been vital to Lithuanian agriculture but underwent major changes during the shift to a market economy and later EU accession. [210]

LITHUANIA

In Lithuania, biomass feedstock is sourced from various crop residues, including deforestation residues, firewood, wood waste, and straw [211]. A critical factor for energy producers is the timing between cutting, shredding, and burning biomass, as prolonged storage of shredded willow wood reduces its calorific value. Consequently, winter is the optimal season for cutting and transporting biomass to boiler houses due to increased biofuel demand. During other seasons, biomass from different plant sources can be used and stored in either whole or shredded form [211].

The annual quantity of crop residues varies by region. In 2020, Klaipėda recorded approximately 4.0 thousand m³ of firewood sales and 1.5 thousand m³ of logging waste. In Telšiai, the total annual average volume of firewood over four years reached 36.89 thousand m³, while Tauragė generated about 51,723 tons of straw per year [20,25,26].

Manure from livestock, including cattle, pigs, and poultry, contributes significantly to biomass potential. Waste composition includes 30.6% forest cutting residues, 22.5% gardening waste, 22.5% mixed municipal waste, and smaller fractions of metal, mineral-origin waste, wood waste, packaging waste, and other sources [212]. The estimated biogas potential from livestock and poultry manure in Klaipėda District Municipality is 1,191,935 m³. In Telšiai, manure production stands at 31,744 tons from cattle, 2,936 tons from pigs, and 456 tons from poultry. Tauragė' s sewage sludge biogas potential is around 106.4 tons of oil equivalent (tne) per year, while the technical energy potential from municipal waste is estimated at 552.4 tne per year [20,25,26].

The potential for growing energy crops for biogas production depends on land availability and climatic conditions. Klaipėda district has 4,157 hectares of unused and degraded land, with tree and shrub plantations capable of yielding approximately 12,471 tons of oil equivalent (toe) from energy crops. Tauragė' s biomass fuel resource potential over the last five years has averaged 30.41 thousand cubic meters of wood, with private forests contributing an estimated 9.52 toe (110.7 MWh) per year. In Telšiai, private forest logging in 2022 generated around 76,732.76 m³ of wood, with 59.18% (45,407.95 m³) categorized as firewood, contributing to a wood fuel resource potential of 12,572.49 toe. However, the amount of wood waste fluctuates annually due to variations in weather conditions [20,25,26].

Feedstock availability is subject to seasonal variations. During the growing season (May–October), willows undergo different developmental stages, including shoot growth, leaf expansion, and autumn leaf coloration. The most active growth period is between June and July, influenced by temperature and precipitation levels. Productivity largely depends on the number of shoots per bush [8]. Several constraints impact feedstock availability, including seasonal fluctuations, unpredictable climate conditions, limited land, labor shortages, technological barriers, pest infestations, fragmented land ownership, and environmental concerns [211].

The existing infrastructure for biomass collection and transportation presents challenges. Industrial enterprises generate excess low-potential heat, requiring additional heat pumps for utilization. The feasibility of heat storage tanks depends on the establishment of biofuel cogeneration plants, which could stabilize operations and provide thermal energy reserves during the heating season. However, such projects currently lack economic incentives for investors and offer limited social benefits [213].

Regarding biogas installations, Klaipėda’ s biogas plant operated by "AB Klaipėdos vanduo" has a total capacity of 654 kW, producing approximately 2,616 m³ of biogas per day. There are no known installations exceeding 2,500 m³/day, and data on the total biogas plant capacity and electricity/methane generation in farms remains unavailable [214]. The preferred biogas system design includes SCADA, DAPDS, and Simone technologies for monitoring and process optimization [215].

In 2020, Lithuania’ s biogas production from sludge treatment plants, through digestion processes, generated a substantial volume of biogas, totaling 2,063,000 m³. The energy building produced 3,701.4 MWh of electricity, with 88.5% of the electricity required for wastewater treatment and sludge management at the company's WWTP coming from its own power-generating units. A portion of this electricity (1,369 MWh) was produced using natural gas in the dryer’ s generator, alongside 205.4 MWh from landfill biogas. Additionally, 1.86 thousand tonnes of dried sludge were processed and transferred to waste managers. Biogas utilization in Lithuania predominantly includes electricity generation, heat production, combined heat and power (CHP), and occasionally injection into the natural gas grid [214].

The feasibility of connecting biogas plants to the national grid is governed by specific transmission rules. These are outlined in Lithuania’ s Electricity Transmission Grid Access Rules, which provide guidelines for electricity producers on how to connect and supply electricity from renewable sources like biogas to the grid [216].

