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Cost-benefit analysis of a municipal waste management project: Using a survey of professional forecasters to provide reliable projections until 2035

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Abstract

The widespread adoption of selective kitchen and garden waste processing in closed biogas plants is often hindered by financial feasibility and social acceptance. This study presents a comprehensive cost-benefit analysis of waste processing through wet and dry fermentation, evaluating energy recovery options from combined heat and power and compressed natural gas installations. Drawing on data from a Polish investment project and a novel concept in waste management research – a survey of professional energy forecasters, we provide financial projections until 2035 to guide sustainable decision-making. Our results emphasize the economic viability of bio-based energy recovery technologies, while also highlighting the potential social and environmental benefits. By diverting waste from landfills and recovering energy, biogas plants contribute to both energy transition goals and the broader objectives of sustainable waste management, including improved resource efficiency and reduced reliance on fossil fuels. This study offers practical insights for municipalities and businesses, promoting policies that support public-private partnerships and the long-term viability of renewable energy projects within the circular economy framework.

Keywords: municipal solid waste, biogas plant, cost-benefit analysis, professional forecasters survey

1. Introduction

In an era of resource scarcity, re-evaluating our approach to waste management is imperative. Landfilling, the traditional approach for managing municipal solid waste, conflicts with contemporary circular economy (CE) principles (Bertanza et al., 2021). Despite discussions on extracting energy from landfilled waste (Kurniawan et al., 2022), escalating costs of landfilling and increasingly stringent regulations demand alternatives.

The circular economy not only promotes resource efficiency but also raises important social and environmental justice concerns. The current linear economy unequally distributes the environmental and social costs associated with energy and material provision, disproportionately affecting vulnerable groups such as low-income communities, which often face higher exposure to environmental hazards and energy poverty (Ashton et al., 2022; Sovacool, 2021). Transitioning to a CE must therefore address these inequalities by ensuring equitable access to resources, energy, and waste management services, leaving no one behind (Schröder et al., 2020).

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In this context, biogas production from organic waste represents a promising pathway for achieving both environmental sustainability and social equity. By diverting bio-based waste from landfills to anaerobic digestion in closed biogas plants, we can recover energy and materials while mitigating environmental impacts (Ibarra-Esparza et al., 2023; Kumar and Samadder, 2017; Skrzypczak et al., 2023). This approach aligns with CE principles and contributes to the energy transition by reducing reliance on fossil fuels, while ensuring that the benefits—such as cleaner energy and reduced pollution—are accessible to all, particularly marginalized communities affected by energy poverty.

Despite significant advances in waste management strategies and material recovery (Fraccascia et al., 2021), a notable gap remains in empirical research supporting the practical implementation of these technologies (Andeobu et al., 2022). This gap is exacerbated by the dominance of a few players in the waste management market and the reluctance to share data, coupled with the complexities of establishing public-private partnerships to finance and operate waste processing facilities (Ibarra-Esparza et al., 2023).

Our contribution

To bridge this gap, our study addresses four key research questions, see Table 1. Firstly, we assess the costs and benefits of four potential waste management scenarios that focus on two key decisions (Pöschl et al., 2010; Xiao et al., 2022): (i) whether to use wet or dry fermentation for kitchen waste processing, and (ii) whether to generate electricity by burning biogas in a combined heat and power (CHP) unit or upgrade biogas to biomethane (bioCNG) for use in public transportation.

Secondly, we introduce a novel concept in waste management research and conduct a survey of professional energy forecasters. Inspired by the *Survey of Professional Forecasters*, the oldest quarterly survey of macroeconomic forecasts in the United States (Croushore and Stark, 2019), it provides a market perspective on the future evolution of energy commodities. With a response rate of ca. 50% among active energy forecasters in the Polish market, the survey offers a representative and realistic projection of wholesale electricity and natural gas prices from 2024 to 2035. In addition, the variability of the responses allows for a probabilistic assessment of the risk-reward relationship of the four scenarios elaborated in this study.

Thirdly, we provide practical, data-driven insights to guide municipalities and businesses in making informed decisions about sustainable waste management. These insights align with environmental directives and support the implementation of innovative waste processing concepts, highlighting the economic viability and scalability of sustainable methods (Piadeh et al., 2024; Skrzypczak et al., 2023).

Finally, recognizing the role of public-private partnerships and social stakeholders in advancing municipal waste management (Hoang et al., 2022; Moreau et al., 2017), this study also addresses how differing waste policies – such as segregation regulations in markets like Denmark – can significantly affect project outcomes.

Article structure

The remainder of the article is structured as follows. In Section 2, we elaborate the anaerobic digestion of waste, covering both wet and dry fermentation methods, as well as energy recovery strategies. Then in Section 3, we discuss the managerial background, addressing the issues such as legislation, investment, regulations and the cooperation between municipalities and private investors. In Section 4, we describe the multi-step methodology followed in this study. Subsequently, in Section 5, we present the results for a municipal waste management project in Poland, along with a detailed cost-benefit analysis of various scenarios and financial projections derived from a survey of professional energy forecasters. In Section 6, we discuss the implications and future perspectives. Finally, in Section 7, we wrap up and conclude this study.

Table 1: Research questions and our contribution

Research question	Our contribution
Economic aspects: • How does the economic viability of biogas plants compare across different waste processing and energy recovery scenarios? • How can realistic, long-term financial projections be made?	• A detailed comparative analysis that uses real-world empirical data from Poland. • A novel concept in waste management research – a survey of professional energy forecasters.
Practical implications: What insights can guide municipalities and businesses in implementing sustainable waste management practices?	Key decision-making considerations based on the outcomes of four realistic scenarios.
Policy and stakeholder influence: How do waste management policies and stakeholder engagement impact the outcomes of waste-to-energy projects?	A discussion of public-private partnerships, importance of stakeholders engagement, policy frameworks, and the need for tailored interventions.

2. Technical background

In this section, we elaborate two key aspects of sustainable municipal waste management in general and for this study in particular. First, in Section 2.1, the processing of solid waste through anaerobic digestion using either wet or dry fermentation. Then, in Section 2.2, recovering energy from biogas by generating electricity in a CHP unit or upgrading biogas to bioCNG.

2.1. Anaerobic digestion of waste

Organic waste is a potential source of energy, heat, and nutrient-rich fertilizer (Chojnacka et al., 2023). Digestion in biogas plants is currently a popular technology for managing kitchen waste. Anaerobic microorganisms conduct the methane fermentation process, resulting in the degrading of the substrate's organic matter and the production of a gas primarily composed of methane, carbon dioxide, and water.

Wet and dry fermentation, the two key anaerobic digestion technologies investigated in this study, are specifically designed for the effective treatment of selectively collected residential kitchen waste. These technologies are categorized based on operating temperature and dry matter content (Cao et al., 2019). Wet fermentation operates at approx. 40^{o}C with a dry matter content of less than 15% and dry fermentation is based on thermophilic fermentation at 50-52^{o}C with a dry matter content of 33-35%.

