

Article

Analysis of Demand-Driven Operation in an Existing Biogas Plant Under Polish Electricity Market Conditions

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Abstract

This study addresses the increasing need for flexibility in the Polish Power System (PPS), particularly in the context of growing price volatility on the Day-Ahead Market (DAM) resulting from the rising share of renewable energy sources (RESs). The aim of the study was to assess the feasibility of implementing demand-driven operation in an existing linear biogas plant in Poland and to develop a Decision-Making Model (DMM) for optimizing its operation based on electricity price forecasts. A machine learning model based on Extreme Gradient Boosting (XGBoost) was developed using historical electricity price, demand and weather data and integrated into the DMM to generate hourly operating schedules. The model achieved high predictive accuracy, with a Mean Absolute Error (MAE) of approximately 51 PLN/MWh, and effectively captured nonlinear price dynamics. Based on predefined decision thresholds—biogas production rate, current biogas storage level, upper and lower limits of pressure in biogas storage capacity, maximum biogas storage duration, power quotient (PQ) and electricity price levels—optimal operating strategies were determined. The results indicate that while demand-driven operation is technically feasible and enables better alignment with market signals, its economic viability remains limited under current market and regulatory conditions. Investment in additional cogeneration capacity was not justified, as costs significantly exceeded potential revenues. Consequently, a more viable approach involves optimizing existing infrastructure through flexible production strategies.



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1. Introduction

RESs are a key tool for mitigating climate change and enabling the production of low-cost energy, which is essential for maintaining economic competitiveness. In European Union (EU) countries, a major catalyst accelerating the energy transition was the introduction of the EU Emissions Trading Scheme (ETS) in 2005, which imposed additional fees on

energy production from high-emission fuels. Consequently, this led to increased energy costs for end consumers in countries largely dependent on fossil fuels, such as Poland [1,2].

To protect consumers and maintain the competitiveness of energy-intensive industries, a large-scale energy transition is necessary, with one of its key elements being an increase in renewable energy production [3]. Among renewable technologies, photovoltaic (PV) installations represent one of the most cost-effective solutions. In 2025, 4.8 GW of new capacity was connected to the PPS, meaning that, for another consecutive year, this was the fastest-growing renewable energy technology in the country [4]. When combined with the installed capacity of onshore wind farms, the system currently has over 37 GW of capacity from variable renewable energy sources (VRESs), with total national demand averaging 23.2 GW [5]. Therefore, the expansion of RESs in Poland should be considered part of a broader energy transition process that also requires the development of complementary technologies, including energy storage, smart metering, and energy management systems [6].

1.1. Impacts of VRESs on PPS

With the rapid growth of VRESs, the problem of balancing the PPS is becoming more acute due to the dependence of these sources on weather conditions and the high variability of generation. The limited controllability of these sources requires maintaining larger reserves of regulating power and more frequent interventions by Transmission System Operators [7]. Curtailment is becoming an increasingly common phenomenon, occurring when wind and solar generation coincide, and system load and export capabilities cannot absorb all active power [8]. While some curtailment is expected and inevitable, persistent or widespread curtailment leads to the loss of significant amounts of energy [9]. For instance, during the seven-day period ending on 21 April 2025 (Easter Monday), Polish Transmission System Operator curtailed 77.5 GWh of renewable generation, exceeding the total curtailment for 2023 and representing more than 10% of the full-year amount in 2024 [5].

Energy storage facilities are the primary solution for reducing losses and the risk of curtailment [10]. In 2024, their capacity in Poland amounted to 8 GWh, of which over 90% consisted of pumped-storage power plants, with the remainder being battery storage systems [4]. Given the estimated demand of approximately 20 GWh, there is a significant infrastructure gap and an urgent need for further technological development and cost reduction [11]. The so-called “duck curve effect” is also being observed with increasing frequency; this phenomenon reflects a drop in electricity prices during periods of high PV generation and a sharp rise in prices in the evening, as solar output naturally declines [12]. The continued growth of PV capacity exacerbates the duck curve effect and increases the occurrence of negative prices, which directly impacts the profitability of all renewable energy installations, because under an amendment to the Renewable Energy Act of 27 November 2024, producers lose eligibility for support mechanisms during periods of negative electricity prices [13,14].

1.2. The Role of Biogas Plants in Stabilizing the PPS

In light of the growing challenges faced by participants in the PPS (distribution and transmission operators, regulators, generators, and consumers), biogas may play a key role in the coming years, as it is the only renewable energy source that is fully independent of the time of day, weather conditions, or seasonality [15]. Biogas plants can operate both during base load and peak-load periods, stabilizing the system by producing electricity primarily during periods of high demand, while reducing or suspending production during periods of lower demand.

The anaerobic digestion process in demand-driven biogas plants does not differ significantly from that in standard facilities; however, the differences concern the method of electricity generation. Of key importance are the biogas storage system, which allows biogas to be stored while the cogeneration unit is idle, and the heat storage system, which ensures stable process conditions and enables the rapid restart of the plant. It is also necessary to increase the capacity of the combined heat and power (CHP) engine and the biogas transmission infrastructure [16,17]. The overall energy efficiency of biogas production systems is strongly influenced by substrate characteristics and pretreatment methods, which determine methane yield and the net energy balance of the process [18].

The implementation of demand-driven biogas plants in Poland is possible for both newly developed biogas plants and existing facilities. For new installations, the decision to switch to this operating mode is determined by legislative changes introduced in the second half of 2023. Insufficient availability of free connection capacity, combined with a growing number of refusals to issue connection conditions, led to a revision of the rules for connecting new installations. As a result, the issuance of connection conditions for biogas plants was permitted, subject to the possibility of temporarily restricting their operation (the so-called interruptible grid connection conditions guaranteeing connection capacity for 12 or 14 h per day, issued pursuant to Article 7(3ba) of the Energy Law).

The key element of such conditions is the operating schedule, which specifies the hours during which the biogas plant has guaranteed grid access and the hours during which it may be disconnected from the grid without penalties for the transmission system operator. Consequently, for newly designed installations, the choice of demand-driven operation is not fully autonomous but largely depends on regulatory conditions and market design, which determine the roles of participants and coordination mechanisms within the power system [19].

Due to the lack of reference installations that would allow for the assessment of actual operating parameters, many investors, upon receiving such connection terms, decide to abandon the project. The modernization of existing facilities and their transition from continuous (linear) operation to demand-driven mode could serve as a potential catalyst for the development of demand-driven biogas plants. However, the implementation of such a solution is contingent upon demonstrating its economic viability.