Digestate, a by-product of biogas production, is generally used as fertilizer or composted to enrich soil quality. It is also employed in land reclamation to enhance agricultural sustainability. Lithuania makes significant use of manure both as a natural fertilizer and for biogas production. Manure management practices are influenced by factors like animal type, age, feed quality, and farm infrastructure. Optimizing the use of digestate involves considering the characteristics of farm operations, such as the type of animals and the production methods, to improve its efficiency and sustainability [20].

However, technical challenges arise in implementing biogas plants, especially in small farms with minimal manure production. The feasibility of building biogas plants in these settings is low. A solution suggested is the use of a mix of animal manure and energy crops such as maize, which has a high biogas yield (202 m³ per ton). Growing maize on unused land for biogas production could circumvent competition with food crops and make biogas plants viable even on small farms [20].

The expected budget for biogas plant installation in Lithuania typically ranges from €2,500 to €4,000 per kW of installed capacity. This cost includes all aspects such as design, equipment, construction, and commissioning. These figures are in line with global trends where the installation costs for biogas plants can vary depending on the size and technology used in the plant [217].

Financial incentives and subsidies are available for biogas plant projects under the "Promotion of Small-Scale Biofuel Cogeneration" measure, which is part of the Future Economy DNA Plan. This initiative supports projects related to energy efficiency and renewable energy production. It is aligned with the European Union's 2014–2020 Funds Investment Action Program, specifically under Priority 4: "Promotion of Energy Efficiency and Renewable Energy Production and Use." The program covers new and additional investments from July 1, 2020, to December 31, 2021 [218].

In terms of return on investment (ROI), biogas plant projects in Lithuania aim to increase renewable energy production. A high-efficiency cogeneration plant is expected to add 8.05 MW of renewable energy capacity, leading to a reduction of approximately 6,981 tons of CO_2 equivalent annually. The electrical capacity of the newly installed cogeneration plant is projected to be 1.25 MW [219].

The operation and maintenance (O&M) of biogas plants vary depending on the size of the plant. For small plants (up to 100 kW), the annual maintenance costs typically range from €10,000 to €20,000. For medium-sized plants (100 kW - 500 kW), maintenance costs increase to between €20,000 and €50,000 per year. Large plants (above 500 kW) can incur maintenance costs of €50,000 to over €100,000 annually. These costs reflect the need for regular monitoring, servicing of biogas production systems, and ensuring optimal functioning of equipment to maintain energy efficiency [220].

In terms of technological integration, some biogas plants are incorporating advanced smart technologies to improve their efficiency. For example, a modern biogas plant in the Baltic region has integrated a biodegradable material preparation line capable of processing animal by-products and waste. This facility is equipped with a sophisticated three-stage air purification system, which ensures that air generated in the facility is cleaned of any unpleasant odors. Such innovations in the integration of smart technologies aim to enhance both the sustainability and operational efficiency of biogas plants [221].

Regarding education and training, Lithuania has made strides in providing specialized training for personnel involved in biogas plant operations. Klaipėda University (KU) has opened the first methodological STEAM center in the country, featuring multiple laboratories dedicated to renewable energy, including IT-Robotics, Chemistry-Biology, Physics-Engineering, and Marine fields. This center also includes a creative FabLab workshop space, further supporting the development of renewable energy expertise through hands-on training [222]. Additionally, private education providers offer various training programs tailored to the renewable energy sector.

Public awareness of local, regional, and national regulations concerning biogas plants is relatively high. Survey results show that most people are familiar with renewable energy sources (RES) and are aware of the potential energy savings and efficiency improvements they can bring. However, there is an acknowledgment that while sufficient information on RES is available, further dissemination of knowledge would be beneficial for broader adoption and deeper understanding [20].