2.1.1. Valorization of waste into pulp with wet fermentation

Wet fermentation begins with the collection of kitchen waste into a hopper, followed by feeding it through a screw feeder into a process tank (Haldar et al., 2022). A pulper equipped with a slow-speed shredder breaks down the waste, and process water is introduced (approximately 0.75 Mg per 1 Mg of kitchen waste, though this may vary based on impurity levels; Esteban-Lustres et al., 2022). The slow-rotating system ensures the cutting of packaging without shredding it into elements smaller than 1 cm. After 12-15 minutes, a valve at the pulper's bottom opens, discharging the pulp with impurities into the separator below. Simultaneously, the separator rotor activates, pumping the resulting biopulp (impurity-free pulp, with dry matter content ca. 12-15%) to the storage and averaging tank for fermentation and biogas production. The digestate obtained after the digestion process finds applications in agriculture or serves as feedstock for high-quality, dry, loose fertilizer production (Deena et al., 2022). This not only aids in waste reduction but also contributes to material recovery, aligning with the CE principles.

2.1.2. Pre-treatment with dry fermentation

Dry fermentation begins with the initial cleaning and shredding of kitchen waste (Hu et al., 2022). A bag bursting machine, a sieve with a diameter of about 50 mm, a shredder with a similar diameter, a ballistic separator, and a heavy metal separator are used in the sub-treatment of waste. This partially reduces contaminants, including metals, plastics, paper, and multi-material trash. The cleaned waste enters the dry digestion reactor, where it is diluted with leachate or freshwater to a dry matter content of 33-35% (as in the LARAN system from Strabag). A minimum of 20 days of hydraulic retention time is required to produce biogas with an average methane content of 50-55% at 55°C (Le Pera et al., 2022). The waste goes to the de-watering module (press, centrifuge) after the digestion process, and once de-watered, it undergoes composting for at least 21 days. It reduces its mass and stabilizes the material, but more importantly, it reduces the content of phytotoxic compounds, e.g., short-chain fatty acids. There are substantial contaminants in the compost, hence it is subjected to another impurities removal process (Li et al., 2022).

2.1.3. Wet vs. dry fermentation

The main difference between the two technologies is the acceptable contamination level within the fermentation substrate. Wet fermentation requires a high-quality biopulp with minimal contamination ca. 0.07% d.m. (Gemidan Holsted, 2022). In contrast, dry fermentation can tolerate higher impurity levels ca. 8.5-14% d.m. (Montejo et al., 2010; Renew Energy, 2022).

Substrate purity holds economic significance in bio-waste treatment. Producing a clean substrate and minimizing biogas loss through impurities is crucial. Furthermore, impurities within the bio-waste substrate can lead to mechanical equipment failures and the formation of sludge within anaerobic digesters (Alessi et al., 2020).

Therefore, the decision between wet and dry fermentation must be approached strategically. Municipalities or waste management companies need to carefully assess their specific waste streams, financial purview, local regulations, and long-term goals. A thorough cost-benefit assessment, like the one done in this study, is crucial. This analysis will determine whether prioritizing higher biogas yields (with a cleaner feedstock) or maximizing waste processing flexibility (with higher impurity tolerance) is the optimal path for achieving both economic and environmental sustainability.

2.2. Energy recovery

Biogas obtained from both wet and dry fermentation requires processing for efficient energy recovery. As the anaerobic digestion process itself requires a certain amount of heat and electricity, integrating energy recovery systems can make the operation self-sufficient. Energy generated from biogas can meet the energy needs of the fermentation process and potentially generate extra revenue through energy sales. Two of the most common ways to use this biogas are either to generate electricity through cogeneration in a CHP unit (Abanades et al., 2022), or to upgrade it to biomethane (bioCNG Ryckebosch et al., 2011).

2.2.1. Cogeneration with a CHP unit

Biogas is allowed to burn in a CHP unit of suitable capacity, which results in production of heat and electricity. CHP is a highly efficient technology that by producing power on-site, minimizes energy losses and captures heat that would otherwise be wasted (Gvozdenac et al., 2017). CHP unit size is determined on the basis of the biogas available from the fermentation process, and considering the downtime for servicing and maintenance (Wu and Wang, 2006). The efficiency of the CHP unit is 65–85% and the output in terms of heat and electricity is equal (US Department of Energy, 2017), i.e., ca. 35-40% of the biogas energy would be obtained as electricity and the same as heat.

2.2.2. *Upgrading biogas to bioCNG*

Biogas undergoes a series of upgrading steps to remove impurities (like carbon dioxide, hydrogen sulfide, and water vapor) and increase its methane content, transforming it into bioCNG. This is a renewable fuel that can be used in natural gas vehicles, for example. The upgrading process involves technologies such as water scrubbing, pressure swing adsorption, or membrane separation, depending on the desired purity level and biogas volume (Ryckebosch et al., 2011). BioCNG is compressed to the higher pressures required for vehicle use and might undergo odorization for safety purposes before distribution at fueling stations or injected into the natural gas grid.

2.2.3. *Cogeneration vs. upgrading to bioCNG*

The choice between energy recovery through CHP or bioCNG depends on several factors, such as the trends in energy consumption, the accessibility of infrastructure, and financial incentives. Areas with consistent and predictable energy needs might find CHP ideal, as it usess biogas for on-site heat and power with high efficiency (ca. 80%; Wu and Wang, 2006), supporting a localized circular model. In contrast, bioCNG enables flexibility and broader energy distribution, promoting circular principles on a wider scale. BioCNG can be compressed for use as car fuel, or power a fleet of buses or injected into natural gas systems to provide energy at various times or places (Ryckebosch et al., 2011). Existing infrastructure, such as gas grids or fueling stations, should also be evaluated when considering bioCNG. Additionally, government incentives or policies may favor one method over the other, influencing the financial viability of each option. In terms of additional energy required for operation, cogeneration with CHP does not require any external energy, but the process of upgrading biogas to bioCNG does. This suggests that combining a CHP unit with the bioCNG upgrading process could provide the best of both worlds, meeting the energy needs of the upgrading process while maximizing the overall energy output.

3. Managerial background

3.1. *Legislation and investment regulations*

Environmental regulations focused on sustainability and environmental impact are increasingly integrated into legislation worldwide (Gunningham and Sinclair, 2019). The European Landfill Directive (ELD) 1999/31/EC and subsequent legislation are key examples. While these outline landfill criteria and promote material/energy recovery, implementation can be hindered by insufficient national and regional waste management strategies, as observed in Croatia and Turkey (Stanic-Maruna and Fellner, 2012; Taşeli, 2007).