1.3. Support Systems for Electricity Production from Biogas Plants

In Poland, facilities utilizing agricultural biogas, regardless of their operating mode, are classified as RES installations under the RES Act, which allows them to benefit from support schemes based on fixed electricity prices. The relevant literature has already provided a detailed analysis of the subjective and objective eligibility criteria for access to these support mechanisms, as well as of the procedures enabling renewable electricity producers to benefit from this form of state aid [20]. Producers planning to build an agricultural biogas plant must complete a prequalification procedure conducted by the President of the Energy Regulatory Office (ERO) to obtain a certificate allowing participation in the Feed-in Tariff (FIT) or Feed-in Premium (FIP) support scheme. Unlike the auction system, FIT/FIP operates on a continuous basis, enabling investors to apply at any time without waiting for a specific auction date.

To initiate the procedure, the producer must submit a declaration of intent to sell unused electricity and provide key documents, including a valid building permit and grid connection conditions or a grid connection agreement. Both documents must remain valid for at least six months at the time of submission. Starting the FIT/FIP procedure also triggers the indexation of the reserved reference price in line with inflation. The President of ERO may refuse access to the support scheme only if formal requirements are not met or if

statutory capacity limits for a given renewable technology have been exhausted. Currently, no such capacity limits have been introduced, allowing investors to continue applying for this RES support system. Compared with the renewable energy auction system, FIT/FIP mechanisms are less restrictive. Producers are not required to achieve a specific level of electricity generation; support depends solely on the actual amount of electricity sold. The main obligation is to commence electricity production within the statutory deadline. Failure to do so results in the loss of the reservation fee of PLN 30 per kW of installed capacity.

In the context of the present discussion, however, particular attention should be paid to the issue of whether electricity generated by so-called demand-driven biogas plants may be sold under the support schemes available to them that are based on a fixed purchase price. Installations with installed capacity of less than 200 kW can choose between the FIT and FIP scheme, while only the FIP system is available for larger units.

Under the FIT system, the obligated buyer has a statutory obligation to purchase a specified amount of electricity generated by the facility at a fixed purchase price set administratively, calculated in accordance with the formula specified by the Act. The price level, expressed in PLN per MWh, is independent of the timing of energy sales. This means that the plant's operating model (linear or demand-driven) does not affect unit revenue, and consequently, there is no economic incentive for shaping the production profile based on price signals from the energy market.

The FIP system operates differently and allows renewable energy producers to sell electricity on the market at negotiated market prices while also receiving a premium payment through the negative balance settlement mechanism. When calculating the premium, the negative balance coverage ratio must also be taken into account. This ratio amounts to 95% for installations with a capacity of up to 499 kW and 90% for installations exceeding this threshold. Under this system, producers generate revenue from two sources:

- Market-based electricity sales to a chosen buyer, typically settled based on DAM prices, in particular the Fixing I index;
- A public support payment (premium) that is 95% or 90% of the difference between the reference price determined under the RES Act and the average price published on DAM according to the TGeBase index.

Importantly, the premium is calculated using the average market price index rather than the producer's actual contract price. As a result, producers can increase their overall revenues by negotiating favorable electricity sales agreements and responding to market price signals, for example by generating more electricity during periods of high demand. The negative balance settlement is administered by Zarządca Rozliczeń S.A., a state-owned company acting as the Renewable Energy Settlement Operator (OREO). Premium payments are financed through the renewable energy surcharge collected from electricity consumers. To receive support, the producer must first conclude a commercial electricity sales agreement, since only sold electricity is eligible for the FIP mechanism. The producer may freely choose the purchaser and negotiate contractual terms, including price and payment conditions. Applications for negative balance settlements are submitted monthly, and the support payment is made within 30 days of filing the claim.

In practical terms, the FIP system provides renewable energy producers with two revenue streams—market revenues from electricity sales and an additional premium paid by the OREO, helping to ensure a stable and predictable level of income.

1.4. Impact of Electricity Market Price Volatility on Biogas Plant Operation

The Polish Power Exchange (PPE) is a key, organized platform for electricity trading in Poland, where market participants conduct transactions in a transparent manner and in compliance with applicable legal regulations [21]. The PPE comprises several market

segments, one of the most important being the DAM. Electricity trading on the DAM takes place on the day preceding the day of physical delivery. This means that sellers must estimate, as accurately as possible, the amount of electricity they will be able to supply to the system one day in advance, and then submit price and volume bids. Each day is divided into 24 hourly trading sessions (billing periods) during which PPE members can buy and sell electricity [22]. Two price indices are particularly important in the context of biogas plants participating in the FIP scheme. Fixing I index is typically used as the reference price in electricity sales contracts between renewable energy producers and chosen buyers, and the TGeBase index serves as the reference price in the FIP scheme. Quotations for the Fixing I index are published daily at 10:30 a.m., while the TGeBase index is published at approximately 3:00 p.m. Prices quoted on the PPE are subject to significant fluctuations. The energy mix—including the share of weather-dependent RESs—plays a particularly important role, causing a marked widening of the price gap during morning and evening peak-demand periods [23,24]. Under these conditions, demand-driven biogas plants have the opportunity to generate additional revenue by selling electricity at higher prices during specific hours—taking advantage of the so-called profile premium. Instead of producing during periods of low or negative prices, it is possible to store biogas and intensify generation during more profitable hours, while simultaneously utilizing the negative balance mechanism.

1.5. Aim of the Study

Despite the growing importance of flexible biogas plant operation, limited research has examined the economic feasibility of implementing such solutions under the Polish electricity market conditions. The aim of this study was to assess the feasibility of implementing demand-driven operation in an existing biogas plant in Poland and to develop a DMM capable of determining optimal operating schedules for the biogas plant based on electricity price forecasts, considering defined decision thresholds. Furthermore, the study evaluates the profitability of implementing demand-driven operation, based on a comparison of capital expenditures with potential additional revenues resulting from increased electricity generation during periods of high electricity prices and reduced revenue losses during periods of negative prices.

2. Materials and Methods

2.1. Case Study Biogas Plant

The possibility of implementing of demand-driven operation and the developed DMM was analyzed for an agricultural biogas plant with a capacity of 499 kWe/560 kWt, located in Śniaty village in west-central Poland, shown in Figure 1.

The selection of this biogas plant was motivated by the fact that it represents a typical agricultural biogas installation operating in Poland, in terms of feedstock composition (predominantly animal manure), fermentation technology (wet anaerobic digestion), and installed electrical capacity (499 kW).

The biogas plant was commissioned in 2024 as an auxiliary installation for a dairy farm. It was constructed using Polish technology, in which the digestate tanks are integrated with a biogas storage system in the form of membrane domes. From there, after passing through a treatment station, the gas is directed to a CHP unit. The plant is equipped with a monitoring and control system comprising sensors installed on individual plant components. These sensors enable continuous measurement of key parameters, including biogas production, tank fill levels, CHP operating time, and electricity generation. Selected parameters are monitored in real time using a Siemens PLC controller and the IXON remote access system, and are also transmitted to a dedicated cloud, where they are analyzed

and archived. Access to these operational data was essential for determining the decision thresholds used in the DMM.



