

BARRIERS AND MANAGEMENT PRACTICES FOR SMALL HYDROPOWER: THE CASE OF THE KUJAWSKO-POMORSKIE REGION IN POLAND'S GREEN ENERGY TRANSITION

Patrycja Sieg✉

ORCID: 0000-0002-0581-5933

Bydgoszcz University of Science and Technology, Faculty of Management, Department of Management of Organizational Innovation
Prof. S. Kaliski Avenue, 7, 85-796 Bydgoszcz, Poland

ABSTRACT

Motives: Decarbonizing energy systems in line with EU and national targets places a premium on diverse renewable resources. In Poland, achieving goals such as a 32% renewable energy share by 2030 requires not only large-scale wind and solar projects but also decentralized solutions. Small hydropower plants. These attributes motivate an examination of SHPs' role in the regional (Kujawsko-Pomorskie) green transition and how to better leverage their potential.

Aim: The aim of this study is to assess the contribution of small hydropower plants to the energy transition in the Kuyavian-Pomeranian Voivodeship (north-central Poland). Using qualitative methods – including semi-structured interviews with small hydropower plant managers and analysis of regional energy data – we identify the number, capacity, and distribution of small hydropower plants, characterize the key barriers faced by small hydropower plant managers (administrative, environmental, and economic), and catalog effective management practices.

Results: Small hydropower capacity in the region totals 23.24 MW. The study shows that SHP development is constrained by administrative and environmental barriers. Respondents emphasize the need for simplified procedures, institutional support, and good practices such as remote monitoring, automation, and ecological measures.

Keywords: sustainable energy management, environmental management, sustainable development, local energy systems, environmental regulations, renewable energy

INTRODUCTION

Small hydropower (SHP) is increasingly recognised as a vital component of the global transition towards renewable energy sources. Its growing relevance stems from the potential to harness local reservoirs and streams that are typically inaccessible to large-scale energy systems. Due to their operational flexibility

and relatively low environmental impact, SHP installations offer an effective means of enhancing energy security and supporting decentralised energy production. Importantly, the role of SHP extends beyond electricity generation. In rural and peripheral regions, SHP systems can stimulate local economic activity, generate employment, improve infrastructure, and promote energy self-sufficiency. Moreover, when

✉ patrycja.sieg@pbs.edu.pl

properly designed, SHP projects can contribute to aquatic ecosystem protection, enhance water retention, and integrate with blue-green infrastructure (Laks et al., 2023).

Recent systematic reviews of renewable energy research in Poland show that the field is dominated by studies on solar PV (photovoltaic) and wind energy, whereas hydropower, particularly small hydropower, remains under-investigated and underfunded, highlighting the need for further analyses of its barriers, management practices and development potential (Aydın et al., 2025). Recent data show that by the end of 2024, Poland had more than 1.54 million renewable energy micro-installations (mostly PV) with a combined capacity of approximately 12.75 GW. Small-scale installations in the 50 kW – 1 MW range have also expanded rapidly, exceeding 5 GW of capacity across nearly 7,000 units (Energy Regulatory Office, 2025). In this small-scale renewable energy segment (50 kW – 1 MW), wind power generated around 0.6 TWh (12% of total output), while hydropower and biogas each contributed approximately 6% (Green Forum, 2025). Despite this presence, these technologies still play a secondary role due to technological and economic limitations, and PV continues to dominate production. This comparison highlights the under-utilisation of SHP and underscores the importance of investigating its development barriers and management practices. Such research can enrich the academic and policy debate on this energy source and provide evidence to support informed decision-making by policymakers and investors.

In this context, the management of SHP systems plays a critical role. It involves not only technical and operational dimensions but also encompasses economic, social, and environmental considerations. In light of growing climate challenges and the imperative to meet sustainable development goals, effective management frameworks are essential to securing the long-term viability and benefits of SHP operations. This entails optimizing energy production, minimizing ecological impacts on aquatic ecosystems, fostering social acceptance, and aligning with broader local and regional development strategies (Bryła et al., 2025).

Although SHP has been widely examined in terms of technical performance and ecological impacts, its socio-economic and institutional dimensions remain under-researched in Poland. Most studies focus on technological efficiency, hydrological modelling or environmental assessment, while issues such as administrative procedures, investment barriers and management practices receive comparatively little attention (Dzikuć et al., 2025; Kałuża et al., 2022). Moreover, few works combine quantitative data with qualitative approaches, such as interviews with plant operators, which can provide unique insights into decision-making and operational challenges (Adeyeye et al., 2021; Li et al., 2025).

This study addresses these gaps by offering a unique analysis of SHPP barriers and management practices in the Kuyavian-Pomeranian Voivodeship – a region where nearly all technically feasible sites have already been exploited (Chomać-Pierzecka et al., 2022; Godyń & Dubel, 2021). Drawing on both statistical data and qualitative evidence from a questionnaire survey and interviews with SHP plants managers – with the questionnaire design informed by the literature review – the study provides novel empirical insights into the challenges and opportunities facing the sector.

The findings have broader significance, offering guidance for other regions of Central and Eastern Europe with similar geographical, institutional and environmental conditions. In doing so, the study contributes to the debate on sustainable development by demonstrating how SHP can support the green energy transition under geographical and regulatory constraints and provides evidence to inform policymaking aligned with EU climate objectives.

The Kuyavian-Pomeranian Voivodeship is a particularly relevant case for examining the development of SHP in Poland. It is a lowland region with limited natural hydropower potential, reflecting the geographical constraints typical of much of the country (Marshal's Office of the Kuyavian-Pomeranian Voivodeship, 2023). Nevertheless, it hosts a relatively high number of SHP installations, including both small privately owned plants and larger facilities inte-

grated into the national energy system. Nearly all technically feasible hydropower sites in the region have already been exploited, making it an excellent setting for examining administrative, environmental and economic barriers rather than resource-related limitations. At the same time, planned large-scale projects such as the Siarzewo hydropower plant highlight the ongoing tensions between renewable energy expansion and environmental protection (GEM, 2025). This combination of factors makes the Kuyavian-Pomeranian Voivodeship a strategic case for understanding how small hydropower plants (SHPPs) can support the green energy transition under restrictive conditions and for drawing lessons applicable to other regions of Poland and Central Europe.

The primary objective of this study is to examine the development of small hydropower (SHP) in the Kuyavian-Pomeranian Voivodeship, with a particular focus on the administrative, environmental, economic and technical factors that influence the sector's performance. The research explores how SHP owners and operators manage their facilities, the strategies they employ to enhance efficiency, and the ways in which these practices interact with broader institutional and regulatory barriers. Furthermore, the study seeks to assess the contribution of SHP to the regional and national energy transition, including its relevance to the European Union's climate and energy objectives, and to formulate practical recommendations for policymakers and investors aimed at fostering the sector's sustainable development.

In pursuing these aims, the analysis considers which barriers most significantly constrain SHP expansion in the region, how managerial practices affect operational outcomes, and whether the experiences observed in the Kuyavian-Pomeranian Voivodeship can provide transferable lessons for other Central and Eastern European regions characterised by similar environmental and institutional conditions. The study suggests that administrative and economic factors may have a stronger impact on SHP development than technical or resource-related issues. It also assumes that sound management practices – such as

systematic monitoring, preventive maintenance and modernisation planning – improve plant efficiency and resilience, yet remain insufficient to overcome systemic external constraints. Finally, it suggests that small hydropower has the potential to contribute to the low-carbon transformation of the energy system, particularly through its ability to stabilise local grids and integrate with water management, provided that coherent regulatory reforms and stable financial support mechanisms are in place.

The remainder of the paper is structured as follows: Section 2 presents a literature review on hydropower, and SHPPs management. Section 3 outlines the methodology of the study, and the results are presented in Section 4. Section 5 discusses the results with the extant literature and section 6 concludes.

LITERATURE REVIEW

In the context of ongoing climate change and growing energy security concerns, energy transition has become a central priority on international policy agendas. Renewable energy sources are assuming an increasingly important role in the global energy mix, responding to mounting challenges such as environmental degradation, climate change and the finite nature of fossil fuel resources. At the international level, there is a clear intensification of efforts aimed at reducing greenhouse gas emissions through the gradual transformation of energy systems towards more sustainable and low-carbon generation technologies (International Renewable Energy Agency [IRENA], 2023). Renewable energy plays a crucial role not only in protecting the natural environment but also in stimulating local economic growth, creating new employment opportunities and improving the overall quality of life for communities. According to Eurostat data, in 2024 renewable sources accounted for 47.3% of electricity generation in the European Union (Eurostat, 2025).

Globally and within the European Union (EU), ambitious climate and energy targets have been established – including a 55% reduction in CO₂ emissions by 2030 and the achievement of climate

neutrality by the mid-21st century. For Poland, whose energy sector remains heavily reliant on coal, meeting these objectives represents a significant challenge and necessitates the accelerated development of renewable energy sources (RES) to replace fossil fuels (Adamczewski & Wójcik, 2023). As an EU member, Poland is pursuing ambitious goals in its energy transition, with a particular focus on expanding the share of renewables in the national energy mix. According to key strategic frameworks – most notably Poland's Energy Policy until 2040 (PEP 2040) – one core priority is the systematic increase of RES in both total energy consumption and electricity generation. The strategic objective of “utilising hydropower potential” is explicitly highlighted in the country's Strategy for Responsible Development as a key element of this transition (Ministry of Climate and Environment, 2023).

Recent statistics underscore the rapid growth of renewables in Poland's energy sector. In June 2025, the total installed capacity of RES in Poland exceeded 35.7 GW. Photovoltaics (solar PV) clearly dominated, accounting for approximately 23 GW (over 64% of total RES capacity), followed by wind power at around 10.4 GW ($\approx 29\%$). By contrast, hydropower installations contributed less than 1 GW, and biomass installations were also under 1 GW; biogas plants accounted for just 320 MW. Other RES technologies, including hybrid systems, played only a marginal role. These figures highlight the strong dominance of solar PV and the steady – though slower – growth of wind power, alongside the relatively minor role of hydropower in the Polish RES mix (Rynekelektryczny, 2025). Focusing on the regional scale, the Kuyavian-Pomeranian Voivodeship (the study area) had a total installed RES capacity of 1,886.2 MW as of December 2024 (based on the Energy Regulatory Office data). In this region, wind power is the dominant source ($\approx 52.4\%$ of regional RES capacity), followed by photovoltaics ($\sim 25\%$) and biomass ($\sim 10\%$). Hydropower represents about 210 MW ($\approx 12\%$) of the region's RES capacity, including 23.24 MW from SHPPs. This indicates that the region contains a notable concentration of small hydropower

installations, making it a relevant case for examining development barriers and management practices. The remaining share of the region's renewables comes from biogas and a single waste-to-energy plant in Bydgoszcz. Such data illustrate Poland's current renewable energy profile – heavily skewed towards solar and wind – and underscore the underutilisation of hydropower, especially small-scale projects, in the national mix.