	MAIZE FOR SILAGE AND GREEN BIOMASS			PERENNIAL GRASSES			FODDER BEET			TOTAL
COUNTY	**Area, ha**	**Yield, t**	**Biogas quantity, mill.m3**	**Area, ha**	**Yield, t**	**Biogas quantity, mill.m3**	**Area, ha**	**Yield, t**	**Biogas quantity, mill.m3**	**Energy value, GWh**
ALYTUS	294	9252	1,7	526	1256	0,8	230	7130	0,6	80,7
KAUNAS	1924	60493	11,2	2189	5232	3,2	259	8042	0,7	90,7
KLAIPEDA	217	6824	1,3	2735	6536	4	201	6239	0,5	35
MARIJAMPOLĖ	1655	52034	9,6	1544	3690	2,3	318	9845	0,9	76,6
PANEVĖŽYS	1465	46068	8,5	1848	4417	2,7	435	13493	1,2	74,6
ŠIAULIŲ	2542	79932	14,8	2351	5618	3,5	455	14094	1,2	116,9
TAURAGE	338	10632	2	2881	6886	4,2	168	5223	0,5	40
TELSIAI	145	4554	0,8	2272	5429	3,3	215	6674	0,6	28,6
UTENA	269	8442	1,6	817	1952	1,2	438	13576	1,2	23,7
VILNIUS	150	4729	0,9	839	2005	1,2	280	8684	0,8	17,2
TOTAL	8999	282960	52,4	18002	43021	26,4	2999	93000	8,2	522

Table 1: Biogas and energy production potential in various counties of Lithuania [221]

COUNTY	LIVESTOCK Quantity of manure, thous.t	LIVESTOCK Energy value, GWh	PIGS Quantity of manure, thous.t	PIGS Energy value, GWh	POULTRY Quantity of manure, thous.t	POULTRY Energy value, GWh	TOTAL Biogas quantity, mill. m3	TOTAL Energy value, GWh
ALYTUS	80,5	12,1	39,7	4,8	6,2	2,6	3,2	19,5
KAUNAS	206,4	31	157,7	18,9	52,5	22,1	12	71,9
KLAIPĖDA	153	22,9	71,3	8,6	10,8	4,5	6	36
MARIJAMPOLĖ	178	26,7	119,2	14,3	5,1	2,1	7,2	43,1
PANEVĖŽYS	197,5	29,6	133,5	16	18	7,6	8,9	53,2
ŠIAULIAI	229,3	34,4	199,4	23,9	8,4	3,5	10,3	61,8
TAURAGĖ	161,7	24,2	62	7,4	3,2	1,3	5,5	33
TELŠIAI	129,7	19,5	38,6	4,6	14,8	6,2	5,1	30,3
UTENA	113,3	17	58,3	7	6,2	2,6	4,4	26,6
VILNIUS	113,3	17	80,8	9,7	72,3	30,4	9,5	57,1
TOTAL	1562,7	234,4	960,5	115,2	197,5	82,9	72,1	432,5

Table 2: Biogas and energy production potential in various counties of Lithuania [221]

POLAND

The Pomeranian Voivodeship has significant potential for biogas production, with various feedstocks available, including crop residues, manure, and dedicated energy crops. Crop residues contribute substantially to biogas feedstock, with cereals leaving 3 to 5 tons of dry matter per hectare, rapeseed producing 10 to 12 tons, and corn yielding between 5 to 15 tons depending on usage. Straw from cereals, rapeseed, and legumes is also a valuable by-product [223]. Annually, the total quantity of agricultural residues is estimated at 48.8 million tons of dry matter, with cereals contributing 39 million tons, rapeseed 1.8 million, oil crops 6.9 million, pulses 0.9 million, and industrial crops 0.2 million [224].

Manure from livestock farming is another critical biogas feedstock. The main sources include dairy cows, other cows, pigs, sheep, and poultry [225]. In Poland, the total annual manure production is approximately 107.08 million tons, with dairy cows producing 42.23 million tons, other cows 31.70 million, other pigs 15.58 million, sows 3.26 million, sheep 0.12 million, and poultry 14.19 million tons [226].

The region also has considerable potential for growing dedicated energy crops for biogas production, such as maize, grass silage, clover, alfalfa, and sorghum. Maize cultivated over 100,000 hectares, with yields of 40-50 tons per hectare and a biogas output of 225 m³ per ton, could generate approximately 900 million m³ of biogas annually. Grass silage, covering the same area and yielding 10-12 tons of dry matter per hectare with 125 m³ of biogas per ton, could contribute an additional 125 million m³ of biogas per year. Sorghum, with yields of 30-40 tons per hectare and biogas production of 200-300 m³ per ton, is also a promising feedstock [227].