Figure 1. Śniaty agricultural biogas plant (499 kW of electric power) (source: Dynamic Biogas Energy company).

The analysis of the potential implementation of the DMM in the Śniaty biogas plant was motivated by the fact that the installation operates under the FIP support scheme, creating opportunities to increase revenues through more flexible electricity generation. An additional factor was the concluded electricity sales contract, under which electricity generated during periods of negative market prices adversely affects the overall monthly settlement. Consequently, electricity sold to the grid during such periods reduces the monthly revenue of the biogas plant. The biogas plant in Śniaty, similarly to many agricultural biogas plants in Poland, is operated either directly by the farmer managing the livestock farm or by farm employees whose primary responsibilities are related to agricultural production. As a result, biogas plant operators often have limited time to continuously monitor electricity market prices and respond rapidly to changing market conditions. This restricts their ability to optimize plant operation manually and creates a practical need for the implementation of the DMM.

2.2. Definition of Decision Thresholds

The definition of decision thresholds is a key component of the proposed DMM. Although the specific threshold values were determined for the Śniaty biogas plant, the procedure used to define these thresholds is universal and can be applied to other installations [25].

The first parameter considered in the DMM is the biogas production rate, which is routinely monitored in every biogas plant. Modern biogas analyzers measure both the volume of biogas produced and its composition, particularly methane and carbon dioxide concentrations [26]. Biogas production depends on the type and quantity of substrate supplied to the installation and reflects the current state of the process. Variations in feedstock composition or feeding intensity influence biogas yield and consequently affect the amount of biogas available for storage and energy conversion. For this reason, the biogas production rate serves as a primary input variable in the DMM and provides the basis for establishing subsequent operational thresholds.

The current biogas storage level determines whether the CHP unit can be temporarily shut down at a given time. This parameter may be assessed using various measurement techniques; however, at the Śniaty biogas plant, ultrasonic level measurement was selected as the most suitable method. The approach is based on measuring the distance between the outer and inner membranes of the double-membrane dome, providing information on both the volume of biogas currently stored and the remaining storage capacity [27].

Another decision threshold affecting the safe operation of the DMM is the definition of the upper and lower pressure limits in the biogas storage system. These limits are established on the basis of pressure measurements obtained from a sensor installed in the gas space of the digestate tank. When the maximum permissible pressure is reached, an alarm signal is generated, and the valve supplying biogas to the digestate tank is automatically closed. At the same time, the control system continuously monitors the minimum allowable pressure and prevents it from falling below a predefined value. Excessive vacuum conditions could lead to inward deformation of the digestate tank.

To estimate the biogas storage duration, it was necessary to determine the maximum biogas storage capacity. This parameter represents the largest volume of biogas that can be stored within the installation. Like current biogas storage, it may be estimated using different approaches. In the Śniaty biogas plant, this value was determined according to the following equation:

$$V_{\text{total}} = \frac{\pi h_{\text{dome}}^2}{3} (3r - h_{\text{dome}}) \quad (1)$$

where

V_{total} = total biogas storage volume [m^3];

r = radius of the digestate tanks [m];

h_{dome} = the height of the dome above the digestate tanks when it is completely full [m].

Another decision threshold is represented by the PQ, defined as the ratio of installed peak generation capacity to the nominal capacity of the existing CHP unit. It is an important technical and economic indicator used to evaluate the operational flexibility of biogas plants and the scale of additional generation capacity required for demand-driven operation [28].

Since the primary objective of the DMM is to adapt biogas plant operation to electricity market conditions, the final set of decision thresholds was established by defining electricity price ranges based on the DAM Fixing I index and assigning appropriate operational actions to each range:

Range 1—Suspend electricity generation

As the Śniaty biogas plant was commissioned before the amendment to the RES Act of 27 November 2024 came into force, electricity generated during periods of negative prices is excluded from the FIP support mechanism only if negative TGeBase prices persist for at least six consecutive hours. In contrast, under the existing electricity sales contract, electricity generated during periods of negative Fixing I prices adversely affects the settlement outcome. Therefore, a single hour with a negative Fixing I price is identified by the DMM as potentially unfavorable for electricity generation. However, the decision to suspend electricity generation is based on the overall 24 h forecasted electricity price profile and remaining decision thresholds.

Range 2—Increase electricity generation

To maximize the economic performance of the demand-driven biogas plant, it was assumed that previously stored biogas would be utilized only during periods when the DAM electricity price exceeded the reference price applicable under the FIP support scheme. For the purposes of the DMM, the reference price was adjusted to account for both the

negative balance coverage ratio and the annual indexation applied from the date on which the Śniaty biogas plant entered the FIP support scheme.

Range 3—Maintain continuous operation

When the Fixing I electricity price remains below the adjusted reference price but is not negative, no economic incentive exists to modify the generation profile, as the difference between the market price and the reference price is compensated through the FIP system. Consequently, the model assumes continuous operation, with the additional CHP unit remaining turned off.

2.3. Development of DMM

The DMM was developed as a decision-support tool for demand-driven operation of agricultural biogas plants. The model integrates electricity price forecasting with predefined decision thresholds, and based on these inputs, identifies the time periods in which electricity generation is expected to be economically favorable or unfavorable. In practical operation, the DMM is intended to support biogas plant operators by providing short-term, data-driven schedules that determine when the plant should SELL (burn gas) or HOLD (store gas) for each hour over the next 24 h. Before the schedule is transmitted to the Plant Control Node, it must be approved by the operator [29]. The operation of the model is captured in Figure 2. The initial version of the DMM architecture and the diagrams below were created using GenAI.

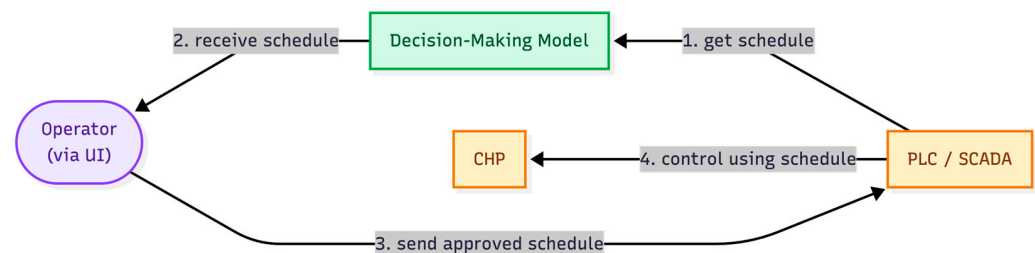


Figure 2. DMM operation diagram.