The ELD adoption triggered further legislation, including directives on landfill acceptance criteria (2003/33/WE) and environmental impact assessments (2011/92/EU, amended by 2014/52/EU), with landfill emissions a key concern (Article 3, ELD). 2018 ELD revisions (to 1999/31/EC) strongly support the shift towards a circular economy, limiting landfilling to 10% by 2035. This prioritizes municipal waste hierarchy: prevention, reuse, recycling, and recovery (Malinauskaite et al., 2017).

The Waste Incineration Directive (2000/76/WE) is another relevant legal act, although it excludes biomass facilities processing kitchen, agricultural and forestry wastes. In this regard, the ELD sets a crucial direction, to use non-recyclable or reusable municipal waste for energy and material recovery purposes. Incentivizing organic waste processing (kitchen and garden) through anaerobic digestion (AD) aligns with EU legislation encouraging sustainable materials management (Alengebawy et al., 2022).

With a growing global population (reaching 8 billion in 2022; United Nations, 2022), the shift towards CE and prioritizing renewable energy sources are crucial, particularly in regions suffering from energy poverty (Ghisellini, 2023). Utilizing non-recyclable waste for energy, optimizes resource potential and create more efficient systems (de Sadeleer et al., 2020). This applies primarily to municipal solid waste with a calorific value of more than 6 MJ/kg and an average of about 10 MJ/kg. While incinerators traditionally handle this waste stream, the revised Waste Incineration Directive (WID 2000/76/EC) encourages bio-waste utilization. Neglected bio-waste contributes to greenhouse gas emissions, making it a prime candidate for biogas generation through AD and subsequent use in CHP or bioCNG production.

In Poland, the Law on Maintaining Cleanliness and Order in Municipalities (Polish Government, 2013) promotes selective waste collection, specifically targeting the biodegradable fraction of municipal waste (Article 3, paragraph 1, item 10). For municipal biogas plants, this includes kitchen waste from homes and businesses, along with residues from food production and distribution.

Biogas plays a crucial role in addressing the challenges of population growth and resource strain. In 2023, it was the largest renewable energy source globally, accounting for 55% of renewable energy and over 6% of global energy supply (International Energy Association, 2023). The European Commission's practical approach and legislative efforts have positively influenced bioenergy investment (EC, 2017). The European biogas sector has grown significantly in recent years. According to the European Biogas Association's 2022 Statistical Report (`https://www.europeanbiogas.eu`), there were over 19,000 biogas plants in operation in Europe as of 2021. While, Germany remains a leader, Poland is actively adopting biogas solutions and rolling out supportive policy interventions.

Poland's 2016 ordinance, following previous enacted Article 3 in 2013, on selective waste collection, particularly bio-waste, further aligns with CE and incentivizes commercial use the separated biodegradable municipal waste. Data from the Polish statistics office shows the positive outcomes of incorporating European legislation into national laws, including an increase in the biological treatment of municipal solid waste. Importantly, clarifications within the Waste Act promote biogas development. Biogas plant feedstock is defined to include biodegradable waste (Article 3, paragraph 1, item 10) and, more specifically, bio-waste such as kitchen waste (excluding animal-derived), garden waste, and similar materials (Article 3, paragraph 1, item 1). The emphasis on aerobic/anaerobic decomposition clarifies the suitability of this material for biogas production. The Waste Law expressly did not include the words "municipal biogas plant" to promote the creation of these facilities for both private and public bodies or to allow collaborative investment under the public-private partnership formula.

3.2. Cooperation between the municipality and the private investor

Effective municipal waste management, particularly the transition to circular economy model, relies on effective cooperation across government levels. Despite directives like the EU's ELD providing framework, implementation ultimately rests with local governments. They understand community waste patterns and have the authority to enact specific waste management strategies (Malinauskaite et al., 2017). Successful projects require local governments to not only oversee administrative decisions but also actively work to maximize energy, economic, and environmental benefits from waste.

In navigating the complexities of projects like a biogas plant, investors must adhere to globally recognized regulations and principles, while understanding the technical and financial aspects. Globally, municipal waste management strategies encompass a variety of models, such as direct municipal operation, outsourcing to private companies, and collaboration between municipalities (Kaza et al., 2018).

Increasingly, *public-private partnerships* (PPP) are gaining prominence in municipal waste management due to their potential advantages in expertise, cost management, and efficient project implementation (Wilson et al., 2012). A PPP is a long-term contractual relationship between a public entity (e.g., municipality) and a private partner to deliver a specific service or infrastructure project. In the context of waste management, there are two common PPP structures:

- the private partner builds and maintains the facility, and
- the private partner manages an existing facility.

In return, the private partner typically receives compensation from the public entity through either budget funds or the right to collect user fees.

In Poland, PPPs are becoming a popular choice for infrastructure projects, particularly within the waste management sector, including the implementation of biogas plants. However, Poland faces distinct challenges in fully realizing the benefits of PPPs (Polish Government, 2023b). These challenges include limited PPP knowledge among public entities, an absence of systematic approaches to considering PPPs, difficulties in managing PPP agreements, high financing costs, and insufficient effectiveness analysis of PPP projects. Importantly, these challenges also extend to other countries, especially developing countries (Dolla and Laishram, 2020). To address these issues, Poland is prioritizing strategies such as maintaining a robust PPP legal framework, developing comprehensive guidelines, providing advisory services, establishing regional competence centers, and incorporating PPPs into central procurement strategies (Polish Government, 2023b). Studies like ours offer crucial insights for both municipalities and private investors to make informed decisions within the PPP framework.

4. Methodology

This study adopts a case-based approach, which is considered appropriate for examining contemporary and complex phenomena, and is therefore well suited to exploring the multifaceted nature of sustainable waste management (Eisenhardt et al., 2016; Yin, 2009). We followed a multi-step process, detailed below, to gather empirical data and analyse it to meet the goal of this study.

4.1. In-depth interviews

Unstructured interviews (Brinkmann, 2020) were conducted with executives, the key informants, from three Polish municipal waste processing installations (two urban, one rural). This allowed us to capture a range of operational practices and regulatory compliance scenarios, thereby enhancing the robustness of the analysis. These discussions were aimed at understanding the waste policies and regulations, waste characterization, possible combinations of anaerobic digestion technology with energy recovery setup, annual waste volume, process parameters, actual financial data, decision-making processes, and the challenges and opportunities associated with different processing methods (Newenhouse and Schmit, 2000; Zurbrügg et al., 2012). The unstructured interviews provided valuable insights into industry practices and financial considerations. The discussions referenced data from budgetary offers made in 2022 by various companies, including Dynamic Biogas, BioWatt, Host Energy, AAT, ProGeo, Renew Energy, and Gemidan Ecogi. The open-ended format facilitated the exploration of diverse perspectives.