As set out in the Energy Policy of Poland until 2040 (Ministry of Climate and Environment, 2021) and in line with the European Union's Renewable Energy Directive – RED II (Directive 2023/2413 of the European Parliament and of the Council, 2023), Poland aims to achieve a minimum 32% share of renewables in electricity generation by 2030. In the longer term, the country has declared its ambition to attain climate neutrality by 2050, in alignment with the objectives of the European Green Deal. Reaching these targets will require a substantial acceleration of investments in zero-emission energy technologies, the development of supporting infrastructure, and effective reduction of greenhouse gas emissions across all sectors of the economy (Ministry of Climate and Environment, 2023). In this context, small hydropower has attracted attention as one potential contributor to Poland's renewable expansion, even though at present it contributes only a small fraction of electricity generation.

One defining characteristic of hydropower in Poland is the country's modest yet strategically significant potential, shaped by predominantly lowland topography. Poland's total theoretical hydropower potential is estimated at approximately 13.7 TWh per year, but only about 12% of this potential is currently being exploited (Kasperek & Głowski, 2019). This underutilisation suggests considerable room for development, particularly through small and run-of-river projects that can harness local watercourses. Notably, Poland ranks 24th in Europe in terms of hydropower potential, yet is utilizing only around 20% of its available *technical* capacity (Piasecki, 2024). The emphasis on harnessing lowland river systems underscores the need to modernise hydrotechnical

infrastructure in a way that increases energy capture while preserving ecological integrity. Piasecki (2024) provides a comprehensive assessment of Poland's hydropower sector under EU climate policy, documenting the small national potential, the long-term contribution of hydropower remaining below 2% of electricity generation, and a sector dominated by pumped-storage facilities. The study argues that future development should prioritise energy storage solutions (including repurposing decommissioned lignite mines as reservoirs) and refurbishment of existing plants rather than construction of large new impoundments. Under these constraints, small hydropower in Poland is likely to remain a niche contributor unless paired with targeted modernisation and system-level solutions – most notably pumped-storage integration – to deliver grid services (e.g. frequency regulation, peak shaving) rather than bulk energy generation (Piasecki, 2024). In other words, while Poland's geography does not favour large hydropower expansion, there is still untapped potential for small-scale projects and upgrades that could bolster energy security and provide valuable ancillary services to the grid.

The economic viability of small hydropower projects is a key determinant of their development in Poland. As noted by Godyń and Dubel (2021), support schemes and market incentives have evolved in recent years to encourage investment in this segment of renewable energy. Advancing small hydropower is not solely a technical endeavour; it also hinges on regulatory frameworks, financial incentives, and environmental considerations. It is therefore imperative that policymakers establish a supportive regulatory environment that lowers administrative barriers and provides financial mechanisms (such as feed-in tariffs or auctions) favourable to SHPPs, while also prioritising sustainability in the planning and operation of these installations (Godyń & Dubel, 2021). Indeed, Poland's experience reflects a broader global trend: decentralised renewable energy sources like small hydropower are increasingly recognised for their role in the clean energy transition. Recent research highlights that more than 82,000 small hydropower plants are currently in operation worldwide – a clear

indication of growing interest in distributed hydropower generation (Cavallaro & Schumann, 2025; Couto et al., 2023). This global deployment underscores the need for coherent, systemic management practices that can make such installations both efficient and environmentally sound. As small hydropower capacity grows, operators and policymakers must ensure that operational efficiency is balanced with the protection of aquatic ecosystems, and that community and stakeholder interests are appropriately addressed. An integrated management approach – one that brings together technical, economic, environmental, and institutional dimensions – can yield tangible benefits in terms of both sustainability and performance of SHPPs.

A primary challenge in managing hydropower installations, especially small ones, lies in the conflict of interests among various water users, including agriculture, energy production, and ecosystem conservation. Implementing sustainable management models is essential to fulfil energy demands while safeguarding the integrity of aquatic ecosystems (Kuriqi et al., 2020). A well-planned and integrated approach can optimise energy production from SHPPs and simultaneously maintain or even enhance the condition of the natural environment in and around these installations. One especially critical aspect of sustainable hydropower operation is the maintenance of ecological flows in rivers. Preserving adequate environmental (minimum) flows downstream of a hydropower plant is the cornerstone of riverine ecosystem health, as it helps reconcile energy generation objectives with biodiversity conservation needs. This is particularly important for safeguarding fish habitats, which are highly sensitive to alterations in flow regimes and water levels caused by water abstraction or dam operations. Therefore, careful design and management of ecological flows are indispensable for the sustainable development of SHP facilities (Di Cicco et al., 2025; Qu et al., 2022). Furthermore, the siting and design of SHPPs should be approached systematically, with thorough consideration of local biodiversity and a goal of minimizing fragmentation of aquatic habitats. By selecting sites that avoid

ecologically sensitive areas or by incorporating fish passages and other mitigation measures, developers can reduce negative impacts. Only through such an approach can energy production objectives be effectively reconciled with nature conservation requirements (Lange et al., 2018).

In practice, sustainable management of small hydropower requires flexible and innovative solutions that address local water resource variability, ecological constraints, and community needs. Effective information flow and data analysis can greatly enhance both operational and strategic decision-making, resulting in long-term social, economic, and environmental benefits. Contemporary approaches to SHP operations increasingly incorporate advanced hydraulic and hydrological modelling, which allows for simulation of flow dynamics and water regimes within rivers and associated infrastructure. As highlighted by Halych et al. (2025), the application of such models in hydropower plant planning and operation helps mitigate adverse effects on aquatic ecosystems while ensuring efficient energy production that can adapt to evolving hydrological conditions (Halych et al., 2025). Software tools like HEC-RAS (Deshays et al., 2021), SWAT+ (Xie & Zhu, 2022), and MIKE 11 (Kumar et al., 2024) enable practitioners to accurately model water level fluctuations, flow velocities, and the impacts of weir or turbine operations on a river system. These tools support the optimisation of turbine performance and help ensure compliance with minimum ecological flow requirements under various scenarios. By combining hydraulic simulations with ecological flow analyses, managers can evaluate trade-offs between maximizing energy output and preserving aquatic habitats. This capability has become increasingly important in the context of climate variability and growing energy demand. In sum, such modelling serves as a foundational tool for the sustainable management of SHPPs, helping to harmonise energy production objectives with the conservation of water resources and biodiversity (Halych et al., 2025).

Another critical aspect of SHP management is risk mitigation in the face of hydrological variability and extreme events. Even small run-of-river plants are not

immune to the impacts of climate change and weather extremes. Oksuz and Brlek (2023) underscore the necessity of implementing risk mitigation strategies for SHP projects, including measures such as enhanced rainfall monitoring, real-time flow forecasting, and thorough natural hazard assessments (e.g. for floods or droughts). Without such strategies, the operational stability and reliability of small installations can be severely compromised during abnormal conditions (Oksuz & Brlek, 2023). The application of advanced algorithms and predictive models further facilitates the optimisation of energy production while ensuring efficient use of available water resources (Huang et al., 2023). In fact, a changing climate is expected to increase flow variability in many regions, and recent studies indicate that even SHP systems – previously considered relatively resilient compared to large dams – can experience reduced performance due to shifting flow patterns. This presents a challenge for energy planners, as unstable river regimes could significantly impact SHP output in the absence of adaptive measures (Couto et al., 2023). Developing and incorporating adaptation strategies is therefore imperative to sustain the long-term efficiency and reliability of these systems amid changing hydrological conditions (Soares et al., 2023). On a positive note, small run-of-river hydropower plants (which operate without large reservoirs) are often seen as valuable components of climate adaptation strategies in the energy sector. Because they do not rely on extensive water storage, they are less susceptible to some risks posed by variable water availability and can be designed to have a lower environmental footprint. Properly designed and managed SHP facilities can thus offer a reliable source of renewable energy that bolsters the resilience of local energy systems in the face of climate uncertainty (Skoulikaris, 2021).

Technological advancements are playing a pivotal role in enhancing the efficiency and sustainability of SHPPs. The selection and design of turbines, for example, are particularly critical for smaller-scale installations that often operate under low-head conditions and variable flow rates. Research and development in this area have led to innovations such

as improved cross-flow (Banki) turbines tailored for low-head applications, which significantly boost energy conversion efficiency in micro-hydropower plants (Nishi et al., 2015). Additionally, there is a trend towards employing variable-speed turbines and generators in small hydropower systems. Unlike traditional fixed-speed configurations, variable-speed setups can dynamically adjust their rotational speed to match the available water flow, thus maintaining higher efficiency over a range of operating conditions. This technology ensures more consistent power generation despite fluctuations in river discharge and has been shown to yield better performance for streams with highly variable flows (Borkowski & Majdak, 2020; Polák, 2019). By continuously optimizing turbine speed, variable-speed systems can improve both the economic viability and the grid compatibility of SHPPs, especially during periods of reduced water availability or changing demand. Beyond traditional hydropower technologies, innovative approaches are emerging to integrate energy generation into existing water management infrastructure. One such approach involves the use of pumps-as-turbines (PATs) within water distribution and irrigation networks. In essence, conventional centrifugal pumps can be operated in reverse as small-scale turbines to recover energy from excess water pressure in pipelines. This method has been demonstrated as a cost-effective solution in scenarios where installing a conventional turbine would be economically or technically impractical due to intermittent or low flows (Alberizzi et al., 2019; De Marchis et al., 2014; Fecarotta & McNabola, 2017). Similarly, micro-hydropower installations have been successfully integrated into urban water systems – for example, by installing turbines at the outlets of wastewater treatment plants. This takes advantage of the continuous flow of treated effluent to generate electricity without the need for new dams or significant environmental impact (Che Munaaim et al., 2018). Adopting these technological innovations and operational strategies can maximise energy production from SHP installations and help sustain their economic feasibility under varying hydrological conditions (Erazo et al., 2022; Polák, 2019).