Description of the DMM cycle:

- Step 1. The Plant Control Node sends a request to the DMM asking for the next 24 h SELL/HOLD schedule. The request should be submitted shortly after the publication of the DAM prices, including the Fixing I and TGBase indices, typically between 1:00 p.m. and 1:30 p.m.
- Step 2. The DMM runs the XGBoost model against the latest market and weather features and returns a 24 h price forecast. The DMM applies decision thresholds to translate each predicted hourly price into a SELL or HOLD recommendation, producing a draft schedule.
- Step 3. The DMM pushes the draft schedule to the biogas plant operator through a visual interface. The biogas plant operator inspects the draft—seeing predicted prices, recommended actions, and any flagged hours (e.g., predicted negative prices). The operator either approves the schedule as is or overrides individual hours before confirming.
- Step 4. The PLC receives the confirmed 24 h schedule and begins executing it—controlling the gas storage and power generation unit to burn or store gas hour by hour according to the plan.

To ensure that the developed forecasting model used in the DMM remains reliable and accurate over time, Machine Learning Operations (MLOps) practices will be imple-

mented to support continuous model monitoring and retraining. Figure 3 captures the full MLOps lifecycle.

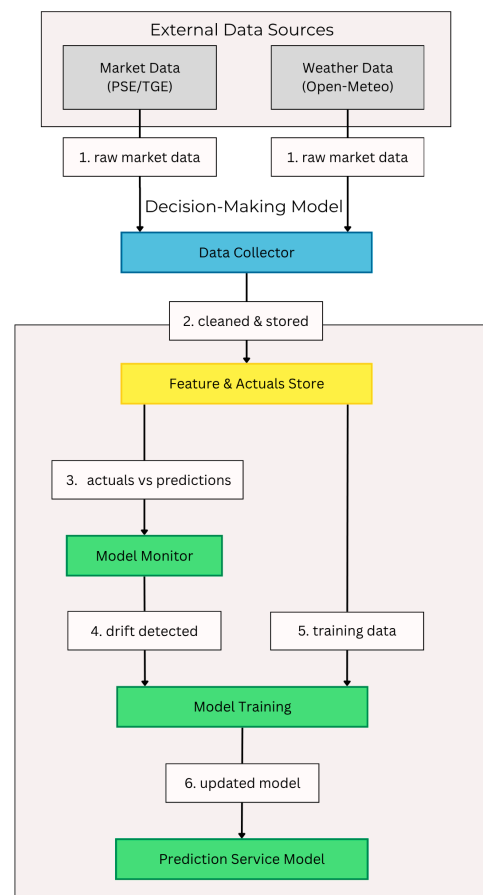


Figure 3. Model retraining flow.

The flow begins when the Data Collector pulls raw market data from the Polish Transmission System Operator and PPE and weather data from Open-Meteo on a fixed schedule (1). The collected data are cleaned and written into the Feature & Actuals Store, which also receives actual settlement prices published daily by the Polish Transmission System Operator and PPE (2). From there, the Model Monitor reads both stored predictions and actuals to measure how accurate the model has been (3). When accuracy drops below an acceptable threshold, the monitor triggers retraining (4). Model Training then reads the full historical dataset from the store (5) and produces a new model version, which is deployed to replace the Prediction Service (6).

2.4. Machine Learning Model for Hourly Electricity Price Forecasting

The operation of the DMM relies on electricity price forecasts. Therefore, it was necessary to develop a machine learning model for hourly electricity price prediction to provide the DAM forecasts required by the DMM for the Polish electricity market. The development, training, and visualization of results were carried out in Python 3.9 (Python Software Foundation, Wilmington, DE, USA) using the Pandas (v2.2.2), Scikit-learn (v1.8.0), XGBoost (v3.2.0), and Matplotlib (v3.10.0) libraries, with Extreme Gradient Boosting (XGBoost) as the core algorithm.

Recent studies have expanded machine learning applications in flexible renewable energy systems, including energy management and electricity price forecasting. These approaches aim to improve system efficiency and operational flexibility [30].

XGBoost was selected because electricity price forecasting in modern electricity markets with high renewable energy penetration and frequent price spikes constitutes a highly nonlinear, non-stationary, and feature-rich regression problem. Unlike the persistence model, also referred to as the naïve forecast, XGBoost does not merely replicate historical price trajectories but can capture complex interactions among multiple explanatory variables [31–33].

In contrast to a linear regression model, XGBoost is capable of modeling nonlinear relationships and higher-order interactions without requiring the explicit specification of a functional form [34]. Electricity prices often exhibit asymmetric responses, threshold effects, and regime-switching behavior, particularly during periods of supply scarcity and high renewable generation variability. Consequently, purely linear approaches may be insufficient for accurately representing electricity market dynamics [35,36].

Traditional statistical approaches, such as ARIMA and SARIMA, are effective for modeling autocorrelation and seasonality. However, they generally assume a relatively stable time-series structure and are less suitable for incorporating a large number of exogenous predictors, which are often relevant in electricity price forecasting applications [37,38].

Relative to Random Forest, XGBoost employs a sequential gradient boosting framework rather than independent bagging. Each successive tree is trained to reduce the residual errors generated by the existing ensemble, which may improve the representation of complex observations, including electricity price spikes. In addition, regularization, learning-rate shrinkage, subsampling, and tree-depth control contribute to improved generalization and reduced overfitting [39].

LightGBM and CatBoost represent strong alternative gradient boosting frameworks. LightGBM may offer superior computational efficiency for very large datasets owing to its histogram-based learning algorithm and leaf-wise tree growth strategy [40]. CatBoost can provide advantages when categorical variables constitute a substantial portion of the predictor set because of its native handling of categorical features. Nevertheless, for structured electricity market datasets composed predominantly of numerical variables, XGBoost has been widely adopted and has demonstrated competitive forecasting performance [41].

The baseline dataset included historical DAM prices from 1 July 2024 to 31 August 2025 (data collected from PPE), electricity consumption volumes (data collected from the Polish Transmission System Operator) and weather data including wind speed, solar generation and temperature (data collected from Free Weather API). To improve model accuracy, 20 features were created, as detailed in Table 1.

Strict validation procedure: To avoid data leakage and simulate real trading conditions, a strict sample split was applied. The model was trained on data from the 8th to the last day of each month, and tested “blindly” on the most difficult period—the first week (1st–7th) of the following months.

Hyperparameter optimization: Hyperparameter optimization was performed via ‘RandomizedSearchCV’ using ‘TimeSeriesSplit’.

Cross-validation was set up for ‘TimeSeriesSplit’ (`n_splits = 3`). The parameters grid for ‘RandomizedSearchCV’ was as follows: (`‘n_estimators’`: [100, 300, 500, 800], `‘max_depth’`: [4, 6, 8, 10], `‘learning_rate’`: [0.01, 0.05, 0.1, 0.2], `‘subsample’`: [0.7, 0.8, 0.9, 1.0], `‘colsample_bytree’`: [0.7, 0.8, 0.9, 1.0]), with settings (`n_iter = 20`, `scoring = ‘neg_mean_absolute_error’`, `random_state = 42`).