4.2. Formation of scenarios

The four scenarios in this study—WetCHP, WetCNG, DryCHP, and DryCNG—were developed to evaluate the economic and environmental trade-offs of key decisions in waste-to-energy systems: (i) whether to use wet or dry fermentation, and (ii) whether to prioritize energy recovery via combined heat and power (CHP) or biogas upgrading to compressed natural gas (bioCNG). Following four criteria were used to develop the four scenarios:

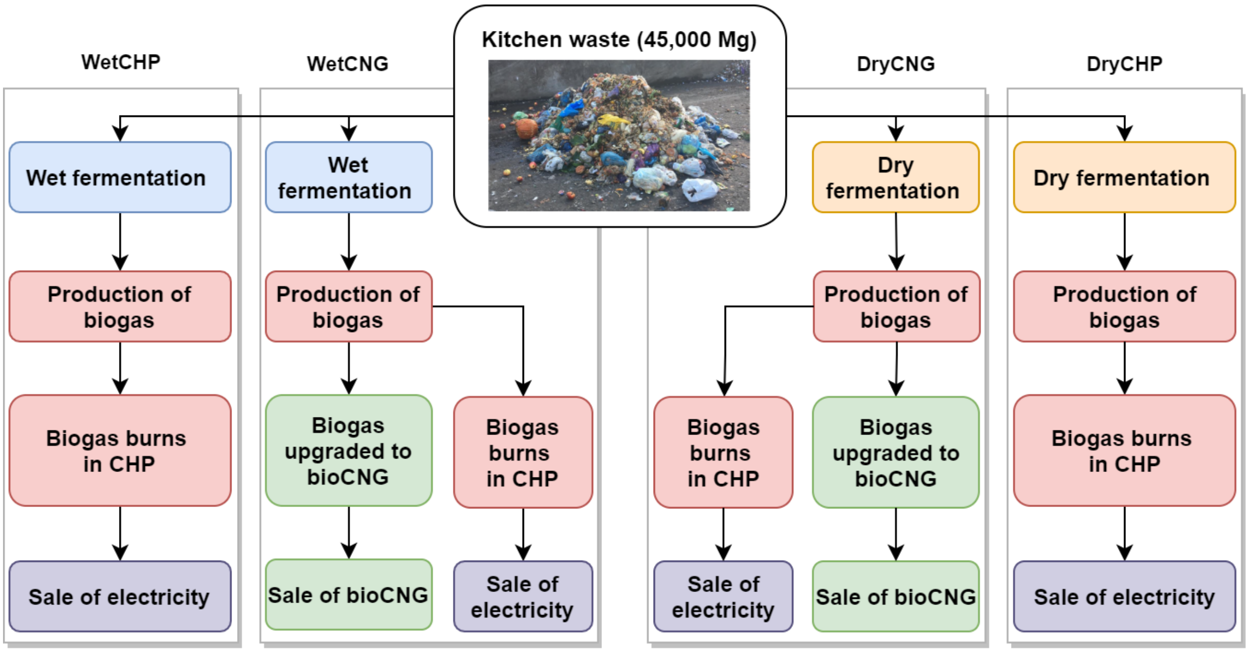

Figure 1: The four scenarios assessed in this research

1. **Technical feasibility:** Wet fermentation was included for its higher biogas yields and suitability for high-purity organic waste, while dry fermentation was considered for its ability to process more impure feedstock, albeit with reduced efficiency (Pöschl et al., 2010; Kumar and Samadder, 2017). CHP and bioCNG systems were chosen to represent two widely applied energy recovery pathways with distinct operational advantages – localized energy generation versus fuel flexibility for transportation (Blondeel et al., 2021).
2. **Empirical data:** The scenarios are based on operational data from three municipal waste processing facilities in Poland, reflecting real-world practices and constraints.
3. **Policy context:** The inclusion of bioCNG aligns with its growing adoption in urban transportation and recent policy incentives, such as Poland's state-guaranteed energy prices (Skrzypczak et al., 2023; Ghisellini, 2023). Similarly, the importance of CHP systems in decentralized energy production and energy autonomy underpins their inclusion (Blondeel et al., 2021).
4. **Social and environmental considerations:** The selected scenarios address energy poverty and promote energy equity, particularly through bioCNG, which supports cleaner energy access in underserved areas. CHP scenarios complement these goals by contributing to localized energy security (Sovacool, 2021).

4.3. Cost-benefit analysis based on 2022 values

A comprehensive cost-benefit analysis (CBA; Wang and Calderon, 2012) for processing municipal kitchen waste was conducted based on the 2022 values (sale prices of electricity and natural gas, gate fee, expenses, etc.) obtained from the unstructured interviews. We began by analyzing scenarios WetCHP and DryCHP, to compare the wet and dry fermentation processes. This allowed us to determine the most efficient anaerobic digestion method. Based on the outcome, we then evaluated energy recovery options: CHP and bioCNG (+ small CHP), i.e., scenarios WetCHP vs WetCNG and DryCHP vs DryCNG.

To carry out this initial cost-benefit analysis, some assumptions were made (Williams et al., 2017). Firstly, we did not consider amortization in the *operating expenditures* (OPEX). Including it would disproportionately disadvantage dry fermentation scenarios and shift the focus away from the comparison of operational expenses, environmental benefits, and energy/material recovery. Another reason is that investment decisions in Poland are mainly made by municipalities. Large grants from the National Fund for Environmental Protection and Water Management cover much of the up-front investment costs, making OPEX less amortization the primary focus.

Secondly, the values denominated in Polish Złoty (PLN) were converted to Euro (EUR) using the average exchange rate for 2022 of 1 EUR = 4.68 PLN. Thirdly, for all scenarios the waste volume processing capacity of the installation was 45,000 Mg/year, as in one of the real ongoing projects in Poland.

4.4. *Survey of professional energy forecasters*

To better address the literature gap concerning empirical evidence, we sought insights from professional energy forecasters. Specifically, we inquired about their perspectives on the anticipated changes in wholesale electricity and natural gas prices in Poland from 2024 to 2035. The Surveys of Professional Forecasters (SPF), conducted by either the Federal Reserve Bank of Philadelphia (Croushore and Stark, 2019) or the European Central Bank (2023), focus on macroeconomic variables such as inflation, GDP and unemployment. There are only a handful of publications(Atalla et al., 2016; Czudaj, 2022) on oil price expectations collected by the European Central Bank (ECB). However, to the best of our knowledge, there are no studies on the long-term evolution of other energy commodities. As such, our approach is a novel concept not only in waste management, but also in energy research.

The survey was conducted in November 2023, and focused on participants' current roles, professional forecasting experience, and forecasts for electricity and gas prices. The survey instrument was hosted on the university's website and ensured complete anonymity of respondents to prevent any traceability to individual participants. Participation in the survey was voluntary and no compensation was offered. Prior to participation, forecasters were given informed consent and were informed of the confidential, aggregated nature of the collected data for academic research.