Selecting optimal locations and configurations for new SHPPs is also essential for maximizing benefits while minimizing environmental and social impacts. One effective development strategy is to utilise existing hydraulic infrastructure to add hydropower capacity. For instance, installing small generating units at the bases of existing dams (often called “dam-toe” hydropower) allows additional electricity to be produced with minimal additional ecological disruption, since it leverages an already-modified section of the river (Singal et al., 2010). In planning new projects, the literature recommends systematic site selection methodologies that evaluate potential locations based on comprehensive criteria – including resource availability (river flow and head), technical feasibility, environmental sensitivity, economic viability, and social acceptance. Such an integrated planning framework helps identify sites where SHPPs can be incorporated harmoniously into existing water systems and communities, thereby reducing the likelihood of negative impacts or public opposition (Jeftenić et al., 2021). These considerations tie into the broader concept of the water-energy nexus, which refers to the close interdependence between water management and energy production. Energy systems often require substantial water resources (for cooling, storage, and generation), while water supply and treatment infrastructure in turn depend on reliable energy access. Understanding this bidirectional relationship is increasingly important given global challenges such as diminishing water availability, rising energy demand, and climate change pressures (Basheer & Ahmed Elagib, 2019). In response, integrated approaches like the water-energy-food (WEF) nexus, or its expanded form including ecosystems (WEFE), have gained prominence in policy and research. Implementing WEF/WEFE nexus frameworks allows planners to identify synergies and manage trade-offs among these interconnected sectors, improving efficiency, resilience, and sustainable resource use (Lucca et al., 2023; Wu et al., 2022). For example, recovering energy within water distribution networks (as with the PATs and in-pipe turbines mentioned above) exemplifies a win-win solution identified through a nexus perspective, where both

water management and energy production benefit (Pérez-Sánchez et al., 2017). By considering energy generation and water resource management together – along with food production and ecosystem health when relevant – stakeholders can make more informed decisions that ensure equitable and sustainable access to natural resources (Apeh & Nwulu, 2024).

The global experience with small hydropower offers additional insight into its role and challenges in sustainable energy development. Small hydropower plants, typically defined as installations with capacity up to 10 MW (up to 5 MW in Poland's classification), represent a crucial component of decentralised renewable energy strategies around the world. A key advantage of SHPs is their ability to meet local energy demands with relatively minimal environmental impact compared to large dams. Case studies from developing regions illustrate that small-scale hydropower projects can often be more sustainable and socially acceptable than large hydro facilities. For example, research in Ethiopia suggests that pursuing numerous micro- and small hydropower projects – as opposed to a few very large ones – tends to involve lower risks of negative socioeconomic consequences, such as displacement of communities or widespread ecological disruption (Bezabih, 2021). In addition, SHP systems can contribute significantly to rural development: beyond providing clean, renewable electricity, they often lead to improvements in local water infrastructure (e.g. irrigation or drinking water systems) and reduce reliance on polluting energy sources, thereby fostering public health and economic growth in isolated communities (Li et al., 2014). Thanks to their relatively low capital and operating costs compared to big dam projects, SHPPs are frequently an economically viable option for communities far from national grids (Girma, 2016). Several studies underscore the role of SHPPs in promoting rural electrification, decreasing fossil fuel use, and stimulating local economies (Pang et al., 2018; Uamusse et al., 2019). For instance, small hydropower mini-grids installed in remote areas of Mozambique have substantially improved energy access for villagers without causing the

extensive environmental disturbances associated with large reservoirs (Uamusse et al., 2019). This growing recognition of socioeconomic co-benefits has positioned SHPs as valuable sources of renewable energy that can sustainably fulfil both local and national energy needs (Girma, 2016). To effectively harness this potential at the local scale, accurate and reliable forecasting of electricity demand is also important, as it supports efficient operation and helps match the output of SHPPs to community needs (Li et al., 2014).

Despite the many benefits of small hydropower, it remains essential to design and operate these projects in a sustainable and socially responsible manner. Notably, while SHPPs generally cause far fewer biophysical disruptions than large dams, they are not entirely without impacts. Research comparing projects of different scales indicates that the socioeconomic effects associated with small hydropower development can in some cases be comparable to those of larger installations (Kibler & Tullos, 2013). This is likely because even a small project can alter water availability or land use in ways that affect local communities (for example, by changing irrigation patterns or requiring resettlement on a small scale). Therefore, thorough assessments of both environmental and social impacts should be conducted during the planning stage of SHPPs, ensuring that any adverse effects are identified and mitigated. A key element of sustainable SHP operation is preserving the downstream river hydrological regime as naturally as possible. Best practices call for conducting flood risk analyses and maintaining adequate environmental flows (minimum flows) below the hydropower site to sustain ecological continuity and protect aquatic biodiversity (Le, 2024). In practical terms, managing an SHPP sustainably means continuously monitoring river flow conditions and ecological indicators, adhering to minimum flow requirements, and considering the needs of local water users (Pang et al., 2018). Such measures help prevent conflicts – for instance, between the plant operators and downstream communities or conservationists – and minimise ecological degradation. Moreover, explicit analysis

of the trade-offs between energy production and downstream river health is valuable. Studies have highlighted how increasing power generation can sometimes significantly alter flow patterns, which may harm aquatic habitats and ecosystem services. By quantifying these trade-offs, decision-makers can balance economic objectives with ecological preservation, crafting water management policies that safeguard natural river functions while still harnessing hydropower potential (Craig et al., 2019). Overall, the goal is to avoid the pitfalls experienced with some large hydropower projects by ensuring that even small projects uphold environmental standards and maintain public trust.

While administrative and financial hurdles often pose the main barriers to SHPP development (for example, lengthy permitting processes, grid connection costs, and limited access to financing), larger hydropower projects tend to face even greater social and environmental scrutiny. In Poland, for instance, a proposed 80 MW dam at Siarzewo on the Vistula River has met with strong public opposition due to concerns about ecological damage and community impacts. This example underscores how the scale of hydropower projects can amplify challenges: smaller run-of-river plants, if managed well, generally have lower footprints and encounter fewer social conflicts, whereas large dams can become flashpoints of controversy. Accordingly, small hydropower occupies a niche but important role in the renewable energy transition – capable of contributing to local energy goals with relatively modest environmental disruption, provided that best management practices and stakeholder engagement are in place.

In summary, the literature suggests that effective small hydropower management must integrate technical innovation, ecological stewardship, risk mitigation, and community involvement. The insights from previous research have directly informed the design of our empirical investigation. For example, findings on hydrological variability and risk management (Huang et al., 2023; Oksuz & Brlek, 2023) shaped the survey questions in our study related to operational monitoring and outage frequencies, as

well as items addressing climatic constraints in small hydropower operations. Likewise, the emphasis in the literature on ecological flows and biodiversity conservation (Kuriqi et al., 2020; Lange et al., 2018; Qu et al., 2022) guided the inclusion of questions on maintaining minimum flows and monitoring environmental impacts in the questionnaire's environmental section. Considerations of community involvement and policy integration (Kaunda et al., 2012; Kouadio et al., 2022; Noda et al., 2020) influenced sections of the survey dealing with strategic management and future development prospects, enabling us to assess issues of social acceptance and institutional support. Furthermore, themes related to technical efficiency and innovation (Agrawal & Pandey, 2020; Borkowski & Majdak, 2020). Were reflected in questions regarding automation, modern control systems, and maintenance practices. Collectively, the questionnaire serves as an applied extension of this literature review – it translates the theoretical and global insights into focused empirical measures for the Polish context. In doing so, our study aims to empirically examine the administrative and environmental constraints on SHPP development and identify best management practices that can support Poland's green energy transition in line with its policy goals.

MATERIALS AND METHODS

This study employed an exploratory case-study design, taking the Kuyavian-Pomeranian Voivodeship as a representative lowland region of Poland. The research combined a statistical review of hydropower infrastructure with a qualitative investigation of socio-economic and managerial aspects of SHPP operation.

The research was conducted between April–May 2025. The statistical component included an examination of datasets and reports from the Energy Regulatory Office (URE) and regional authorities (as of December 2024), identifying the location, capacity, ownership structure, and operational status of all registered SHPPs in the region.

A desk-based statistical review was carried out to establish the regional context of SHP development.

This process involved mapping installations to compiling aggregated capacity data and comparing the regional share of SHP with other RES technologies such as wind, photovoltaics, biomass, and biogas. These analyses served as a baseline for estimating the contribution of SHPPs to the regional energy mix.

Given the relatively small number of SHPPs operating in the voivodeship, a purposive sampling strategy was adopted. Three respondents, each responsible for more than one installation, were interviewed, collectively covering eight out of the twenty-four SHPPs in the region. These plants account for approximately 10% of the region's installed SHP capacity, ensuring meaningful coverage of plant sizes, technical characteristics, and ownership structures. Although the sample is not statistically representative, it is considered sufficiently diverse and typical to provide robust exploratory insights into prevailing management practices and barriers.

The eight SHPPs included in the study varied in terms of age and equipment. The oldest installation had been in operation for over 40 years, while the most recent was commissioned in 2015. Most plants were run-of-river facilities equipped with Kaplan or semi-Kaplan turbines (three plants) and Francis turbines (two plants), while the remaining installations used cross-flow or Archimedes screw turbines adapted for low-head conditions. The diversity of turbine types and commissioning periods provided insights into both modernisation needs and long-term operational practices across the regional SHP sector.

Primary data were collected through semi-structured interviews supported by a structured questionnaire entitled *Small Hydropower as an Element of the Green Transition – The Perspective of Small Hydro-power Operators*. The questionnaire was designed based on the categories identified in the literature review and consisted of seven thematic modules: general plant characteristics, strategic management, operational practices, environmental compliance, financial aspects, barriers to development, and future prospects. It included 46 questions combining closed-ended (rating scales, multiple choice), open-ended, and hybrid formats. Interviews were conducted in per-

son or online, with responses recorded directly into a secure digital form (Google Forms) to allow immediate verification and reduce transcription errors.

Qualitative responses were reviewed manually by the author. Codes were assigned directly to interview transcripts and grouped into broader categories informed by the research objectives and the literature review (e.g. administrative barriers, environmental regulations, financial constraints, technical practices, stakeholder involvement). Although the coding process was primarily deductive – guided by themes identified in the literature – additional categories were allowed to emerge inductively where respondents mentioned issues not covered by the initial framework. Each response was systematically classified and compared across cases. This approach provided a clear and replicable structure for interpreting the qualitative data and capturing both theoretically anticipated and context-specific insights. A detailed overview of the questionnaire structure is provided in Table 1.

During the semi-structured interviews, responses were recorded in real time using an online questionnaire tool (Google Forms), enabling immediate data entry and ensuring accuracy and completeness. This approach allowed the interviewer to document verbal answers concurrently, probe for clarification or additional details when necessary, and maintain a structured format for subsequent qualitative and quantitative analysis. The digital platform provided secure storage and facilitated the direct export of data for thematic coding, thereby minimising transcription errors and improving the reliability of the collected information.