The best combination of hyperparameters was: (`‘subsample’`: 0.7, `‘n_estimators’`: 500, `‘max_depth’`: 6, `‘learning_rate’`: 0.01, `‘colsample_bytree’`: 0.8).

A conservative learning strategy was chosen (`‘learning_rate = 0.01’`, `‘n_estimators = 500’`) with powerful regularization (`‘subsample = 0.7’`, `‘colsample_bytree = 0.8’`), which protected the model from overfitting.

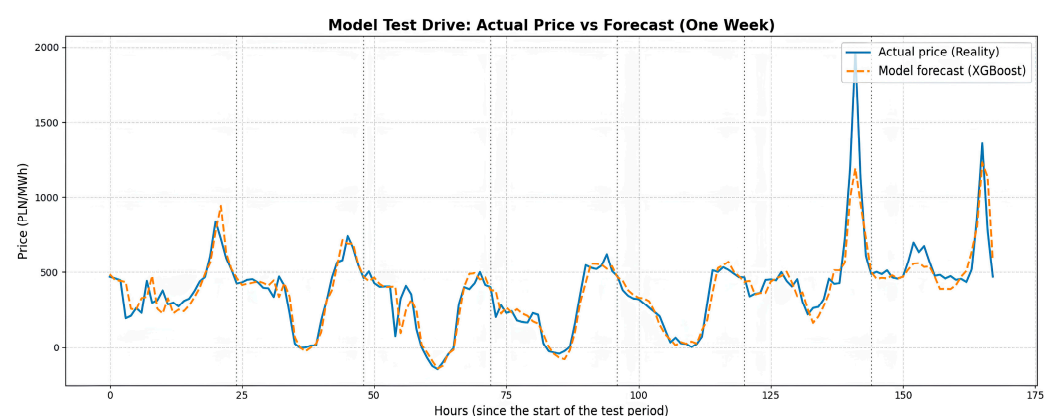
Table 1. Summary of features used in the analysis.

Symbol of Feature	Explanation of Feature
price_lag_1h	The electricity price from DAM from one hour ago
demand	Electricity consumption volumes
weighted_temperature	Spatial averaging where temperature data from different geographic locations are prioritized based on their specific impact on the national energy system.
price_lag_24h	The electricity price from DAM from 24 h ago
wind_generation	The actual volume of electricity produced by wind power plants and supplied to the national power grid during a specific hour
hour	Hour of the day
solar_drop	The domain-specific metric that calculates the rate of decline in solar power generation, described as “sunset speed”
day_of_month	Day of the month
demand_lag_24h	The electricity consumption volumes from 24 h ago
price_roll_mean_6h	The 6 h rolling average (moving average) of electricity prices
weighted_solar_rad	Spatial averaging where solar radiation data from different geographic locations are prioritized based on their specific impact on the national energy system.
price_roll_mean_3h	The 3 h rolling average (moving average) of electricity prices
month	Month of the year
wind_lag_1h	The wind generation from one hour ago
price_roll_mean_24h	The 24 h rolling average (moving average) of the electricity price
demand_lag_1h	The electricity consumption volumes from one hour ago
demand_roll_mean_3h	The 3 h rolling average (moving average) of the electricity consumption volumes
solar_lag_1h	The solar generation from one hour ago
solar_generation	The actual volume of electricity produced by solar power plants and supplied to the national power grid during a specific hour
solar_roll_mean_3h	The 3 h rolling average (moving average) of solar generation

3. Results and Discussion

3.1. Feature Importance and Model Performance

Although electricity price forecasting constitutes a component of the proposed DMM, the performance of the machine learning model was evaluated as the first stage of the analysis because it directly affects all subsequent operational decisions generated by the framework. All economic results were expressed in Polish złoty (PLN). For reference, the average exchange rate during the analyzed period was 1 EUR = 4.25 PLN. Figure 4 illustrates the ability of the XGBoost model to reproduce the complex dynamics of the DAM during a one-week test period (168 h).

**Figure 4.** Model test drive: Actual price versus forecast (one-week trial).

The predicted curve (orange dashed line) closely follows the observed market prices (blue solid line) during typical daily cycles, including accurate prediction of hours with negative electricity prices. The extreme price shock at the end of the graph, where the real price reached around 2000 PLN/MWh, is illustrative. Although the model conservatively smoothed the amplitude of this jump (stopping at ~1200 PLN/MWh), it captured the

timing and direction of the market movement. This result indicates that the model can provide an effective early warning signal for market anomalies.

The final Mean Absolute Error (MAE) was 51.37 PLN/MWh, and the Root Mean Square Error (RMSE) was 95.95 PLN/MWh on a complex test sample. The model successfully identified periods characterized by negative electricity prices. These results are consistent with previous studies conducted by Manfre Jaimes [42], Song et al. [43] and Kraska and Hanzel [44], in which XGBoost also showed strong performance.

The obtained results confirm the suitability of XGBoost as the core forecasting algorithm for several reasons:

- Ability to capture nonlinear relationships: Electricity prices often respond to explanatory variables in a nonlinear manner. For example, a temperature change from +20 °C to +25 °C has almost no effect on the price, but a jump from +25 °C to +30 °C causes a widespread turn-on of air conditioning and a sharp jump in demand. Tree-based algorithms such as XGBoost effectively identify and model such nonlinear effects without requiring explicit specification of the functional form.
- Strong performance on structured data: For structured data, where there is a mix of physical quantities, prices and calendar features such as hour or month, gradient boosting has historically demonstrated strong predictive performance.
- Robustness to extreme market events: The Polish electricity market is characterized by occasional extreme price spikes and negative prices (from −860 to +2700 PLN). A regular regression model would perform poorly when trying to adjust to these anomalies. Although XGBoost tends to smooth the magnitude of extreme price spikes, it captured the timing and direction of the market movement, which is sufficient for supporting the proposed DMM.
- Model interpretability (Feature Importance): XGBoost provides transparent feature importance metrics, allowing the contribution of individual predictors to be quantified. This helps verify that the model relies on physically meaningful drivers of electricity prices, including renewable generation, electricity demand, and weather conditions.

Based on the provided research material, Figure 5 presents the results of the feature sensitivity analysis for the variables included in the XGBoost model.