> The Pomerania Voivodeship can produce **3.4 million m³** of biogas annually, yielding around 0.13 PJ of energy—equivalent to 13 GWh of electricity and 0.07 PJ of heat per year. [131]

However, there are seasonal variations in feedstock availability. Most energy crops are harvested between late summer and autumn, requiring efficient storage solutions to ensure a continuous supply throughout the year. Silage is the primary method used for preserving feedstock post-harvest. Crop rotation and diversification strategies help maintain feedstock availability, while weather conditions, such as droughts and heavy rainfall, can affect yields. Manure production is consistent year-round but varies in collection methods depending on the season—livestock kept indoors during winter results in more concentrated manure collection, whereas grazing in warmer months reduces immediate availability [228].

Several challenges affect feedstock

availability, including unpredictable weather conditions, fluctuating market prices, competition for land between energy crops and food production, high input costs (e.g., seeds, fertilizers, fuel), long transport distances between sources and biogas plants, and compliance with environmental regulations regarding greenhouse gas emissions and waste management [229].

The region has a well-developed infrastructure for feedstock collection and transportation. This includes farm-level storage facilities, modern harvesting equipment, a robust transportation network, and specialized logistics services. Collaboration between biogas plants and local farmers, along with technological advancements, ensures an efficient supply chain [230,231]. To minimize costs and emissions, biogas plants are generally located within 10-20 km of major feedstock sources. Bulk transportation of feedstock occurs during harvest seasons, with storage facilities ensuring year-round supply [231].

Currently, there are 10 biogas plants in the region with capacities between 100-2500 m^3/day and two larger installations exceeding 2500 m^3/day [232]. At the end of 2021, Poland' s registered agricultural biogas plants produced over 513 million m^3 of biogas annually, with 342.913 million m^3 undergoing methane fermentation. Of this, 335.335 million m^3 was used for electricity generation [233]. The total installed electrical capacity of these plants is 125.323 MWe [234].
Regarding system design, the Continuous Stirred Tank Reactor (CSTR) is the preferred choice due to its efficiency, versatility, and suitability for various agricultural feedstocks. While other systems like Upflow Anaerobic Sludge Blanket (UASB) and Plug-Flow reactors have specific applications, the agricultural focus and feedstock diversity in the region make CSTR the most practical and widely adopted solution [235]. Biogas system design varies depending on application, feedstock availability, and economic considerations. In Poland, the Continuous Stirred-Tank Reactor (CSTR) is the preferred choice for agricultural biogas plants due to its ability to handle a variety of feedstocks and its stable operation. For wastewater and industrial biogas applications, the Upflow Anaerobic Sludge Blanket (UASB) reactor is commonly used. The selection of a specific biogas system depends on multiple factors, including plant size, regulatory framework, and overall economic feasibility [193].

Biogas utilization in Poland primarily focuses on energy production. The majority of biogas is used for electricity generation (31.805 GWh, accounting for 61%), followed by heat and cooling applications (19.192 GWh, or 37%). A smaller portion (1.263 GWh, or 2.4%) is used as fuel, amounting to a total energy production of 52.260 GWh [236].

Connecting a biogas plant to the natural gas grid involves several technical and regulatory requirements. Unlike residential connections, a biogas plant requires a dedicated transfer station to comply with legal and contractual standards, including quality measurement, quantity tracking, gas compression, and odorization. The grid operator charges a grid access fee based on actual expenses incurred for the connection. However, the grid user has the option to install the connection line independently, which can waive the access fee. The legal framework for biogas grid connections was revised in April 2008 under Section 33 GasNZV to standardize the process, as practical experience was previously limited [237,238].

In 2022, methane fermentation of agricultural feedstocks generated over 374 million m³ of biogas, with more than 359 million m³ allocated for electricity production. The remainder was either sold, burned in a candle, or used in gas boilers [239,240]. Connecting biogas plants to the grid presents regulatory challenges, as obtaining grid connection conditions takes more than 150 days. The process includes securing an environmental decision, development conditions, and submitting a connection application with necessary technical documentation. Despite an official timeline of 150 days, practical implementation can extend to approximately six months [241].

Digestate from biogas plants is widely utilized as fertilizer due to its nutrient-rich composition. Local farmers apply it directly to agricultural fields to improve soil fertility. Increasing interest in advanced digestate processing methods, such as drying, pelletization, and nutrient recovery, aims to enhance sustainability and efficiency [242].

Optimization strategies include regular nutrient analysis to balance digestate composition for various crops, obtaining organic fertilizer certification for better marketability, and implementing mechanical separation processes to divide digestate into solid and liquid fractions. These fractions can serve different agricultural purposes—solid fractions for soil improvement and liquid fractions as nutrient-rich fertilizers. Additionally, improving digestate storage facilities can prevent nutrient loss, mitigate odors, and reduce contamination risks. Market development for digestate-based products, such as compost or pelletized fertilizers, along with farmer education on best practices, further strengthens its utilization [243].