The combination of secondary data, semi-structured interviews, and questionnaire-based responses provided a form of data triangulation, strengthening internal validity. While results cannot be generalised statistically to all SHPPs in Poland, they offer indicative findings for regions with similar geographical, institutional, and regulatory settings and form a robust basis for practical recommendations. Although limited in statistical scope, this design enables a nuanced understanding of barriers and management practices that may be relevant for other regions in Central and Eastern Europe facing similar conditions.

Table 1. Structure of the Questionnaire for Interviews with SHPPs Managers

Section (Question Range)	Purpose and Description	Key Elements/Examples
I. General Information (1–9)	To gather contextual data on the SHP installation for classification and comparison, including technical and organisational profiles.	Year of commissioning; turbine type (e.g., Kaplan, Francis, Pelton, Archimedes); head height (low, medium, high); water impoundment type; ownership form; number of employees; daily operational challenges (e.g., technical maintenance, hydrological variability). Example: Question on turbine type allows analysis of operational issues in older vs. modern installations.
II. Strategic Management (10–13)	To examine long-term planning aspects, assessing whether SHPPs management is proactive and sustainability-oriented in the green energy transition.	Existence of formal development strategy; strategic goals (e.g., modernisation, capacity increase, RES diversification); strategic decision-makers; frequency of plan reviews (annually, every few years, one-time). Closed questions with multiple choices quantify trends; open questions identify unique strategies.
III. Operational Management and Maintenance (14–24)	To focus on daily operational practices, identifying efficiency and risk management that impact SHPPs reliability and sustainability.	Service schedule (daily, weekly, monthly); monitoring and automation systems; staff qualifications; spare parts availability; failure rate; OHS training (Occupational Health and Safety); health hazards; safety-critical elements; overall safety level (scale 1–5); cooperation with local institutions. Scales quantify opinions; open questions describe automation systems.
IV. Environmental Protection (25–29)	To analyse ecological aspects, evaluating compliance with environmental requirements critical for sustainable development.	Compliance with environmental impact assessment; fish pass installation; ecological flow provision (including value in l/s); measures to limit ecosystem impact (scale 1–5); monitoring of water quality or fauna. Yes/no questions with descriptions verify legal compliance; scales measure perceived effectiveness of pro-ecological actions.
V. Financing and Economics (30–33)	To investigate economic aspects, understanding SHPPs profitability and the role of financial support in their development.	Funding sources (own funds, loans, subsidies); operational profitability (scale 1–5); revenue covering costs; use of guaranteed tariffs or tax reliefs. Multiple-choice identifies dominant financing models.
VI. Development Barriers (34)	To identify key constraints on sector development, directly relating to the research hypothesis.	Significance of barriers (scale 1–5), e.g., investment costs, administrative procedures, environmental regulations, energy profitability, financing access, social opposition. Open-ended with scale for prioritisation.
VII. Prospects (35–46)	To explore SHPPs future, collecting developmental perspectives and recommendations.	Expected support; expansion possibilities; development facilitators; RES integration; future assessment of SHPPs in Poland; energy policy support; good management practices; educational activities; recommendations; community initiatives. Open questions for free responses; multiple-choice for data aggregation.

Source: own elaboration.

RESULTS

Analysis of the Status of Small Hydropower Plants in the Kuyavian-Pomeranian Voivodeship

The Kuyavian-Pomeranian Voivodeship, despite its predominantly lowland character, presents a noteworthy case within Poland's energy transition land-

scape due to its untapped SHP potential. The presence of rivers such as the Vistula, Brda, and Drwęca, along with existing hydrotechnical infrastructure, creates favourable conditions for the development of SHP installations. Regionally, SHP offers not only opportunities for renewable electricity generation but also the potential to support water retention, drought mitigation, and the prevention of water resource degradation, functions that are particularly relevant for

sustainable water management in lowland territories. To provide a clearer spatial context, Fig. 1 illustrates the location of the Kuyavian-Pomeranian Voivodeship, indicating its position within Poland and Poland's location within Europe.

Table 2 presents the distribution of hydropower installations across the voivodeship. A total of 26 hydropower facilities has been identified, collectively contributing to an installed capacity of approximately 210.04 MW. Among these, two are large-scale power plants: Samociążek (24.8 MW) and Włocławek (162 MW). The aggregate capacity of SHP installations in the region amounts to 23.24 MW. The spatial distribution of SHP systems reveals that hydropower infrastructure is present in 11 out of the 19 counties, indicating that over 40% of the region remains without such facilities. This uneven distribution underscores both the existing developmental gaps and the potential for further expansion of SHP as part of a decentralised energy transition strategy.

This spatial concentration stands in stark contrast to the distribution of photovoltaic and wind power installations, which are found in virtually all counties, often in substantial numbers. The limited presence of hydropower facilities is primarily attributed to their strong dependence on local natural conditions – such as the availability of watercourses, terrain gradient, and compliance with environmental and hydrological requirements. The construction of such installations necessitates not only suitable topographical features but also adherence to stringent criteria related to nature conservation and water management regulations.

Consequently, despite its theoretical significance, hydropower potential is inherently more challenging to harness compared to other renewable energy technologies with broader geographic applicability. Currently, the Kuyavian-Pomeranian Voivodeship utilises approximately 57% of its theoretically available hydropower potential, as estimated by the Kuyavian-



Fig. 1. Geographical location of the research area
Source: own elaboration.

Table 2. Number of hydropower installations in the Kuyavian-Pomeranian province as of 31.12.2024

Installation location	County	Municipality	Installed capacity [MW]	Owner
Grzmieca	brodnicki	Zbiczno	0,055	Private property
Łochowo	bydgoski	Białe Błota	0,075	MEWAT Sp. z o.o., Bydgoszcz
Łochowo	bydgoski	Białe Błota	0,075	
Samociążek	bydgoski	Koronowo – gm. m.-w.	24,800	ENEA NOWA ENERGIA Sp. z o.o., Radom
Tryszczyn	bydgoski	Koronowo – gm. m.-w.	4,000	
Bydgoszcz	bydgoski	M. Bydgoszcz	4,000	
Świecie nad Osą	grudziądzki	Świecie nad Osą	0,055	Eko Energia Jacek Dulka, Świecie n/Osą
Bydgoszcz	m. Bydgoszcz	M. Bydgoszcz	0,435	Małe Elektrownie Wodne Spółka Cywilna Jerzy, Maria, Piotr Kujawscy, Kościerzyna
Bydgoszcz	m. Bydgoszcz	M. Bydgoszcz	0,945	MEWAT Sp. z o.o., Bydgoszcz
Bydgoszcz	m. Bydgoszcz	M. Bydgoszcz	0,108	Państwowe Gospodarstwo Wodne Wody Polskie, Warszawa
Grudziądz	m. Grudziądz	M. Grudziądz	0,055	Mała Elektrownia Wodna „Trynka” Dorota Kubiak, Grudziądz
Włocławek	m. Włocławek	M. Włocławek	162,000	Energa Wytwarzanie Spółka Akcyjna, Gdańsk
Włocławek	m. Włocławek	M. Włocławek	0,075	Centralne Towarzystwo Handlowe Spółka z ograniczoną odpowiedzialnością, Warszawa
Nakło nad Notecią	nakielski	Nakło nad Notecią – miasto	0,225	Mała Elektrownia Wodna „LIS” Rogala Spółka Jawna, Osiek nad Notecią
Gromadno	nakielski	Kcynia – gm. m.-w.	0,150	„TELKOM” Szmidt Mieczysław, Piła
Radzicz	nakielski	Sadki	0,077	
Kozłowo	świecki	Świecie – gm. m.-w.	0,490	Małe Elektrownie Wodne Spółka Cywilna Jerzy, Maria, Piotr Kujawscy, Kościerzyna
Świecie	świecki	Świecie – gm. m.-w.	0,500	GPEC Energia Spółka z ograniczoną odpowiedzialnością, Gdańsk
Gródek	świecki	Drzycim	3,888	ENEA NOWA ENERGIA Sp. z o.o., Radom
Żur	świecki	Osie	3,520	
Żur	świecki	Osie	3,520	
Klocek	tucholski	Tuchola – gm. m.-w.	0,530	GPEC Energia Spółka z ograniczoną odpowiedzialnością, Gdańsk
Nowy Młyn	włocławski	Lubień Kujawski – gm. m.-w.	0,075	Przedsiębiorstwo Produkcyjno-Handlowo-Usługowe EKOWAT Spółka Cywilna Roman, Zbigniew, Leszek Gromotka, Wysoka
Łabiszyn	żniński	Łabiszyn – gm. m.-w.	0,160	Małe Elektrownie Wodne Spółka Cywilna Jerzy, Maria, Piotr Kujawscy, Kościerzyna
Łabiszyn	żniński	Łabiszyn – gm. m.-w.	0,075	
Frydrychowo	żniński	Łabiszyn – gm. m.-w.	0,150	Marwind Spółka z ograniczoną odpowiedzialnością, Grudziądz

Source: own elaboration based on data from Energy Regulatory Office.

-Pomeranian Spatial and Regional Planning Office in Włocławek. In terms of technical capacity, the utilisation rate approaches 100%, indicating that nearly all sites deemed technically viable have already been developed (Urząd Marszałkowski Województwa Kuyawsko-Pomorskiego [Marshal's Office of the Kuyavian-Pomeranian Voivodeship], 2023). The distribution of hydropower installations across the region is illustrated in a map prepared by the

author (Fig. 2). Green dots represent small hydropower plants, blue dots represent large hydropower plants, and the orange dot indicates a facility currently in the pre-construction phase (Siarzewo). Arrows link plant names and their installed capacities with their exact geographical locations on the map. The map was compiled by the author on the basis of data from the Energy Regulatory Office and additional verification of individual plant locations and capacities.