The survey employed two distribution methods: the snowball sampling approach (Goodman, 1961) and respondent-driven sampling (Heckathorn, 1997). It commenced within the authors' professional forecaster network to broaden its reach within the niche target populations. The questionnaire was designed to be flexible, not mandating responses in all fields. Throughout the survey period, we received 24 responses. Of these, 18 respondents provided forecasts for both electricity and natural gas prices spanning 2024-2035, while 6 respondents provided electricity price paths only.

It should be emphasized that 24 responses correspond to a response rate of about 50% among active energy forecasters in Poland. This ensures that our survey provides a representative and realistic projection of wholesale electricity and natural gas prices in this market. At the same time, this number is relatively high compared to the 40-50 European entities that typically provide oil price forecasts in the ECB survey (Czudaj, 2022).

4.5. *Financial projections*

The recorded price paths are illustrated using so-called *fan charts* of the Bank of England, which provide an easy-to-interpret preview of the future evolution of a process (Dowd, 2007). The chart shows the median (solid line), the 20%, 40%, 60% and 80% prediction intervals (PIs; shades of red or blue – from dark to light), and the minimum and maximum forecasts (the lightest color). Note that we consider whole price paths. This preserves temporal dependencies between predictions for the different time horizons but limits the number of samples. Hence, the jagged PIs in the plots. An alternative approach would be to use copulas to model the multidimensional and temporal dependence structure, but this would require a larger number of responses for calibration (Serafin et al., 2022).

The dashed black line in the chars show the state guarantee, a policy intervention recently introduced by the Polish government. The recorded price trajectories from the responses served as the input sales prices for calculating revenues in each respective year based on the final yields by energy recovery processes, CHP or CNG, using equations (1) and (2), respectively. Subsequently, the respective Earnings Before Interest, Taxes, Depreciation and Amortization (EBITDA) were determined using eq. (3), providing insights into the profitability. To enhance our understanding of the financial projection of the project over the years, a probabilistic forecast of EBITDAs was conducted using quantiles. These were illustrated using overlapping fan charts to compare the projection over the years 2024-2035.

5. Results

5.1. Characteristics of kitchen waste in Poland

According to the latest Statistics Poland (2023) report, there was 13.42 million tons of municipal waste collected in Poland in 2022. Of which 26.7% was designated for recycling, 14.2% for composting or fermentation, 21.1% for incineration, and 38.1% for landfilling. Morphological studies from the same year indicate that kitchen waste accounted for ca. 28.68% of all municipal waste (Szczepański et al., 2022, p. 23). Most of this kitchen waste is either composted or fermented. This reveals a potential for improved kitchen waste diversion and new biogas plants, even more so as ca. 18.3% still ends up in mixed municipal waste (Szczepański et al., 2022, p. 40).

Kitchen waste is characterized by a high organic content, most of which is composed of easily biodegradable compounds, such as carbohydrates, proteins and smaller lipid molecules (Zhang et al., 2021). However, depending on the period of the year, the morphological composition and physio-chemical properties of the waste may vary. Based on the interviews with key informants, the properties of kitchen waste on which the anaerobic digestion plants work in Poland and have been adopted for the purposes of this study are: dry matter content of 23%, pH of 5.6, dry organic matter content of 75-85%, nitrogen content of 1.6%, carbon to nitrogen ratio (C:N) of 22:1, and 25% of impurities.

The assumed dry matter content of 23% determines the amount of water needed for the initiation of the fermentation process. Depending on the choice of dry fermentation (20-40% d.m.) or wet fermentation (<15% d.m.), an appropriate amount of water must be supplied to provide sufficient moisture for the process. The slightly acidic reaction of the waste (pH = 5.6) makes the analyzed waste stream a valuable input to the fermentation process. The waste stream contains a high dry organic content (80-90%) and nitrogen at the level of 1.6%. The impurities content of 25% is a slightly overestimated value (usually, we observe about 17-20% of impurities in kitchen waste), but it was adopted to reduce the risk of overoptimistic cost-benefit assessment.

5.2. CBA based on 2022 values

5.2.1. CBA of wet and dry digestion

The comparison of the process parameters for wet and dry fermentation based on the recorded data is illustrated in Figure 2. It should be noted that scenarios WetCHP and WetCNG use the same process parameters for wet fermentation, as do scenarios DryCHP and DryCNG for dry fermentation. The biogas yield from the untreated waste for wet fermentation is estimated at 136.8 m^3/Mg in Poland based on tests provided by Ecogi and testing of in-house samples according to German standards (DIN 38 414/S8, VDI 4630; Gemidan Holsted, 2022). This is lower than the Danish market's 165.0 m^3/Mg of untreated