Biogas plant implementation faces several technical challenges, including securing a consistent feedstock supply, seasonal feedstock variations, and contamination from non-organic waste. Maintaining stable anaerobic digestion conditions is crucial, as fluctuations in temperature, pH, and microbial balance can reduce methane yields. Additionally, raw biogas requires purification to remove hydrogen sulfide, ammonia, and siloxanes, which can otherwise damage equipment. Grid integration is another concern, as biogas plants must ensure synchronization with voltage and frequency levels while avoiding costly infrastructure upgrades. Digestate storage and application must also comply with environmental regulations to minimize odor emissions and nutrient runoff. The overall high initial investment and ongoing maintenance costs demand a skilled workforce with expertise in anaerobic digestion technology and plant operation [244].

To mitigate these challenges, several solutions are being explored. Pre-treatment technologies, such as shredding, grinding, and thermal hydrolysis, improve feedstock quality. Advanced monitoring systems optimize anaerobic digestion conditions in real time, ensuring stable biogas production. Multi-stage digestion systems and enhanced biogas purification technologies, like activated carbon filters and biological scrubbers, help remove impurities. Grid challenges can be addressed by promoting smaller, decentralized biogas plants near demand centers, reducing reliance on extensive grid infrastructure. Additionally, combined heat and power (CHP) systems can improve energy efficiency by utilizing both electricity and heat from biogas [230].

Biogas plant installation costs vary by scale. Small-scale plants (up to 100 kW) range from €4,000 to €6,000 per kW, while medium-scale plants (100 kW to 500 kW) cost between €3,000 and €4,500 per kW. Large-scale plants (500 kW to 2 MW) benefit from economies of scale, with installation costs between €2,500 and €4,000 per kW. For example, a 300 kW biogas plant with an estimated cost of €3,500 per kW would require a total investment of approximately €1.05 million [245].

Several financial incentives support biogas projects. The European Union provides funding through the Common Agricultural Policy (CAP), including the Rural Development Program (RDP) and the European Agricultural Fund for Rural Development (EAFRD), aimed at improving agricultural sustainability. Horizon Europe offers grants for research and innovation in biogas technology, while the Cohesion Fund and European Regional Development Fund (ERDF) support infrastructure projects promoting environmental sustainability. National programs such as Poland’ s National Fund for Environmental Protection and Water Management (NFOŚiGW) provide grants and loans for construction and technological upgrades. Additional incentives include feed-in tariffs (FiTs), feed-in premiums (FiPs), and auction systems for long-term energy contracts [246,247].

Regional support programs also play a role. The Regional Operational Programs (ROPs) offer funding for renewable energy projects, while local governments provide municipal incentives, including tax breaks and land grants. Other financial mechanisms include green bonds, attracting investment from sustainability-focused investors, and carbon credits through emissions trading schemes. The EU Modernization Fund has allocated €357 million for municipal biogas cogeneration development, offering grants covering up to 50% of eligible costs or loans covering 100%. The European Funds for Infrastructure, Climate, and Environment (FEnIKS) program dedicates over €93 million to biogas industry growth, while the “Energy for the Countryside” program injects €750 million into rural energy infrastructure. The Ecological Credit under FENG 2021-27 supports renewable energy investments, including biogas [248,249].

The development of biogas plant projects in Poland presents promising investment opportunities, with the expected Return on

Investment (ROI) varying based on plant size, technology, feedstock availability, and market conditions. Studies indicate that the Return on Equity (ROE) for biogas plants is competitive within the energy sector, making them attractive for investors. Additionally, the Polish government has implemented financial support mechanisms, such as feed-in tariffs (FIT) and feed-in premiums (FIP), to enhance the economic viability of biogas projects. ROI expectations for biogas plants typically range from an Internal Rate of Return (IRR) of 10-20% and a payback period of 5-10 years, with projects demonstrating positive Net Present Value (NPV) over their lifespan. For example, a medium-scale biogas plant (300 kW) with a capital investment of €1,050,000 can generate annual revenue from electricity, heat, and digestate sales, along with government subsidies, leading to an estimated payback period of 5.25 years and an annual ROI of approximately 19% [248,250].