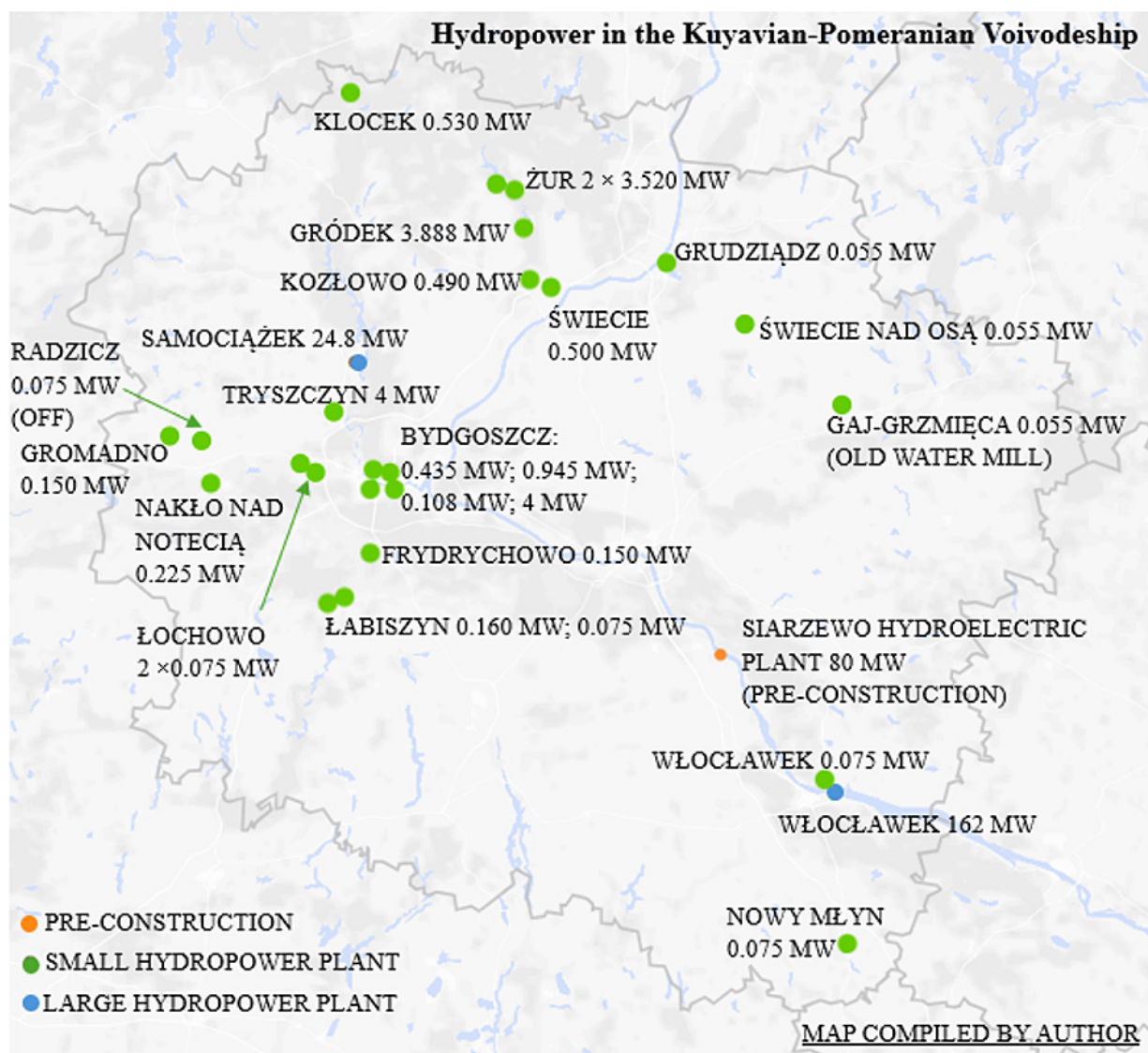


Fig. 2. Hydropower plants in the Kuyavian-Pomeranian Voivodeship with the capacity (2025)
 Source: own elaboration.

The Siarzewo hydropower plant, planned on the lower Vistula River in the Kuyavian-Pomeranian Voivodeship, is one of Poland's largest post-1989 hydropower initiatives. With a projected capacity of 80 MW and annual production of 315–350 GWh, it aims to support renewable energy goals while integrating flood protection, drought mitigation, and improved navigation. It is also expected to reduce CO₂ emissions by approximately 250,000 tonnes annually. Project documentation emphasises the multifunctional character of the facility. In addition to energy production, it is expected to contribute to flood protection, improve water retention to mitigate drought effects, and enhance navigability along the Vistula River. A further advantage is the anticipated reduction of CO₂ emissions by approximately 250,000 tonnes annually, aligning the investment with national decarbonisation objectives (Toborek, 2025).

Despite these benefits, the project remains stalled due to environmental concerns. Its permit was revoked in 2024 over potential impacts on Natura 2000 areas and river hydrology. The case reflects the broader tension between renewable energy expansion and ecological protection in large-scale hydropower development in Poland (Toborek, 2025).

A synthetic summary of the conducted research is presented for the Kuyavian-Pomeranian Voivodeship, showing the number and installed capacity of individual types of renewable energy sources and their percentage share in the region's total RES capacity (Table 3). The “share in capacity” indicator expresses the proportion of a given source's capacity relative to the total installed capacity in the voivodeship and is presented as a percentage. The analysis indicates that wind power is the dominant source, accounting for over 53% of the region's renewable capacity, while photovoltaics contribute around 19%. The column “number of installations in the voivodeship [%]” shows the share of each source type in the total number of renewable energy installations, revealing that wind and solar installations have a comparable share of around 46% each. The total installed RES capacity in the voivodeship at the end of September 2024 was 1,761 MW, highlighting the significant scale of renewable energy deployment in the region. Although SHPPs constitute just 1.3% of the total regional RES capacity, their presence across 24 sites highlights their continuing importance in the local energy landscape and their potential contribution to diversified renewable generation.

Table 3. Mix of RES in the Kuyavian-Pomeranian Voivodeship in 2024

Type of Renewable Power Plant	Total Installed Capacity [MW]	Share in Regional Capacity [%]	Number of Installations	Share in Total Number of Installations [%]
Hydropower	210	12	26	3,7
– including SHPPs	23,24	1,3	24	3,4
Wind	929	53	328	46,4
Photovoltaic	330	19	323	45,7
Biogas	19	1	20	2,8
Biomass	177	10	5	0,7
Waste-to-Energy	14	1	1	0,1
Co-firing	64	4	3	0,4
Geothermal Combined Heat and Power	18	1	1	0,1
Total	1761	100	706	100

Source: own elaboration based on data from Energy Regulatory Office.

RESULTS OF STRUCTURED INTERVIEWS

Financing Sources and Ownership Structure

All respondents unanimously identified three primary sources of financing for their installations: owner equity, external debt financing (e.g., bank loans or leasing), and public subsidies from national or European Union programmes, such as the National Fund for Environmental Protection and Water Management (NFOŚiGW). These funding profiles reflect the nature of the sector – SHPPs are operated as private ventures. Each facility is either part of a company managing multiple SHPP units or is owned by an individual conducting business activity in the field. As such, the development and operation of SHPPs require not only securing capital through internal or external sources but also active engagement in acquiring available financial support mechanisms.

The predominance of privately owned SHPPs, many of which operate as small family businesses, highlights the importance of designing support mechanisms that are accessible to small-scale investors and that reduce administrative burdens. Limited involvement of municipal authorities or energy utilities suggests that public–private partnerships remain underutilised, which may slow down the modernisation of ageing facilities. These findings indicate that policy interventions should focus on improving access to financing, simplifying permitting procedures, and encouraging institutional actors to engage in joint investment initiatives, which would collectively enhance the sector's contribution to regional energy transition goals.

Strategic Management

The interviews revealed that the strategic management of SHPPs primarily focuses on addressing key challenges related to maintaining stable and efficient energy production. The most significant operational difficulty cited by respondents was the variability of hydrological conditions. Fluctuating river flows

directly affect generation output, complicating long-term planning and limiting the ability to maintain consistent production levels. Periods of drought or low water levels often necessitate a reduction in turbine operation, while sudden floods may require emergency protective actions.

A second major challenge concerns the maintenance of technical infrastructure. Ensuring the reliability of components such as turbines, generators, and bypass mechanisms demands both careful scheduling of operational downtime and adequate financial resources for servicing. Effective strategic planning must therefore incorporate life cycle management of critical equipment, including modernisation or replacement schedules, to avoid major failures and preserve operational efficiency.

Notably, none of the surveyed entities had implemented a formal quality management system (e.g., ISO standards) in their SHPPs operations. The absence of such frameworks may reflect the limited organisational capacity of small enterprises or a lack of regulatory incentives. Only one respondent reported having a written strategic development plan focused on enhancing energy efficiency through equipment upgrades. This plan outlined a long-term objective: to maximise the hydropower potential of the installation while systematically modernizing the infrastructure.

Although the remaining respondents did not have formalised strategies, all expressed a consistent goal of maintaining the highest possible production levels within the constraints of existing hydrological and technical conditions. This orientation can be characterised as a defensive-adaptive strategy prioritizing operational optimisation and reactive adjustments rather than proactive development planning. Despite this informal approach, most managers indicated interest in implementing technical upgrades or even expanding their facilities. However, they emphasised significant obstacles, primarily related to complex legal regulations concerning riverbed modifications and environmental opposition to hydrotechnical infrastructure. These external constraints pose a serious barrier to more ambitious strategic initiatives in the SHPP sector.

Operations management

In the domain of operations management, the surveyed power plants were found to implement diverse inspection and maintenance schedules, customised to the unique requirements of each installation. Continuous monitoring of plant operations is universally employed, with the majority of respondents utilizing remote systems that facilitate round-the-clock tracking of critical parameters, including generated power, turbine speed, and water levels at upstream and downstream stations. This capability enables operators to promptly address deviations from normative values and optimise equipment performance without necessitating perpetual on-site presence.

Technical inspections of core infrastructure components are performed at intervals determined by technical specifications and manufacturer guidelines. Certain equipment and subsystems demand weekly evaluations or servicing, for instance, the cleaning of inlet grates to remove accumulated debris and river sediment is frequently conducted every few days to maintain unobstructed water flow to the turbines. Other components undergo assessments every few months, typically on a quarterly basis; turbines and generators, for example, are routinely examined for mechanical and electrical integrity during these cycles, whereas basic automation systems may require more frequent diagnostic evaluations. This phased scheduling ensures uninterrupted plant functionality while mitigating the accumulation of deferred maintenance tasks.

The respondents highlighted that certain critical system components necessitate particularly rigorous and routine oversight owing to their pivotal role in ensuring safety and operational continuity. These components include turbines – the damage or failure of which could halt energy production – impoundment mechanisms and sluice gates that regulate water flow and mitigate flood risks, intake grates that prevent debris from entering and clogging the system, generators and electrical installations where overvoltage protection and insulation integrity are critical, and guards for moving machinery parts

(e.g., pulley guards that protect personnel from accidental contact with rotating elements). Scheduled and ad hoc inspections of these components, following adverse events such as floods or windstorms, are imperative for maintaining safe and uninterrupted plant operations.