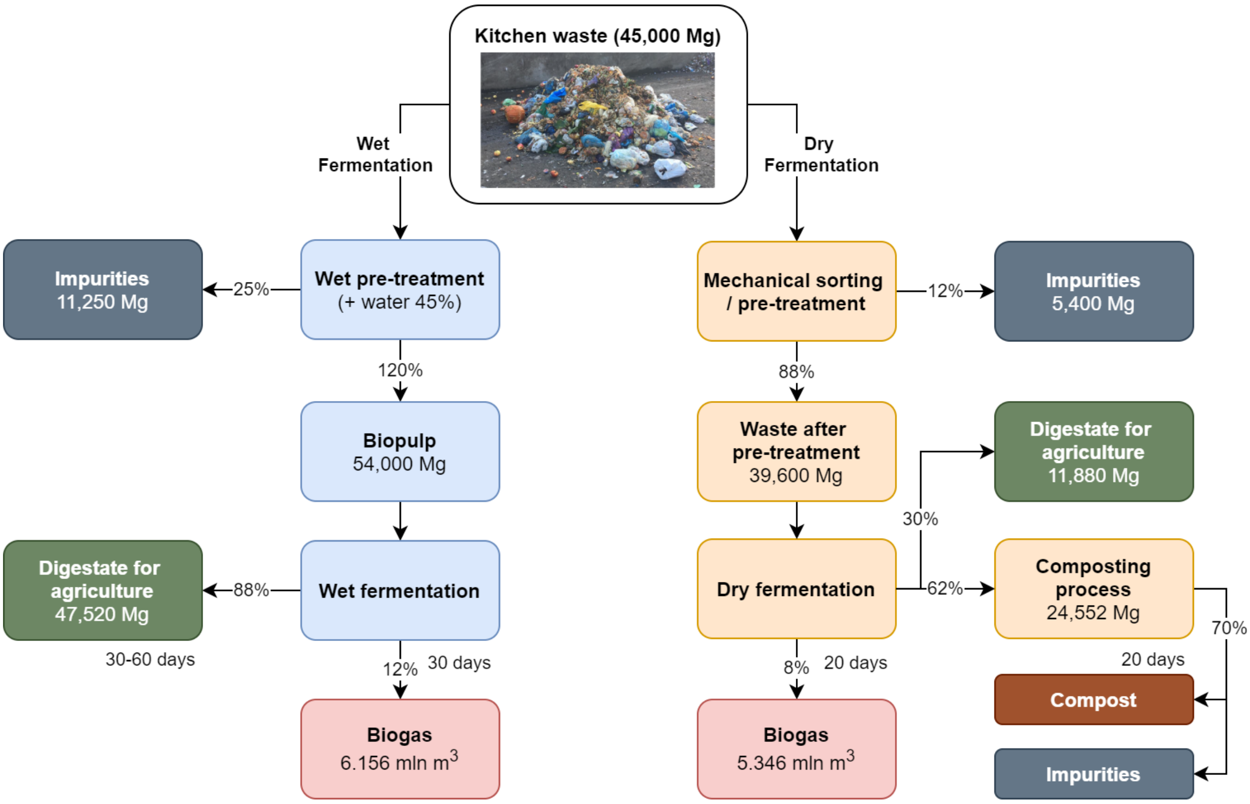

Figure 2: Comparison of wet and dry anaerobic digestion given ±45,000 Mg/year of substrate. Clearly, wet fermentation has a substantially higher biogas yield.

waste, a difference attributed to Poland's policy of excluding meat from kitchen waste fraction. Similarly for dry fermentation, in Poland it is 118.8 m^3/Mg of untreated waste, where it is 136,8 m^3/Mg for waste with 5% of impurities in other markets (Hagenmeyer, 2014). Therefore, the total biogas yield is estimated at 45,000 Mg × 136.8 = 6.156 mln m^3/year for the wet and 45,000 Mg × 118.8 = 5.346 mln m^3/year for the dry fermentation, see Table 2.

It is clear from Figure 2 that for the same amount of kitchen waste, wet fermentation (left part of the flowchart) produces ca. 15.2% more biogas than dry fermentation (right part of the flowchart). The generated biogas can be further used for energy recovery, as discussed in Sec. 2.2. The residual digestate from wet fermentation is four times larger than after dry fermentation. It is a desirable byproduct that can be used as a fertilizer in agriculture, and has a market value of ca. 6.41 Euro/m^3. After wet fermentation, there is no necessity for processing the biopulp, leading to 0.361 Euro/year reduction in OPEX. Although the calorific values of the biogas produced in both cases are similar, the quality of the digestate for agriculture from wet fermentation is higher (Alessi et al., 2020). Additionally, the pre-treatment in wet fermentation can remove more than twice the amount of impurities than the mechanical sorting can in dry fermentation. Consequently, wet fermentation demonstrates superior efficiency in both energy and material recovery, yielding more biogas and a greater volume of high-quality digestate suitable for direct application as an agricultural fertilizer, thereby reducing the reliance on synthetic fertilizers and promoting a more sustainable approach to nutrient management. The revenue from the digestate is not included in this research, as exact parameters of digestate were unavailable from the key informants, and the focus of this study was more towards

Table 2: Biogas yield and financial comparison for the wet and dry fermentation, in 2022

Parameters	**Wet**	**Dry**
Time required for the completion of the overall process (days)	30–120	60–120
Time required for biogas production (days)	30–60	ca. 20
Biogas yield per ton of untreated waste (m^3/Mg)	136.8	118.8
Total biogas yield (mln m^3/year)	6.156	5.346
Capital expenditures, CAPEX* (mln EUR)	15.641	34.545
Operating expenditures, OPEX* (mln EUR/year)	3.063	3.714
Revenues* (mln EUR)	5.615	5.445
EBITDA* (mln EUR)	2.551	1.731

*The above calculations include energy recovery through CHP through a 1.57 MW unit with wet fermentation (scenario WetCHP) and a 1.37 MW unit with dry fermentation (scenario DryCHP).

cost-benefit in terms of energy recovery. The market value of such digestate in Poland is ca. 1.37 EUR/m^3, hence it would only result in additional revenue. This is an avenue for further research.

For the CBA, as detailed in Table 2, we consider Scenarios WetCHP and DryCHP. The *capital expenditure* (CAPEX) and OPEX for scenario WetCHP are ca. 54.7% and 17.5% lower than that for scenario DryCHP, respectively. Importantly, the investment for setting up dry fermentation has rapidly increased over the last few years due to additional material handling requirements stemming from changes in environmental regulations. Biogas production is at least 33.3% faster in scenario DryCHP; however, it requires additional composting of byproducts. Hence, the completion of the overall process in scenario DryCHP could be twice as time-consuming, while producing 0.81 mln m^3/year less biogas than in scenario WetCHP.

To calculate the revenue, the payment at the gate for processing the waste, the so-called *gate fee*, is 96.154 EUR/Mg. In Poland this value is decided and paid by the state, and already includes the cost of residue disposal or additional processes such as torrefaction, and is the same for all scenarios in this research. Note, that it is important to secure the possibility of ballast disposal during the entire investment period due to the ban on landfilling this type of waste. The produced biogas in both wet and dry fermentation is then considered to be utilized for cogeneration of heat and power in CHP units (see Sec. 5.2.2) with a nominal power output of 1.57 MW and 1.37 MW, respectively. 106.84 EUR/MWh is the average wholesale electricity price in 2022 based on price paths reported by the key informants. Further, for the analysis we assume that all the output byproducts are fully sold. Under this condition, the revenue for both wet and dry fermentation (WetCHP and DryCHP, respectively) can be calculated as the sum of gate fee revenue (gate fee $\times$ waste volume) and electricity sales revenue (wholesale electricity price $\times$ units of electricity produced). Hence resulting in revenues of 5.615 and 5.445 mln EUR, and EBITDA of 2.551 and 1.731 mln EUR, respectively for WetCHP and DryCHP.

Not only does WetCHP exhibit a superior output of biogas and digestate, but its EBITDA and revenues surpass those of DryCHP by 34.8% and 11.2%, respectively. It is worth noting that for wet fermentation, the economic viability of the biopulp, the product of first-stage pre-treatment, itself is high. Over a 10-year investment period, for 45,000 Mg/year of substrate and a plant construction cost of 6.667 mln EUR, the internal rate of return would be as high as 14%. Clearly, wet fermentation (WetCHP) demonstrates a higher cost-benefit ratio, both in terms of economic and sustainability outcomes, as compared to dry fermentation (DryCHP). It should be noted, however, that scenario WetCHP is not suitable for garden waste. This means that wet fermentation is the preferred option only for areas with little garden waste, i.e., densely populated cities, mostly with apartment buildings.

Both wet and dry fermentation processes recover energy and raw materials from waste, aligning with the circular economy principles. Biogas and digestate are used for energy generation and as agricultural fertilizer. However, complete circularity requires addressing residual impurities from the pre-treatment stage. Torrefaction is a preferred method for processing these impurities (Zaleski and Chawla, 2020). However, additional impurities after composting in the dry fermentation require incineration. The ash from biomass combustion and biochar from pyrolysis can enhance the creation of organic-mineral fertilizers (Chojnacka et al., 2021). Ultimately, wet fermentation demonstrates better alignment with circular economy principles.