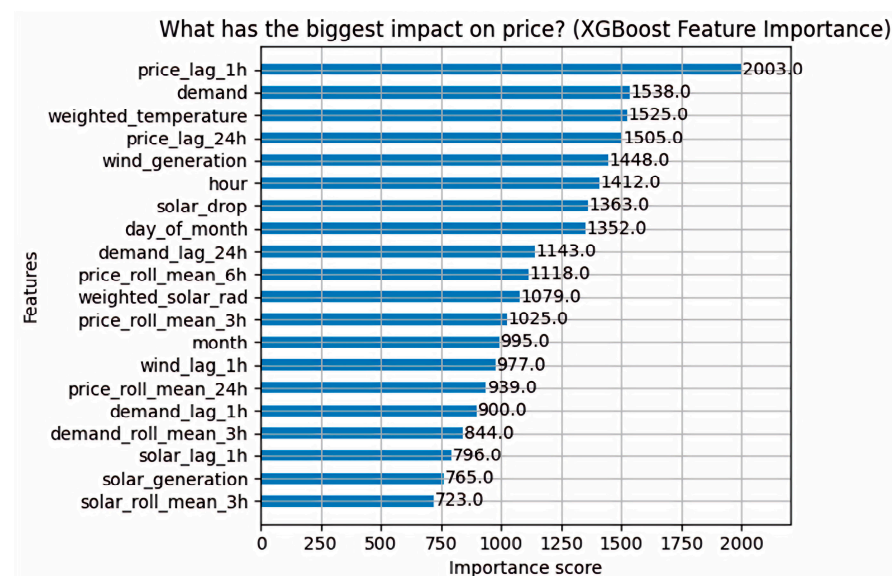


Figure 5. Sensitivity analysis of parameters in the tested model.

Feature importance analysis indicates that price inertia is the dominant factor. The price lag from the previous hour (price_lag_1h) achieved the highest score (2003), while the daily lag (price_lag_24h) ranked among the top features (1505).

3.2. Decision Threshold Values

Based on operational data collected in 2025, biogas production at the Śniaty biogas plant varied significantly between individual hours, primarily due to fluctuations in substrate availability and the absence of advanced biotechnological process control. To align the analysis with the performance of comparable agricultural biogas plants utilizing the same technology and to ensure a conservative assessment of storage requirements, a biogas production rate of 232 m³/h was adopted for further analyses. This value corresponds to the maximum biogas production rate recorded in 2025.

Considering the maximum storage capacity of 1417.84 m³, the available storage volume corresponds to approximately 6.11 h of biogas storage at the assumed production rate. For the purposes of the subsequent analyses, a biogas storage duration of 6 h was adopted. It should be emphasized that the digestate level in the tank does not affect the available biogas storage capacity. This is because the flexible membrane covering the tank cannot be drawn below the level defined by the tank walls due to the presence of a dedicated supporting mesh. In the Śniaty biogas plant, the biogas storage system is based on a quarter-spherical membrane dome installed above the digestate tank. From a technical perspective, the biogas storage capacity could be increased to approximately 2700 m³ by replacing the existing membrane dome with a hemispherical structure. Such a modification would extend the biogas storage duration from approximately 6 to 12 h and was therefore included as an additional scenario in the subsequent economic analysis.

While the maximum storage capacity is a fixed parameter determined by the physical characteristics of the digestate tank, the current biogas storage level is a dynamic variable that changes continuously over time. Under demand-driven operation, its value would be directly influenced by the operational decisions generated by the DMM. It should be noted that the ultrasonic sensor is not currently installed in the biogas plant in Śniaty; however, its installation is part of the modernization required for the implementation of the DMM.

The upper and lower pressure limits were defined as 5 mbar and 0.5 mbar, respectively, based on the technical constraints of the installation and the safe operating conditions of the biogas storage infrastructure.

To determine an appropriate PQ value, it was first necessary to analyze the relationship between periods of negative electricity prices and periods during which market prices exceeded the adjusted reference price.

An analysis based on DAM prices on the Fixing I index for the years 2023–2025 indicates a significant increase in the occurrence of negative prices over time, with 19, 186, and 330 hourly observations recorded in 2023, 2024, and 2025, respectively. The longest continuous period of negative prices was recorded on 1 January 2025, when the price of electricity remained below 0 PLN/MWh for 16 consecutive hours. However, this event was exceptional and occurred only once during the analyzed period. Most frequently, periods of negative prices lasted 6 consecutive hours (17 instances), followed by 3 and 7 h (13 instances each). In contrast, prices above 1025 PLN/MWh occurred 16, 170, and 116 times, respectively. Unlike negative prices, episodes of high prices were typically short-lived and most often lasted 1 h (55 instances), 2 consecutive hours (37 instances), and 3 consecutive hours (27 instances).

In 2023 and 2024, the number of hours with negative prices was comparable to the number of hours with prices exceeding 1025 PLN/MWh. This suggests that a similar number of hours could be allocated to biogas storage and its subsequent utilization during

periods of elevated electricity prices. Assuming a maximum biogas production rate of $230 \text{ m}^3/\text{h}$, the volume of biogas available for electricity generation during demand-driven periods would be approximately $460 \text{ m}^3/\text{h}$. Such a consumption rate would require a CHP unit with an electrical capacity of approximately 1 MW, corresponding to a PQ value of 2.

Different results were obtained when the 2025 data were considered. In that year, the number of hours with negative electricity prices increased substantially relative to the number of hours with prices exceeding the profitability threshold. Under these conditions, assuming that biogas is accumulated for 6 h and subsequently utilized over a 3 h generation period, the CHP unit would need to process approximately $690 \text{ m}^3/\text{h}$ of biogas. This would require a CHP unit with an electrical capacity of approximately 1.5 MW, corresponding to a PQ value of 3.

Similar PQ ratio values were reported in the study by Hochloff and Braun [45], which found that for a biogas plant operating in demand-driven mode, the optimal cost–benefit ratio is achieved at $\text{PQ} = 1.7$, while the highest revenues from energy sales on the market are observed at $\text{PQ} = 3.3$. In turn, the results presented by Dotzauer [46] indicate that regardless of price signals in the energy market, a PQ ratio of at least 4 allows one to avoid reinvestment in a cogeneration unit over a 20-year horizon. On the other hand, Schröer and Latacz-Lohmann [47] concluded that such high PQ values are associated with substantially higher capital expenditures, thereby reducing their economic attractiveness. Consequently, an intermediate configuration corresponding to a PQ value of approximately 2 may represent a more balanced and economically justified solution.

The final decision threshold involved assigning specific operating states to predefined electricity price ranges on DAM, as follows:

- State 1: If the electricity price is below 0 PLN/MWh, both the primary and the additional CHP units are turned off and biogas is stored.
- State 2: If the electricity price is between 0 and 1008.81 PLN/MWh, only the primary CHP unit is in operation and the biogas plant remains in continuous operation.
- State 3: If the electricity price exceeds 1008.81 PLN/MWh, both CHP units operate, previously stored biogas is utilized, and electricity generation is increased.