Operational and maintenance costs for biogas plants depend on their scale. Small-scale plants (50-150 kW) require daily monitoring of feedstock input, temperature, and gas production, with annual maintenance costs ranging from €5,000 to €10,000. Medium-scale plants (150-500 kW) demand continuous monitoring of feedstock quality and regular system inspections, leading to annual maintenance expenses between €10,000 and €20,000. Large-scale plants (500 kW and above) involve 24/7 monitoring and scheduled component replacements, with maintenance costs reaching €20,000 to €50,000 or more, depending on plant complexity [251,252].

The integration of smart technologies in biogas plants is improving efficiency and sustainability. Advanced systems like SMARTFERM® optimize organic waste processing, while AI and IoT solutions enable real-time monitoring and predictive maintenance. In Poland's Pomeranian Voivodeship, the adoption of these technologies is progressing, with companies such as Enricom Biogas Sp. z o.o. contributing to the region' s biogas infrastructure [253,254].

Training and education for biogas plant personnel are available in the Pomeranian Voivodeship. Organizations like the Gdańsk Water Foundation offer courses on digestate management, providing crucial knowledge for industry professionals. Companies such as Enricom Biogas Sp. z o.o. also play a role in biogas sector development, and further training opportunities can be found through regional renewable energy associations and agricultural institutions. [255]
Regulatory awareness is essential for biogas project implementation in Poland. The country has faced challenges due to unstable legal frameworks, but recent legislative updates, including new regulations introduced in September 2023, aim to support agricultural biogas development. Regionally, the Pomeranian Voivodeship promotes biogas projects through initiatives like the "Pomeranian Biogas Model," which seeks to optimize production processes and regulatory compliance. [256]

Despite progress, regulatory barriers still exist.

Investors and developers face complex permitting processes, environmental restrictions related to Natura 2000 areas, and difficulties in integrating biogas plants into the national energy grid due to low tariffs. Location-related issues, such as social resistance and zoning limitations, further hinder project development. Additionally, financial constraints and the classification of digestate as waste impose operational challenges. Addressing these barriers requires stable legal frameworks, simplified permitting processes, and greater financial support for small and medium-sized projects. [257–259]

VOIVODESHIP	MANURE (MWEL)	WASTE (MWEL)	ENERGY CROPS (MWEL)	TOTAL (MWEL)
ŁÓDZKIE	33	5	146	184
MAZOWIECKIE	43	7	289	339
MAŁOPOLSKIE	3	1	94	98
ŚLĄSKIE	10	4	63	77
LUBELSKIE	16	11	203	230
PODKARPACKIE	5	2	94	101
ŚWIĘTOKRZYSKIE	7	1	80	88
PODLASKIE	16	3	155	174
WIELKOPOLSKIE	95	20	223	338
ZACHODNIOPOMORSKIE	58	9	91	158
LUBUSKIE	11	0	49	60
DOLNOŚLĄSKIE	15	3	111	129
OPOLSKIE	12	0	56	68
KUJAWSKO-POMORSKIE	31	0	141	172
WARMIŃSKO-MAZURSKIE	23	18	128	169
POMORSKIE	23	3	94	120
TOTAL	**400**	**87**	**2017**	**2504**

Table 3. Estimated electrical power for voivodeship for different kinds of biogas plant substrate. Based on [210]

Country-Specific Outlook

GERMANY

Germany remains one of the most ambitious and influential players in Europe' s energy transition. Underpinned by the Climate Law, the country has set a binding target to reach net zero emissions by 2045, with a key milestone of achieving 80% renewable electricity by 2030 and 100% by 2035 [260]. The complete phase-out of nuclear power in 2023 and the planned coal exit underscore Germany' s commitment to reshaping its energy system around renewable sources.

Germany' s Energiewende is supported by robust legislative and regulatory reforms aimed at accelerating the deployment of wind, solar, and green hydrogen. By 2030, the country aims to reach 100–110 GW of onshore wind, 30 GW of offshore wind, and 200 GW of solar PV capacity [261]. Additionally, 10 GW of hydrogen production capacity is planned, supporting sector coupling and hard-to-abate sectors.

Significant progress has already been made. Renewable energy' s share in gross electricity consumption has risen from around 6% in 2000 to nearly 50% by the early 2020s, with wind and solar playing leading roles [260]. The rapid cost decline of solar PV and the expansion of onshore wind have established them as the core drivers of Germany' s clean power mix. Meanwhile, biomass and hydropower continue to contribute as stable, dispatchable sources within the overall energy portfolio.