5.2.2. *CBA of cogeneration vs. CNG production*

Since wet fermentation demonstrated superiority in all aspects, for further analysis of energy recovery we focus on scenarios WetCHP and WetCNG. The produced biogas can be used in two processes: cogeneration to produce heat and power (→ **CHP process**) and upgrading to biomethane, which yields *bio-compressed natural gas* (→ **CNG process**). In this study, the CNG process employs an additional CHP unit to ensure that all energy needs are met using recovered energy. This makes the system self-sufficient and enables a robust cost-benefit analysis.

Analysis of the CHP process

The cogeneration plant burns biogas to generate heat and electricity, see the left part of the flowchart in Fig. 3. Although we do not discuss it in the text, for completeness we present the analogous comparison for dry fermentation (scenarios DryCHP and DryCNG) in Fig. 4. The latter flowchart provides additional evidence in favor of our choice to evaluate only scenarios WetCHP and WetCNG.

For 6.156 mln m^3/year of biogas with a ca. 56% methane content, the total available energy is 34,474 MWh/year. In the Wrocław based project, a CHP unit of 1.57 MW was considered with the assumption that it would function at maximum capacity for 8760 hours per year after taking into account maintenance and downtime. Considering the overall energy efficiency of this CHP unit at 80%, half of the energy is available as heat, while the other half is obtainable as electricity. Additionally, in the process of electricity generation, it's crucial to account for a turbine efficiency factor of 95% when determining the actual electricity obtained. Hence the CHP unit will generate 13,100 MWh of electricity each year. Now, approximately 8% of this is required for sustaining wet fermentation (Dynamic Biogas, 2022). The rest, i.e., 92% or 12,052 MWh, can be delivered to the power grid, yielding a revenue of 12,052 MWh × 106.84 EUR/MWh = 1.288 mln EUR per year. In addition, about 20% of the heat generated is consumed by the wet fermentation process (Dynamic Biogas, 2022). The remaining 80% is either lost – as is assumed in this business plan – or sold and delivered to end users, given that an appropriate infrastructure (pipeline) exists and is available.

Analysis of the CNG process

In this process, the biogas is upgraded to biomethane in a process that requires heat. Hence, 20% of the biogas produced has to be burned in a CHP unit with a nominal power output of 0.31 MW to produce enough heat to be used in the upgrading process and in wet fermentation (Renew Energy, 2022), see the right part of the flowchart in Fig. 3. The methane content in biogas is ca. 56% (Dynamic Biogas, 2022), and with an availability and efficiency factor of 95%, the upgrading process yields 6.156 × 95% × 56% = 2.620 mln m^3/year of bioCNG.

With an availability and efficiency factor of 92%, the 0.31 MW cogeneration unit will produce 2,537 MWh of electricity each year. Approximately 85% of this is required for sustaining fermentation and

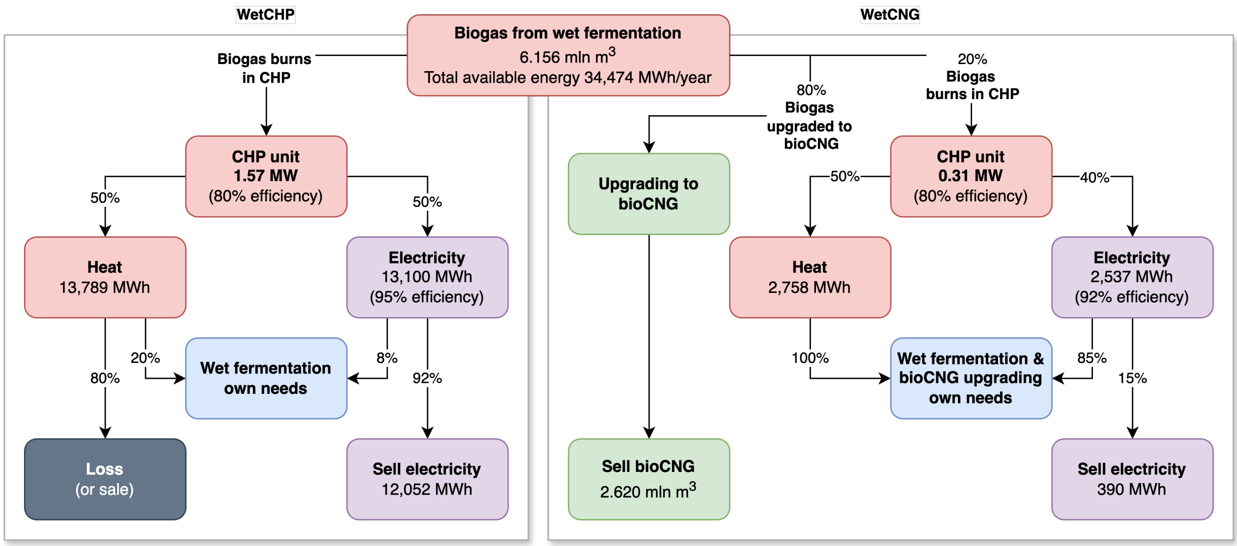

Figure 3: Comparison of WetCHP (*left*) and WetCNG (*right*) scenarios. In WetCHP, 100% of the biogas after wet fermentation is used for cogenerating heat and electricity, whereas in WetCNG, only 20%; the rest is upgraded to bioCNG. Moreover, in WetCHP, only 20% of the heat generated when burning biogas is reused for wet fermentation and the rest is lost.

upgrading. The rest, i.e., 15% or 390 MWh, can be delivered to the power grid, yielding a revenue of 390 MWh × 106.84 EUR/MWh = 0.042 mln EUR per year.

CHP vs CNG processes

Both CHP and CNG processes use the biogas recovered from waste and produce energy, either in the form of electricity or biomethane and electricity. Hence both are in line with the principles of the circular economy. The main factors differentiating these two processes are efficiency and profitability, see Table 3.

The CHP efficiency of the 1.57 MW unit in WetCHP is 3% higher, at 95%, as compared to 92% of the smaller unit (1.37 MW) in WetCNG, see Fig. 3. The basic difference between the two arises because in WetCHP (left part of the flowchart), 100% of the biogas after wet fermentation is used for cogenerating heat and electricity, whereas in WetCNG, only 20%; the rest is upgraded to bioCNG. Moreover, in WetCHP, only 20% of the heat generated when burning biogas (to produce electricity) is reused for wet fermentation and the rest is lost; the latter could potentially be resold if an appropriate infrastructure was available. On the other hand, in WetCNG, 100% of the heat generated in the (smaller) CHP unit is reused in the system – 80% in wet fermentation and 20% in the upgrading process, see Fig. 3.