Notwithstanding the inherent hazards associated with hydrotechnical facilities, the overall safety level of SHPP operations was rated highly. Respondents assigned an average score of 4 on a five-point scale, where 1 denotes highly hazardous conditions and 5 signifies highly safe environments. Among the most salient threats to employee health and life were electrocution risks and falls into water, particularly during tasks involving equipment positioned above or on the water surface, such as grate cleaning or turbine maintenance. These hazards are intrinsic to the operational nature of hydropower plants. Nonetheless, the elevated safety rating implies that operators have instituted robust occupational health and safety protocols and training programmes to attenuate accident risks. Standard practices include equipment shutdown and lockout-tagout procedures prior to maintenance, the utilisation of personal protective equipment (e.g., safety harnesses over water surfaces and insulated tools for electrical work), and mandatory teamwork for high-risk activities. Such measures have culminated in an absence of major incidents; over the past 12 months, none of the surveyed facilities experienced outages exceeding 24 hours, underscoring the installations' reliability and the efficacy of preventive strategies implemented by the personnel.

The availability of spare parts for turbines and generators emerged as a contentious issue, with managers exhibiting marked divergence in their perspectives. One respondent, concurrently serving as a manufacturer or distributor of components for SHPPs, asserted that spare parts are readily accessible – encompassing both standard mechanical elements and specialised components, which can be procured expeditiously from domestic sources or established international suppliers. In contrast, other managers reported divergent experiences, highlighting

challenges in the timely acquisition of requisite parts. These difficulties predominantly pertained to protracted lead times for bespoke components (e.g., non-standard turbines or control systems, frequently necessitating custom importation) and the constrained pool of domestic suppliers. Consequently, for numerous operators, the maintenance of sufficient inventories of critical components or the identification of alternative procurement channels constitutes an integral facet of operational management.

The analysis of the interviews also revealed that the economic profitability of operating SHPPs is viewed with considerable scepticism by the managers themselves. Two out of three respondents rated the current profitability at 3 on a scale of 1 to 5, corresponding to moderate profitability (neither high nor entirely unsatisfactory). This implies that, under prevailing electricity prices and operational costs, the management of these facilities yields, at best, average profit margins. A more concerning indicator is the assertion by one manager that certain installations are wholly unprofitable (assigning a rating of 1), suggesting that older or less efficient plants may incur losses or generate revenues that are disproportionate to the associated expenditures. In this context, it is noteworthy that several of the surveyed installations continue to benefit from the Feed-in Tariff (FIT) mechanism – a policy framework designed to support renewable energy sources by guaranteeing the purchase of electricity from producers at a predetermined, fixed price over a specified duration. This system, implemented in Poland for select renewable energy installations, has provided stable and more favourable revenues from energy sales. However, not all small-scale hydropower plants remain eligible for such incentives, as some have surpassed the age threshold for preferential tariffs or tax exemptions. For these facilities, energy sales occur under market conditions, which adversely affects their profitability. Overall, the financial landscape emerging from the interviews depicts a sector precariously balanced on the threshold of viability, where profitability hinges on multiple factors, including access to support mechanisms, maintenance costs, and hydrological conditions, and profit margins remain narrow.

The respondents expressed considerable criticism regarding their collaboration with local institutions and the broader administrative framework governing their power plant operations. Uniformly, all participants characterised this cooperation as poor or very poor. In practical terms, this implies that, rather than the anticipated partnership or assistance from municipal governments and administrative offices – such as expedited procedural handling or advisory support – managers of SHPPs encounter substantial formal impediments. Among the principal issues highlighted were protracted administrative processes, excessively intricate legal regulations pertaining to water management and renewable energy, and the absence of explicit guidelines for their interpretation. Several managers observed that permitting procedures (e.g., for water rights or construction approvals) can extend over several years, thereby impeding investments in modernisation. Moreover, a perceived lack of engagement and support from local authorities was evident, with SHP seemingly accorded low priority by decision-makers, who seldom proactively facilitate the functioning of such facilities within their jurisdictions. This strained interaction with the institutional milieu represents a formidable barrier to the sustained management and strategic planning of SHP plant development.

Environmental Aspects of Operations

All interviewed managers emphasised that their power plants operate in full compliance with legal requirements for environmental protection. Each surveyed installation possesses a formal environmental permit, issued on the basis of an environmental impact assessment (EIA), which authorises both the construction and ongoing operation of the facility. This indicates that a comprehensive analysis of the project's effects on the local ecosystem was undertaken prior to commissioning. A primary measure to mitigate the adverse impacts of damming structures on river ecosystems involves ensuring fish migration pathways. As reported by the respondents, all power plants are equipped with fish passes or equivalent structures (e.g., rapids or bypasses), or they leverage pre-existing

fish passes constructed during prior hydrotechnical developments. Such provisions enable upstream and downstream fish movement despite the presence of dams or weirs, thereby reducing the fragmentation of aquatic habitats. Complementing these fish passes, the maintenance of a minimum flow in the riverbed downstream of the power plant, termed ecological flow, represents a standard practice. All managers confirmed adherence to this requirement, whereby a portion of water is continuously diverted through bypass mechanisms external to the turbines, sustaining a constant downstream flow to support the survival of aquatic organisms. Ecological flow is typically stipulated in the water permit for each installation and serves as a critical parameter in constraining the power plant's negative influence on the river's biocenosis.

Despite the implementation of the aforementioned solutions, respondents exhibited variability in their evaluations of the effectiveness of mitigating the adverse environmental impacts of their SHPPs. When solicited for an overall rating (on a scale from 1 to 5, where 1 denotes the absence of pro-environmental measures and 5 signifies comprehensive mitigation efforts), two managers assigned a score of 3, while one provided a rating of 4. This divergence implies heterogeneity in approaches to supplementary environmental measures exceeding statutory minima. A rating of 3 suggests that certain managers perceive their installations as only moderately attenuating ecosystem impacts – likely adhering primarily to obligatory protocols (e.g., fish passes and ecological flows) without extensive adoption of supra-standard initiatives, such as environmentally enhanced turbines or restorative measures for local fauna. Conversely, the rating of 4 from one respondent indicates a marginally more proactive stance towards environmental stewardship, albeit falling short of maximal engagement. Notably, none of the respondents rated their facilities at 5, signifying that no participant views their plant as wholly sustainable or optimally environmentally benign. Consequently, opportunities for enhancement persist in this domain.

The Interviews also unveiled a notable deficiency in environmental monitoring practices. None of the examined power plants implemented systematic monitoring of water quality or aquatic fauna (e.g., assessments of fish populations) within their zones of influence. In essence, following project commissioning, no subsequent environmental investigations were undertaken to substantiate the long-term ecological impacts, or the absence thereof, on the ecosystem. Managers predominantly operate under the presumption that adherence to environmental permit stipulations (e.g., the provision of fish ladders or the maintenance of minimum ecological flows) suffices for biodiversity conservation. However, the absence of robust monitoring data precludes access to precise insights regarding potential adverse phenomena, such as sediment accretion, alterations in fish species composition, or declines in water quality proximate to the facility. This shortfall may stem from financial limitations (as monitoring entails substantial costs) or the lack of statutory mandates in this domain. Nonetheless, from a scientific standpoint, this represents a critical informational lacuna, rendering a comprehensive evaluation of the environmental ramifications of SHP plant operations inherently challenging without such empirical evidence.

Barriers to the Development of Small Hydropower Plants

During the interviews, managers were solicited to identify the factors that, in their view, most impeded the advancement of small hydropower plants, encompassing both the construction of new facilities and the modernisation or expansion of existing ones. To systematically organise the identified barriers to the development of small SHPPs, as derived from the interviews with managers, the following table categorises them according to the degree of severity reported by respondents. Barriers are grouped into “Most Severe” (strongly inhibiting or blocking development), “Significant” (substantially limiting

but not entirely halting progress), and “Insignificant” (minimal or easily surmountable). The table 4 includes a description of each barrier and its implications for development, facilitating a structured analysis of constraints in the sector.

However, it is noteworthy that in open-ended questions, respondents elaborated on the theme of public opposition, highlighting specific challenges encountered in practice. In particular, they described conflicts with immediate neighbours of the installations and the protracted legal disputes arising therefrom. One manager recounted instances where individuals or groups of residents from the vicinity lodged appeals and complaints against modernisation or expansion plans, resulting in administrative proceedings that extended over several years, despite the investor’s adherence to formal requirements. Another respondent detailed a case where such

actions precipitated legal proceedings lasting a decade, effectively hinder any modifications to an operational power plant. These situations illustrate that, although public opposition was not formally identified as a predominant barrier in structured responses, localised conflicts can, in practice, entirely halt the development of specific installations. This issue also underscores inefficiencies in the legal framework for resolving disputes, including the absence of robust mediation mechanisms or expedited complaint resolution processes, which permit even unsubstantiated or peripheral objections to prolong impasses detrimental to all stakeholders. Consequently, respondents advocated for legislative reforms to achieve a balanced reconciliation of public interests – such as advancing clean energy development – with citizens’ rights to voice concerns, thereby averting extended stalemates.

Table 4. Barriers to the Development of Small Hydropower Plants: Classification Based on Perceived Severity

Barrier Category	Barrier	Description	Implications for Development
Most Severe	High Investment Costs	Substantial capital expenditure required for hydrotechnical works, turbines, generators, and grid infrastructure; long-term and uncertain return on investment.	Acts as a prohibitive entry barrier for potential investors, deterring new projects despite available financing options.
	Complex Administrative Procedures	Prolonged processes for obtaining environmental, water rights, building, and energy concessions; bureaucratic delays and coordination challenges.	Effectively stalls initiatives, increasing uncertainty and costs, even for technically viable projects.
Significant	Environmental Constraints	Stringent regulations (e.g., EU Water Framework Directive 2000/60/EC) mandating ecological continuity, high standards for fish passes, and nature compensation.	Restricts new impoundments on certain watercourses, extending timelines and elevating costs, though necessary for sustainability.
	Low Energy Profitability	Small-scale production combined with low energy purchase prices and absence of preferential tariffs post-support schemes.	Prolongs payback periods, discouraging investors and financial institutions from funding.
	Limited Access to External Financing/Subsidies	Highly competitive support programmes; banks’ caution due to regulatory and revenue risks.	Impedes capital acquisition, causing viable projects to stall at the funding stage.
Insignificant	Social Opposition	Generally neutral or favourable community attitudes towards existing SHPPs.	Rarely escalates to significant obstacles, with concerns typically arising only during planning phases.
	Lack of Qualified Personnel	Availability of specialists on the market; automation reduces staffing needs.	Easily overcome through hiring or contracting, posing no substantial limitation to growth.

Source: own elaboration.