Germany is also targeting a reduction of 500 TWh in energy consumption by 2030, equivalent to about 20% of 2022 consumption, under its Energy Efficiency Act [261]. This dual focus on clean energy expansion and demand-side efficiency makes Germany a model for a balanced and sustainable energy transition.

Looking forward, Germany will continue to play a central role in shaping the renewable energy trajectory of the SBS region. Its leadership in offshore wind, green hydrogen, and grid modernization offers valuable lessons and opportunities for regional cooperation. Challenges remain, particularly in terms of transmission infrastructure, permitting speed, and public acceptance. However, Germany' s deep industrial base, policy experience, and innovation ecosystem position it to overcome these barriers.

In the context of a joint SBS green policy strategy, Germany can act as a technological and policy anchor driving harmonization of energy targets, supporting cross-border infrastructure development, and facilitating knowledge transfer across the region.

In conclusion, Germany' s commitment to climate neutrality and renewable leadership sets a high benchmark within the SBS region. Through continued innovation, investment, and regional collaboration, the country will remain a key enabler of the region’ s transition to a secure, sustainable, and integrated clean energy future.

LITHUANIA

Lithuania has undergone a substantial transformation in its energy landscape over the past decade. Once heavily dependent on electricity imports, historically sourcing up to 70% of its electricity from abroad, primarily from Russia, the country has shifted decisively toward a more secure and diversified energy model [262]. This transition has been driven by a strong national consensus on the strategic importance of energy independence and sustainability.

The evolution of Lithuania’ s energy policy has seen a clear pivot from nuclear energy to renewables. This shift was accompanied by progressive policy instruments, such as the launch of technology-neutral renewable energy auctions.

Renewable energy development in Lithuania continues to make steady progress. Wind energy has been the frontrunner, but solar power remains underdeveloped, pointing to significant untapped potential. Efforts to expand the role of prosumers, households and small producers generating their own electricity, have been supported by government incentives and favorable grid policies, which are expected to further stimulate decentralized renewable deployment.

Looking forward, Lithuania is well-positioned to deepen its energy transition. Strengthening support mechanisms, simplifying regulatory procedures, and improving grid infrastructure will be key to unlocking additional renewable capacity. Enhanced regional cooperation within the SBS framework can further accelerate progress, particularly in areas such as cross-border energy trade, joint grid planning, and technology exchange.

In the context of a joint green policy strategy, Lithuania can play a leading role by contributing its experience in policy innovation, auction design, and public engagement on energy issues. The country’ s path demonstrates that targeted policy reforms and a strong strategic narrative around energy independence can yield rapid progress in renewable deployment.

In conclusion, Lithuania’ s trajectory signals a resilient and increasingly self-sufficient energy future. With continued commitment, the country can solidify its role as a regional model for clean energy transition, while contributing meaningfully to shared sustainability and security goals in the SBS region.

POLAND

Poland faces one of the most challenging energy transitions in the South Baltic Sea region due to its continued reliance on coal, which still accounts for approximately 70% of its electricity generation [263]. Decarbonization is a national priority, and nuclear energy is expected to play a central role in this shift. The government plans to commission six large nuclear reactors between 2033 and 2043, aiming to supply around 20% of domestic electricity demand. In parallel, energy-intensive industrial companies are exploring the deployment of small modular reactors (SMRs), with the first units expected by 2029 through a partnership between NuScale Power and KGHM Polska Miedź SA. Wind energy, though still underutilized (9% of generation as of 2021), is poised for significant growth, with over 50 operational onshore wind farms and targets for 5.9 GW of offshore wind capacity by 2030, expanding to 11 GW by 2040 [263].

Poland has one of the largest agricultural production potentials in Europe, yet the development of biogas and biomethane remains limited [264]. As of the end of 2023, the country had just 218 agricultural and 148 municipal biogas plants, mostly small-scale facilities with capacities of up to 1 MW—far below its potential [265]. Poland had just over 350 small-scale biogas plants by the end of 2023, but new legislative changes are set to accelerate growth [265]. The 2023 amendment to the Energy Act established a legal basis for biomethane grid integration, backed by major infrastructure operators [266]. Simplified permitting, revised biomass waste rules, and planning reforms now offer a clearer and more attractive investment environment, particularly for agricultural stakeholders. While still emerging, the biomass sector is finally positioned to play a greater role in Poland' s broader energy transition.