The threshold value of 1008.81 PLN/MWh was derived from the reference price guaranteed for the Śniaty biogas plant in 2024 (1025 PLN/MWh). As the economic analysis was conducted using data from 2025, the reference price was adjusted to account for the annual indexation based on the inflation rate reported by Statistics Poland (GUS) for 2024 (3.6%). Subsequently, the negative balance coverage ratio applicable to biogas plants with an installed electrical capacity of up to 499 kW under the FIP support scheme was applied, as shown in the equation below:

$$1025 \text{ PLN} \times 1.036 \times 0.95 = 1008.81 \text{ PLN}$$

3.3. Economic Assessment of Demand-Driven Operation Implementation

To evaluate the profitability of implementing demand-driven operation, an economic analysis was conducted using DAM data from 2025, including both the Fixing I and TGeBase indices.

The analysis assumed a doubling of the electrical capacity ($\text{PQ} = 2$) through the addition of a second CHP unit. Two alternative connection schemes were considered. In the first, the additional CHP unit is connected to the existing transformer station, resulting in a total installed electrical capacity exceeding 499 kW. In the second, the additional CHP unit is connected to a new, separated transformer station.

The distinction between these configurations is particularly relevant under the current Polish support scheme. Exceeding the 499 kW installed capacity reduces the reference

price from 1025 PLN/MWh to 941 PLN/MWh and lowers the negative balance coverage ratio from 95% to 90%. By contrast, connecting the additional CHP unit through a separate transformer station allows the newly installed unit to be classified as a separate renewable energy installation and avoid a reduction in the reference price.

In addition to the CHP configuration, the analysis also examined the influence of biogas storage capacity on the economic performance of demand-driven operation. Therefore, two storage scenarios were considered: the existing storage capacity of the Śniaty biogas plant, enabling biogas accumulation for up to 6 h, and an expanded biogas storage scenario of enabling biogas accumulation for up to 12 h.

The availability factor, representing the annual operational availability of the installation, was included in the analysis because it directly affects electricity production. Based on operating data from the Śniaty biogas plant and other biogas plants built using Dynamic Biogas technology, an annual availability of 95% was assumed for linear operation. For the demand-driven operating mode, an effective availability factor of 100% was assumed for the purposes of the economic analysis, as scheduled maintenance activities can be performed during periods when electricity generation is intentionally halted.

All analyzed variants, together with the parameters adopted for the economic analysis are summarized in Table 2.

Table 2. Adopted parameters for individual variants.

Parameter	Variant 0	Variant 1	Variant 2	Variant 3	Variant 4
Demand-driven operation [-]	no	yes	yes	yes	yes
Number of CHP units [-]	1	2	2	2	2
Installed electrical capacity of CHP units [kW]	499	499 + 499	499 + 499	499 + 499	499 + 499
Number of transformer stations [-]	1	1	1	2	2
Reference price [PLN]	1025	941	941	1025	1025
Negative balance coverage ratio [%]	95	90	90	95	95
Reference price after taking into account inflation for 2024 and negative balance coverage ratio [PLN]	1008.81	877.39	877.39	1008.81	1008.81
Biogas storage time [h]	-	6	12	6	12
Availability per year [%]	0.95	1.00	1.00	1.00	1.00
Annual electricity production [MWh]	4153	4371	4371	4371	4371

As described in Section 1.3, the annual revenue of the Śniaty biogas plant operating under the FIP support scheme consists of two components: revenues from electricity sales and payments received through the negative balance settlement mechanism. Consequently, the total revenue can be calculated as follows:

$$R = (P_{\text{Fixing I}} - M) \times Q_h + N \times (P_r - P_{\text{Tgebase}}) \times Q_d$$

where:

R—annual revenue [PLN];

$P_{\text{(Fixing I)}}$ —price on Fixing I index (for each hour) [PLN/MWh];

M—margin of the electricity purchaser [PLN];

Q_h —hourly production [MWh];

N—negative balance coverage ratio [%];

P_r —reference price [PLN/MWh];

P_{Tgebase} —price on Tgebase index (daily average) [PLN/MWh];

Q_d —daily production [MWh].

The annual revenues obtained for the analyzed variants were calculated assuming a trading margin of 10 PLN/MWh and an average hourly electricity production ranging from 0.47 MWh to 0.50 MWh, depending on the variant considered. The differences in electricity production result from the higher availability factor assumed for the demand-driven operating scenarios. The results are presented in Table 3.

Table 3. Annual revenue for individual variants.

Revenue	Variant 0	Variant 1	Variant 2	Variant 3	Variant 4
Revenue from electricity sales [PLN thousands]	1794	1950	1951	1932	1945
Revenue from covering the negative balance [PLN thousands]	2312	1864	1861	2430	2428
Total [PLN thousands]	4106	3814	3812	4363	4373

A comparison of Variants 1–4 with Variant 0, representing the linear operation of the Śniaty biogas plant, indicates that demand-driven operation increases total annual revenue only when the additional CHP unit is connected to a separate transformer station. In the case of Variants 1 and 2, annual revenues were lower than in the reference scenario by PLN 292,000 and PLN 294,000, respectively. Although these variants generated the highest revenues from electricity sales among all analyzed scenarios, the additional market revenue was insufficient to compensate for the reduction in revenue obtained through the FIP scheme. The highest total annual revenue was achieved for Variant 4, resulting in an increase of approximately PLN 267,000 compared with the reference scenario. However, the annual revenue obtained for Variant 3 was only about PLN 10,000 lower. This relatively small difference indicates that increasing the biogas storage capacity from 6 h to 12 h provides only limited additional economic benefits under the market conditions observed in 2025.

The next and most important stage in assessing the profitability of demand-driven operation in the Śniaty biogas plant was the identification of operating costs resulting from the implementation of demand-driven operation. Only those costs that increase directly as a consequence of demand-driven operation were included in the analysis presented in Table 4. These consisted of the servicing costs of the CHP unit, estimated at approximately PLN 270,000 per year.

Table 4. Annual income for individual variants.

Income	Variant 0	Variant 1	Variant 2	Variant 3	Variant 4
Total revenue [PLN thousands]	4106	3814	3812	4363	4373
Annual CHP maintenance costs [PLN thousands]	270	540	540	540	540
Total [PLN thousands]	3836	3274	3272	3823	3833

In addition, Table 5 presents the investment expenditures required to implement demand-driven operation under each analyzed variant.

After accounting for the additional operating costs, all demand-driven operation variants generated lower income than the reference case. Furthermore, the investment expenditures required to implement the proposed solution, ranging from PLN 2.247 million to PLN 3.297 million depending on the analyzed variant, substantially reduced the economic attractiveness of demand-driven operation in the Śniaty biogas plant.