Development Prospects for Small Hydropower Plants

When queried about the future trajectory of the small hydropower sector as a whole, managers conveyed a moderately pessimistic outlook regarding its developmental potential. All participants concurred that realistic expansion of their existing hydropower facilities is infeasible, attributable to a confluence of technical and legal/environmental constraints. Technically, many installations have already attained their maximum exploitable head and flow capacities, effectively exhausting the site's inherent potential. Augmenting installed capacity would necessitate alterations to fundamental hydrological parameters, such as elevating water levels or enlarging structural scales, which are precluded by prevailing regulations and permits. Moreover, these facilities frequently operate within zones subject to diverse forms of nature conservation or spatial development plans, further prohibiting substantial infrastructural modifications.

Concurrently, each respondent acknowledged the theoretical viability of constructing new SHPPs in the vicinity (e.g., on alternative watercourses or at underutilised dams). However, they qualified this possibility by stipulating the imperative of leveraging preexisting weirs and executing projects in full compliance with environmental mandates. In essence, novel undertakings could only materialise in locales where the river has already undergone anthropogenic transformation (e.g., impoundment), thereby minimizing supplementary ecological repercussions. Nonetheless, participants underscored that even such developments proximate to extant weirs would entail adherence to stringent prerequisites and pose considerable challenges – including investments in weir modernisation, securing approvals from owners or custodians (often state entities), and conducting comprehensive environmental impact assessments for the proposed plant.

Integration of Small Hydropower Plants with Other Renewable Energy Sources

An important topic emerging from the interviews was the potential integration of SHPPs with other renewable energy sources. The concept of hybrid systems – such as combining hydropower with solar photovoltaic installations – holds theoretical promise for improving infrastructure efficiency and stabilizing energy supply. However, only one of the interviewed managers reported seriously considering such integration, and none of the surveyed installations had yet been connected with complementary renewable technologies such as photovoltaic panels or small-scale wind turbines.

This observation suggests that the hybridisation of energy sources is not yet widespread within the SHPP sector. This may result from technical constraints (e.g., lack of space for solar modules at existing hydropower sites, limitations of grid connections), or from financial barriers associated with the additional costs of integrating multiple technologies. As a result, such initiatives remain the domain of individual pioneers rather than a mainstream development strategy across the sector.

Integrating SHPPs with other renewable energy sources plays a crucial role in enhancing the resilience of the regional energy system. While solar and wind power are characterised by intermittency and strong dependence on weather conditions, small hydropower plants can offer partially controllable generation that smooths fluctuations in electricity supply. This balancing effect improves grid stability, ensures a more predictable energy output, and reduces the risk of power shortages during periods of low solar irradiance or weak wind conditions. In the Kuyavian-Pomeranian Voivodeship, where wind power accounts for over half of installed RES capacity, such complementarities are particularly valuable for supporting the green energy transition under geographically constrained conditions. These findings underscore the potential of SHPPs to function as flexible system components that complement

other renewables and contribute to a more reliable and secure energy mix (Fekete et al., 2023; Ren et al., 2022; Tsuanyo et al., 2023; Xu et al., 2021).

Moreover, the interaction between SHPPs and other renewable technologies is significantly enhanced when energy storage solutions are considered. Small hydropower systems can be complemented by battery storage or, where feasible, pumped-storage hydropower (PSH) facilities, creating flexible storage frameworks that allow surplus energy generated during periods of high production to be stored and utilised later. This approach not only balances supply and demand more effectively but also improves the overall efficiency and reliability of the regional energy system (Guruprasad et al., 2023; Ramos et al., 2022).

Outlook for the Small Hydropower Sector

The cautious attitude of SHPPs managers towards the future of the industry was reflected in their assessments of its development prospects in Poland. When asked to evaluate the future of small hydropower on a scale from 1 to 5 (where 1 indicates “no development potential” and 5 indicates “dynamic growth”), respondents provided ratings between 1 and 3. These results indicate a lack of confidence in the sector's future expansion, with most responses expressing either pessimism or only moderate optimism.

The lowest ratings (1) reflected concerns about stagnation or even decline, driven by the previously described regulatory, environmental, and economic challenges. Intermediate ratings (2–3) suggested the possibility of sustaining existing operations, albeit without expectations for substantial sectoral growth.

Respondents attributed this outlook to the current energy policy environment in Poland, which they unanimously viewed as unsupportive of SHPP development. Factors contributing to this perception include the absence of dedicated support programmes, frequent changes in regulatory frameworks, and the prioritisation of other renewable sources such as solar and wind in national strategies. This marginalisation, both in strategic planning and in institutional support, was perceived as a major obstacle and a key factor shaping the pessimistic forecasts of SHPP managers.

Factors Supporting the Development of Small Hydropower in the Region

Despite the aforementioned challenges, managers expressed optimism regarding potential improvements, contingent upon proactive interventions by relevant authorities and institutions. The following key factors were proposed to bolster the regional development of small hydropower.

First, the simplification of legal regulations and administrative procedures could substantially enhance the investment climate. Entrepreneurs anticipate reductions in processing times for permit applications, fewer required documents and approvals, and greater regulatory transparency to limit administrative discretion. Streamlining water and construction laws relevant to SHP would lower transaction costs and remove a major entry barrier. Second, the enhanced availability of external financing through dedicated support programmes could incentivise investors and accelerate project implementation, which is particularly important given the high initial costs. Third, the introduction of fixed feed-in tariffs at viable levels, similar to the Feed-in Tariff mechanism but adjusted to current conditions, would create a stable investment environment. A guaranteed purchase price ensuring cost recovery within a feasible period would make SHP projects more predictable and financially attractive.

Fourth, facilitating access to sites near existing dams was identified as crucial, as most managers agreed that the most suitable locations for new SHPPs are those with existing hydrotechnical structures such as weirs or small dams. Overcoming formal barriers, such as the lack of clear leasing rules for state-owned dams or complex tendering procedures, would allow the use of existing infrastructure with minimal environmental impact. Fifth, respondents proposed establishing a public database of water stages that would include relevant hydropower data such as head height, flow rate, technical condition and ownership. Currently, information is dispersed across various institutions, and a centralised registry would improve transparency, facilitate planning and reduce potential conflicts.

Sixth, the implementation of a modernisation and maintenance programme for SHP was recommended, as many existing weirs and dams are in poor condition. A government-led or co-financed initiative could support their renovation and enable their use for energy generation, while also preserving technical heritage and improving flood safety. Finally, respondents stressed the need to facilitate access to the most promising sites for a broader range of entities, including private investors. Allowing greater private participation, under transparent and responsible criteria, could accelerate project implementation and attract capital currently unavailable within public budgets.

Best management practices for small hydropower plants

Despite the challenges encountered, respondents identified several best management practices that they use or consider valuable in operating SHPPs. Fig. 3 summarises the most important of these practices, which contribute to improving the efficiency, reliability and sustainability of small hydropower operations.

The fishbone diagram illustrates best management practices for SHPPs, with a central focus on maintaining high operational efficiency as the ultimate goal. On the left side of the spine, it emphasises technical and proactive elements, including monitoring and automation (encompassing remote monitoring systems and advanced control systems), as well as maintenance and planning (involving proactive planning and regular maintenance). On the right side, it highlights relational and analytical aspects, such as cooperation and communication (featuring collaboration with local authorities and contact with technology suppliers), alongside transparent documentation, continuous performance monitoring, and performance analysis. This integrated framework demonstrates how these multifaceted practices converge to optimise SHPP operations, underscoring the importance of both technological and collaborative strategies in achieving sustainable energy production.

Remote monitoring enables real-time tracking of turbine and generator operating parameters, facilitating rapid detection of anomalies such as performance deterioration, abnormal vibrations, or voltage fluctuations. Such capabilities allow plant operators to respond swiftly to deviations from normal

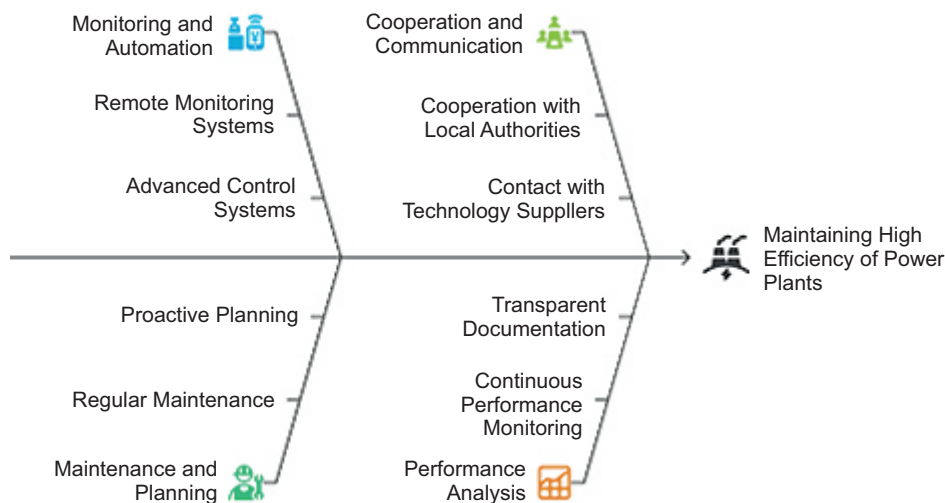


Fig. 3. Best management practices for SHPPs
Source: own elaboration.

operational conditions, often preventing minor issues from escalating into significant problems that would require plant shutdowns.

The implementation of automation in SHP plant control systems significantly streamlines operational management and optimisation processes. Notably, one of the power plant owners surveyed developed a specialised controller enabling partial adjustments of plant settings both remotely (via a dedicated web application) and on-site. This solution provides flexible management of turbines and auxiliary equipment, effectively integrating the advantages of automated controls, such as rapid responsiveness and maintenance of optimal operational parameters, with the option for manual intervention during situations that demand precise calibration or non-standard procedures. Ongoing enhancements to this system include developing remote turbine-blade adjustments based on current hydrological conditions. Importantly, this controller and its accompanying application have been commercially offered to other companies within the sector, exemplifying a valuable technology and knowledge transfer initiative that promotes best practices and elevates the overall technical standard of SHP operations.

Many managers have adopted a workflow model whereby plants do not require continuous staffing during nighttime hours and holidays, instead operating automatically under remote supervision. In this scenario, staff remain on-call, ready to intervene only in response to alarms or faults identified by the automated system. This approach, particularly prevalent among smaller installations, significantly reduces labour expenses by eliminating the necessity for around-the-clock personnel presence. Advanced monitoring and alarm systems ensure that this practice does not compromise operational safety or reliability. Upon detection of irregularities, such as water-level fluctuations, mechanical blockages, or electrical protection alarms, the system immediately alerts the on-call operator, who can then respond remotely or conduct an on-site visit as necessary. Respondents assessed this operational model as highly effective and cost-efficient, particularly given the current degree of automation deployed within the SHP sector.