Joint Green Policy Strategy

The South Baltic Sea (SBS) region is undergoing a pivotal transformation in response to the dual crises of energy security and climate change. Triggered by the war in Ukraine and the resulting energy crisis, marked by an over 80% reduction in Russian gas deliveries to Europe in 2022. This shift underscores the urgent need for an accelerated transition to a resilient, low-carbon economy [267]. In this context, both the SBS and the broader Baltic Sea Region (BSR) serve as important laboratories for energy transformation, offering practical insights and strategic recommendations that extend beyond their borders [268].

Central to this transformation is the recognition that the energy transition must not only be technologically feasible but also socially acceptable and inclusive. Policymakers must therefore carefully design legal and financial instruments that empower citizens, simplify complex procedures, and account for regional and cultural specificities. Regulatory frameworks must be streamlined to accelerate the deployment of renewable energy technologies. Currently, inconsistent legal procedures and bureaucratic delays across the SBS region hinder the implementation of both centralized and decentralized energy projects. A unified approach to permitting, through digital systems, harmonized environmental standards, and regional fast-track schemes for projects like offshore wind farms and hydrogen corridors, is essential to reducing development risks and responding swiftly to geopolitical pressures.

Equally important is the need to build social acceptability rather than merely social acceptance [267]. Whereas the former implies active engagement and support, the latter often reflects passive compliance. Policies must be tailored to reflect local circumstances and ensure transparency, fairness, and accessibility. Social justice must be a guiding principle, with incentives and opportunities made available across all social strata to avoid reinforcing existing inequalities. This includes protecting the rights of prosumers and energy communities under EU law and ensuring these rights are clearly transposed into national legal frameworks.

Financial incentives must also be designed to foster long-term trust. They should be simple, predictable, and transparent, avoiding perceptions of top-down imposition or attempts to "buy" public consent. A successful policy mix must simultaneously ensure cost-effectiveness in the energy system and support for local consumption models that respond to actual market signals. Additionally, Member States should refrain from imposing fees on self-consumed electricity below certain thresholds to enable more widespread participation.

Beyond regulatory measures, a robust education and training agenda is essential. The energy transition is as much a societal shift as it is a technological one. Countries in the SBS region must collaborate on developing cross-border training programs, university curricula, and certification schemes in fields like offshore wind, solar photovoltaics, battery storage, and green hydrogen. Public outreach campaigns are also necessary to counter disinformation and inform communities, especially those affected by energy price volatility, about the benefits of the energy transition and the roles they can play in it.

Innovation must also be prioritized. The SBS region should invest in pilot and demonstration projects that allow for experimentation, data collection, and de-risking of emerging technologies. Such projects, especially in offshore wind, energy storage, and integrated heating systems, can be jointly developed to foster regional solidarity and maximize learning. These initiatives must include resilience planning to address risks posed by cyber threats, sabotage, and other hybrid warfare tactics.

A successful transition also depends on multilateral cooperation. The SBS region must strengthen collaborative platforms involving governments, municipalities, energy companies, civil society, and research institutions. Coordinated planning can prevent redundancy, such as overlapping LNG terminal developments, and ensure strategic alignment with EU-level goals. Shared databases, regional investment mechanisms, and a united voice in Brussels can enhance the region's ability to attract funding and shape favorable regulatory conditions.

Crucially, these efforts must be grounded in local engagement. Social acceptability can only be achieved through clear communication of the opportunities, costs, and support structures related to the energy transition. Citizens must have access to actionable information and be able to make informed decisions. Participation mechanisms must be designed with cultural and socio-political contexts in mind, taking into account demographic differences and legal landscapes.

Furthermore, energy transition strategies should remain open to alternative pathways and technological breakthroughs. Geographic, economic, and political circumstances vary, and flexibility in national plans is necessary to accommodate innovation and unexpected developments. Policymakers must support both top-down strategies and bottom-up grassroots activities, including energy cooperatives, municipal initiatives, and community-owned renewable energy projects.

In conclusion, the SBS region is uniquely positioned to lead by example. If its countries adopt a joint strategy focused on simplified regulations, inclusive education, pilot project investment, and multilateral coordination, they can turn the current crisis into a transformative opportunity. The region' s diversity, across geography, political systems, and civic cultures, makes it an ideal testing ground for adaptive energy governance. Balancing centralized policies with decentralized engagement, short-term urgency with long-term vision, and technical progress with social cohesion, the SBS region can become a beacon of sustainable and democratic energy transformation. The lessons drawn from this context, particularly around activating citizen participation, fostering social acceptability, and enhancing regional solidarity, are vital not only for local resilience but also for Europe' s broader transition to climate neutrality.

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