Similar results were presented by Barchmann et al. [48], who pointed out that flexibly generating power through biogas plants requires a series of technical components at the

biogas plant and that not every concept of sustainable flexibilization of existing biogas plants is necessarily economically beneficial compared to the status quo.

The obtained results are consistent with previous studies, which indicate that flexible biogas plant operation is often not economically competitive without additional support mechanisms. Lauven et al. showed that the revenue potential of flexible biogas plants has significantly decreased over time, and that additional incentives have become indispensable to ensure their economic viability under current market conditions [49].

Table 5. Cost of modernization for individual variants.

Scope of Modernization	Variant 0	Variant 1	Variant 2	Variant 3	Variant 4
Purchase of an ultrasonic sensor [PLN thousands]	-	17	17	17	17
Purchase of an additional CHP engine [PLN thousands]	-	1650	1650	1650	1650
Construction of a transformer station [PLN thousands]	-	-	-	650	650
Construction of a heat storage system [PLN thousands]	-	580	620	580	620
Enlarge biogas storage [PLN thousands]	-	-	360	-	360
Total [PLN thousands]	-	2247	2647	2897	3297

Similarly, Lauer et al. demonstrated that, at the system level, the costs associated with flexible biogas operation may exceed the resulting benefits, leading to benefit–cost ratios below unity in all analyzed scenarios. This is largely attributed to the presence of alternative flexibility options within the power system, which reduces the marginal value of additional flexible generation capacity [50].

Instead of increasing generation capacity, the implementation of demand-driven operation in the Śniaty biogas plant should be based on temporarily limiting base-load biogas production, so that during periods of high energy prices, the existing engine capacity (499 kW) is sufficient to burn the biogas stored during periods of negative prices. This approach also appears justified in light of historical production data for the years 2024–2025, which indicate that for a significant portion of the time, hourly biogas production in the Śniaty biogas plant was below 232 m³. To optimize biogas production, the operation of the biogas plant in Śniaty can be based on the concept of flexible feeding, presented, among others, by Dittmer et al. [51], in which a model predictive control model was used to control production in a demand-dependent manner. This solution was implemented in an existing 355 kW biogas plant, achieving good alignment of production with demand (MAPE < 20%). In the case of the biogas plant in Śniaty, this approach appears particularly promising due to the relatively stable and repeatable substrate composition, based mainly on waste from the owner’s farm. It should be emphasized, however, that the effective implementation of such solutions requires significant improvements in the substrate recording and monitoring system, covering both quantity and quality parameters, which is a prerequisite for the proper functioning of predictive models.

In the context of further research, it is crucial to continue analyzing electricity price trends on the DAM. In line with Poland’s energy policy objectives, the share of weather-dependent renewable energy sources is expected to continue growing in the coming years, which will likely lead to increased price volatility. One can expect more frequent periods of very low prices during hours of high generation (mainly during the day) and high prices during periods of increased demand, especially in the evening. Such market conditions will favor improved profitability of demand-driven biogas plants.

However, the FIP system remains a significant constraint, as its relatively high reference price limits the biogas plant's ability to respond to market signals. As a result, the economic incentives to switch from linear to demand-driven operation are insufficient. Similar phenomena were observed in the German market, where the development of flexible biogas plant operation occurred mainly after the expiration of support schemes and the establishment of flexibility premiums.

In addition, current regulations do not distinguish between different operating modes (linear vs. demand-driven), focusing instead on installed capacity rather than actual electricity generation. A potential direction for legislative changes could be to link the support system and regulatory obligations to the volume of energy generated, which would allow for the installation of larger units without losing the benefits of staying below the 499 kW capacity.

4. Conclusions

The study confirms that an XGBoost-based forecasting model is an effective tool for supporting operational strategies in biogas plants. The developed model demonstrated high predictive accuracy (MAE = 51.37 PLN/MWh and RMSE = 95.95 PLN/MWh) and the ability to capture complex, nonlinear relationships between weather conditions, demand, and electricity prices on the Polish market. The resulting forecasts can serve as the basis for a DMM that identifies the most cost-effective hours for electricity production and generates operating schedules for CHP unit control. However, implementing a DMM requires the definition of several key decision thresholds, including biogas production rate, current biogas storage level, pressure limits of pressure in the biogas storage capacity, maximum biogas storage duration, PQ value, and electricity price levels. The values of these decision thresholds must be determined individually according to the technical and operational characteristics of the biogas plant in which the DMM is to be implemented.

Although implementing demand-driven operation solutions is technically feasible, an economic analysis indicates that, in the case of the Śniaty biogas plant, it is not currently justified. To evaluate its profitability, an analysis was conducted using DAM data for 2025. Five operating variants were considered. A comparison of Variants 1–4, representing different demand-driven operation scenarios, with Variant 0, representing the current operating mode of the Śniaty biogas plant, showed that demand-driven operation increased total annual revenue only when an additional CHP unit was connected to a separate transformer station. The highest annual revenue was achieved for Variant 4, in which CHP capacity was doubled ($PQ = 2$) and biogas storage duration was increased to 12 h. However, after accounting for the additional operating costs, all demand-driven variants generated lower net income than the reference case. Furthermore, the investment expenditures required for implementing of the proposed solutions, ranging from PLN 2.247 million to PLN 3.297 million, substantially reduced the economic attractiveness of demand-driven operation in the Śniaty biogas plant.

Under current conditions, demand-driven operation in the Śniaty biogas plant should be based on temporarily limiting base-load biogas production so that the existing CHP unit (499 kW) can utilize the biogas accumulated during periods of negative electricity prices. This approach is supported by operational data, which show that hourly biogas production was very often below 232 m³/h. Further optimization may be achieved through the implementation of flexible feeding, especially since most of the substrate comes directly from the owner's farm, which ensures a repeatable substrate composition.

Further research should focus on implementing flexible feeding. At the same time, electricity price trends on the DAM will be crucial for the development of demand-driven operation at biogas plants. A significant constraint remains the FIP support system, in

which a relatively high reference price limits the plant's ability to respond to market signals. Additionally, regulations focus on installed capacity rather than actual electricity production, which limits the potential for implementing more flexible operating models.

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Abbreviations

The following abbreviations are used in this manuscript:

PPS	Polish Power System
DAM	Day-Ahead Market
RESs	Renewable energy sources
DMM	Decision-Making Model
XGBoost	Extreme Gradient Boosting
PQ	Power quotient
EU	European Union
ETS	Emissions Trading Scheme
PV	Photovoltaic
VRESs	Variable renewable energy sources
CHP	Combined Heat and Power
ERO	Energy Regulatory Office
FIT	Feed-in Tariff
FIP	Feed-in Premium
OREO	Renewable Energy Settlement Operator
PPE	Polish Power Exchange
MLOps	Machine Learning Operations
MAE	Mean Absolute Error
RMSE	Root Mean Square Error

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