DISCUSSION

The results of this study, which reveal that SHPPs development in the Kuyavian-Pomeranian Voivodeship is primarily constrained by institutional and economic barriers, are consistent with national-level findings indicating that hydropower accounts for only 0.6% of total electricity generation in Poland, despite a technically feasible potential estimated at 13.7 TWh per year (Olkuski, 2024). This underlines that the barriers identified in this case study are systemic rather than region-specific. The literature further emphasises that the future of hydropower development in Poland lies in the modernisation and optimisation of existing facilities rather than the construction of large new dams, a conclusion that supports the recommendations formulated in this research regarding targeted financial mechanisms and regulatory streamlining. Moreover, the strategic role of pumped-storage hydropower (PSH) in balancing variable renewable generation highlights the importance of integrating SHPPs with grid management and potentially hybridising them with other renewables and storage solutions – an area that merits further research and pilot projects.

The technical characteristics of the SHPPs surveyed in this study – including Kaplan, Francis and Archimedes screw turbines – reflect the most commonly used turbine types in Poland, confirming the representativeness of the sample in terms of technological configuration (Wornalkiewicz, 2024). This finding reinforces the relevance of the results for informing sector-wide strategies. Furthermore, the national plans for the modernisation of 13 hydropower plants to improve their production efficiency, announced in 2020, are in line with the recommendations of this study, which call for targeted financial mechanisms and technological upgrades as key measures to unlock the underutilised potential of SHP in Poland.

As most technically feasible hydropower sites in the region have already been exploited, innovative approaches are needed to expand the sector. Recent studies indicate that existing water infrastructure, such as wastewater treatment plants, can be retrofitted with micro turbines to generate additional renewable

electricity. Tomczyk et al. (2023) demonstrated the feasibility of installing a Francis micro-hydro turbine in a wastewater treatment plant in Toruń. Their results showed a maximum turbine efficiency of approximately 64.8% and an estimated annual energy production of 150 MWh, confirming the potential of wastewater treatment infrastructure as a source of stable renewable energy generation (Tomczyk et al., 2023).

Climate-induced hydrological variability could jeopardise progress towards Poland's 2030 energy targets, reinforcing the need to address managerial, regulatory and financing barriers alongside resource constraints (Kubiak-Wójcicka & Szczęch, 2021). The interviews and literature review highlighted that environmental considerations remain a key factor shaping the development of SHPPs. As emphasised by He et al. (2024), dams and impoundments can fragment habitats and alter river flow regimes, with significant implications for biodiversity. These insights underscore the importance of designing management strategies and regulatory frameworks that reconcile energy production with ecological integrity – an aspect that emerged as relevant in the responses of SHPP operators interviewed in this study (He et al., 2024).

The findings of this study, which highlight the prevalence of continuous monitoring and modernisation planning among SHPP operators, align with recent European research emphasising the need for digitalisation, turbine upgrades and flexible operation modes to enhance system flexibility (Vagnoni et al., 2024). This convergence suggests that targeted investment in technological modernisation, such as variable-speed turbine systems and advanced monitoring tools, could significantly strengthen the contribution of SHP to regional and national energy transitions.

EU 2030 scenarios indicate that hydropower will meet over 30% of flexibility needs across all time horizons, yet hydropower currently attracts only 0.7% of EU RES funding, highlighting a structural financing gap for modernisation and flexibility-enabling upgrades (Vagnoni et al., 2024). The institutional

and economic barriers identified in the Kuyavian-Pomeranian Voivodeship – especially lengthy permitting procedures and the absence of dedicated financial mechanisms – mirror these Europe-wide challenges. Addressing such barriers is thus crucial not only at the regional level but also for achieving EU-wide climate and energy transition targets.

These findings are consistent with broader European research emphasising that unlocking the potential of small hydropower requires coordinated regulatory, financial, and technological measures (Godyń & Dubel, 2021; Vagnoni et al., 2024). By aligning with these trends, the present study reinforces the view that regional actions can contribute meaningfully to national and EU energy transition objectives.

This study is not without its limitations. First, the sample size was relatively small, comprising three respondents responsible for eight SHPPs, representing approximately 10% of the installed small hydropower capacity in the Kuyavian-Pomeranian Voivodeship. Although purposive sampling ensured diversity in plant size, technical characteristics and ownership structures, the findings cannot be generalised statistically to all SHPPs in Poland.

Second, the analysis relied on self-reported information gathered through semi-structured interviews and a questionnaire, which may be subject to recall bias or subjective interpretation by respondents. However, this limitation was partly mitigated by cross-checking responses against secondary data obtained from the Energy Regulatory Office and other official sources.

Finally, the focus on a single region limits the external validity of the results, although the Kuyavian-Pomeranian Voivodeship is considered representative of other lowland areas with similar geographical, institutional and regulatory conditions. The results should therefore be regarded as indicative and exploratory, providing a foundation for further research based on a larger and more diversified sample of SHPPs across Poland and Central Europe.

CONCLUSIONS

This study has successfully achieved its four research objectives. By combining statistical data with qualitative evidence from interviews and questionnaires, the research provides an integrated picture of the socio-economic and institutional factors shaping the development of small hydropower in the region.

In relation to the first research question, the analysis revealed that institutional and administrative barriers, such as lengthy and complex permitting procedures, together with economic constraints, particularly high capital costs and limited profitability, are the dominant obstacles to SHP development. Resource- and technology-related limitations were found to be of secondary importance. Regarding second research question, the study showed that operators rely on defensive–adaptive management practices, including continuous remote monitoring, preventive maintenance, efficiency-oriented modernisation, and flexible operational planning under hydrological variability. These measures help ensure operational stability but cannot remove the external institutional and economic constraints that limit sector growth.

Addressing third research question, the findings confirm that SHP can contribute to the regional and national energy transition, especially by improving local system stability and complementing water resource management. However, this potential can only be fully realised if regulatory frameworks are streamlined and financial incentives for refurbishment and modernisation are strengthened. In response to fourth research question, the case study provides insights relevant to other lowland regions with similar institutional and environmental settings in Central and Eastern Europe, making the results a useful reference point for comparative analyses and policy development.

The findings also validate most of the stated hypotheses. First hypothesis is confirmed, as institutional and economic barriers – such as lengthy permitting procedures, high capital costs, and low

profitability – emerged as the most significant constraints on SHP development, outweighing technical or resource-related limitations. Second hypothesis also finds qualitative confirmation: operators apply good management practices, including remote monitoring, preventive maintenance, and targeted modernisation, which improve operational stability and plant efficiency, yet cannot fully overcome systemic obstacles. Third hypothesis is supported by evidence that SHP can contribute to the regional and national energy transition by improving grid stability and complementing water management functions, though its impact remains contingent on regulatory simplification and financial support mechanisms. Finally, the last hypothesis appears plausible, as the barriers and practices identified in the Kuyavian-Pomeranian Voivodeship reflect challenges reported in other lowland European regions, suggesting that the findings are transferable and relevant for policy design at a broader, Central and Eastern European scale.

The findings of this study highlight the need for systemic measures to unlock the potential of small hydropower in the Kuyavian-Pomeranian Voivodeship. Key priorities include simplifying administrative procedures, establishing stable and targeted financial support for SHPPs modernisation, and improving the coherence of legal and regulatory frameworks. Strengthening management standards and fostering collaboration between plant operators, policymakers and local communities are equally important to enhance efficiency, investment attractiveness and public acceptance. These general priorities are translated below into a set of concrete, evidence-based recommendations.

Based on the insights from the structured interviews with SHPPs managers, highlighting barriers such as high investment costs, administrative delays, and limited financing, alongside good practices like remote monitoring, as well as the scientific discussion grounded in the literature review, the following recommendations have been formulated to address these challenges and enhance sector sustainability. These proposals integrate empirical findings from the interviews with established research, aiming to

mitigate constraints and build on identified strengths for effective policy and managerial action.

- a. **Introduce Dedicated Funding Schemes for Upgrading Existing Facilities:** Establish a grant programme subsidising up to 70% of costs for variable speed operation technologies in SHPPs, potentially enhancing energy efficiency by 15–20% and reducing payback periods to under 5 years, as modelled by Borkowski and Majdak (2020). This directly mitigates the financial barriers reported by managers, facilitating technological modernisation amid variable hydrological conditions.
- b. **Mandate Integration of SHPPs with Local Smart Grids:** Require new permits to include connections to digital monitoring systems for energy recovery from water networks (e.g., via pumps as turbines, PAT), which could elevate the renewable share in regional energy mixes by 10%, aligning with Fecarotta et al. (2014). Interviewees' emphasis on low profitability and hybridisation potential supports this, promoting operational stability.
- c. **Launch Educational and Participatory Campaigns for Local Communities:** Implement mandatory municipal programmes with at least two annual workshops on SHPP benefits for water retention and biodiversity, potentially halving social opposition and boosting project acceptance, inspired by Noda et al. (2020). This responds to managers' observations of neutral community attitudes but challenges in expansions, enhancing local engagement.
- d. **Develop a Centralised Database of Potential SHPP Sites:** Create a publicly accessible digital platform mapping existing hydrotechnical structures, reducing investment preparation time by 40% through identification of low-impact sites, as suggested by Lange et al. (2018). Respondents' frustration with procedural hurdles reinforces the need for such a tool to streamline site selection.
- e. **Incentivise Hybridisation of SHPPs with Other Renewables:** Offer tax reliefs covering up to 30% of costs for integrations with photovoltaics or wind, potentially improving energy stability by 25% and profitability under fluctuating flows, based on

Pang et al. (2018). This addresses interviewees' interest in diversification to counter hydrological variability and economic challenges.

These recommendations, rooted in empirical findings, provide a roadmap for policymakers and practitioners to overcome barriers and amplify SHPP contributions to Poland's green energy transition. Further pilot implementations and evaluations are warranted to assess their efficacy.

Finally, this research contributes to the academic discourse by filling an important gap in the literature concerning the socio-economic and institutional dimensions of SHPPs operations in Poland. Future studies could expand on these findings by including a larger sample of plants, conducting longitudinal analyses, and exploring innovative financing to unlock the untapped potential of small hydropower in the energy transition. Investigating the technical and economic feasibility of hybrid systems that combine SHPPs with photovoltaics, wind power, or energy storage would provide valuable insights into their potential to enhance grid flexibility and resilience. Finally, investigating integrated business models that combine energy generation with water retention services, drought mitigation, and biodiversity enhancement could strengthen the case for supporting SHP development within public policy frameworks.

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