The overall energy available from biogas in WetCHP and WetCNG scenarios is 124.106 TJ, i.e., 34,474 MWh ÷ 277.778 MWh/TJ, while the overall energy recovered in the CHP process is 12,052 MWh or 47.160 TJ. On the other hand, in the WetCNG scenario, the overall energy recovered amounts to (2.620 mln m^3 × 0.01 MWh/m^3 + 2,030.92 MWh) ÷ 277.778 MWh/TJ = 95.723 TJ. Here the energy from bioCNG is assumed to be 10 kWh/m^3, as recorded from the Wrocław based project. This indicates that the WetCHP and WetCNG can recover respectively 38.0% and 77.1% of the energy that is available at the beginning of the process. Clearly, WetCNG is more efficient.

For the cost-benefit analysis, the CAPEX and OPEX for WetCNG are estimated to be respectively 16.39% and 4.17% higher than for WetCHP. The revenue for the WetCHP is generated only through the

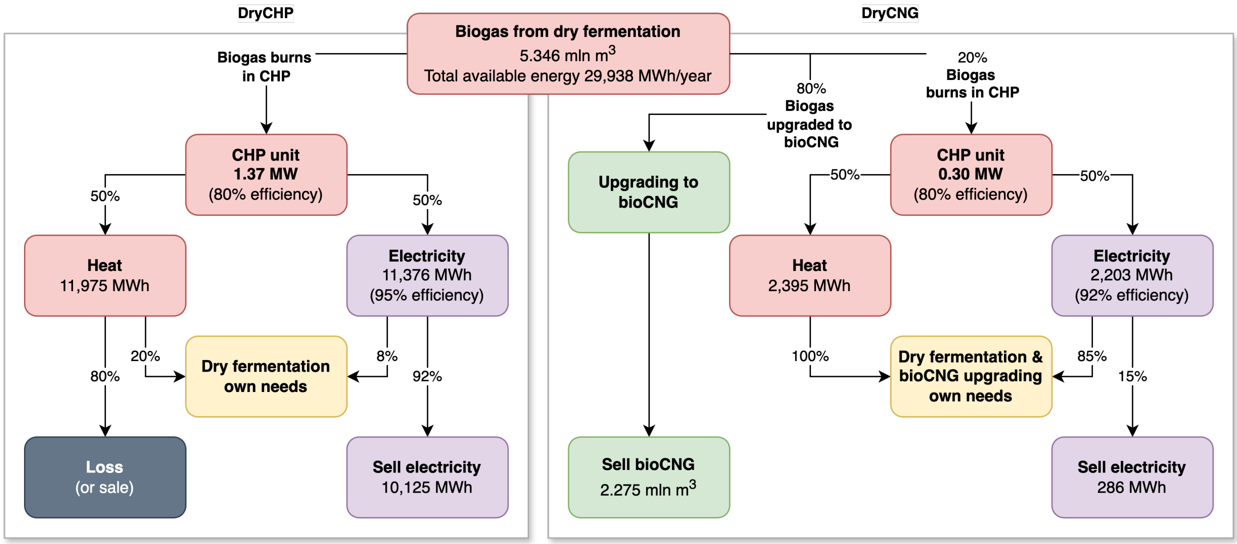

Figure 4: Comparison of DryCHP (*left*) and DryCNG (*right*) scenarios. Note that smaller CHP units than in Fig. 3 are needed to meet operational energy needs, especially for the DryCHP scenario. In DryCHP, 100% of the biogas after dry fermentation is used for cogenerating heat and electricity, whereas in DryCNG, only 20%; the rest is upgraded to bioCNG. Moreover, in DryCHP, only 20% of the heat generated when burning biogas is reused for dry fermentation and the rest is lost.

gate fees and sale of electricity, where as for WetCNG it is through gate fees, sale of electricity, and sale of bioCNG. Hence yearly revenue for WetCHP and WetCNG can be calculated as:

$$\begin{aligned} \text{WetCHP}_{\text{Revenue}} &= (\text{Volume of waste} \times \text{Gate fee}) + (\text{Units} \times \text{Price of electricity}) \\ &= (45,000\,\text{Mg} \times 96.154\,\text{EUR/Mg}) + (12,051.97\,\text{MWh/year} \times 106.84\,\text{EUR/MWh}) \\ &= 5.615\,\text{mln EUR/year} \end{aligned} \tag{1}$$

$$\begin{aligned} \text{WetCNG}_{\text{Revenue}} &= (\text{Volume of waste} \times \text{Gate fee}) + (\text{Units} \times \text{Price of electricity}) \\ &\quad + (\text{Volume} \times \text{Price of gas}) \\ &= (45,000\,\text{Mg} \times 96.154\,\text{EUR/Mg}) + (389.65\,\text{MWh/year} \times 106.84\,\text{EUR/MWh}) \\ &\quad + (2.620\,\text{mln m}^3/\text{year} \times 1.068\,\text{EUR/m}^3) \\ &= 7.168\,\text{mln EUR/year} \end{aligned} \tag{2}$$

Thereafter, Earnings Before Interest, Taxes, Depreciation and Amortization:

$$\text{EBITDA}_{\,scenario} = \text{Revenue}_{scenario} - \text{OPEX}_{scenario} \tag{3}$$

can be calculated as 2.551 mln EUR/year and 3.976 mln EUR/year, respectively for the WetCHP and WetCNG scenarios.

Clearly, the revenue and EBITDA are higher for WetCNG by ca. 28% and ca. 56%, respectively. Thus, moving away from aiming to maximize electricity production to upgrading biogas and using biomethane as, e.g., a fuel for the city's internal needs could mean a financial benefit of ca. 1.425 mln EUR/year, as

Table 3: Energy recovery and financial comparison of the four scenarios

Parameters/Scenarios	WetCHP	WetCNG	DryCHP	DryCNG
CHP unit nominal power output (MW)	1.57	0.31	1.37	0.30
Electricity sold to the grid (MWh/year)	12,052	390	10,125	286
CNG yearly output (mln m^3/year)	—	2.620	—	2.275
Energy recovered ‡ (TJ/year)	47.160	95.723	36.450	82.931
– as a percent of the total available energy	38.0%	77.1%	33.8%	76.9%
Capital expenses, CAPEX* (mln EUR)	15.641†	18.205	34.545†	37.110
Operating expenses, OPEX* (mln EUR/year)	3.063†	3.191	3.714†	3.842
Revenues* (mln EUR/year)	5.615†	7.168	5.445†	6.792
EBITDA* (mln EUR/year)	2.551†	3.976	1.731†	2.950

†Values identical to those in Table 2.
‡Values have been calculated based on the recovered electricity and biogas, see Figs. 3 and 4.

shown in Table 3. This justifies the initial higher CAPEX for scenario WetCNG compared to WetCHP. In particular, based on this point calculation the benefits would cover the higher CAPEX in just over a year, considering tax issues. It should be noted here, that these numbers are possible if the city's own fleet of trucks or buses is adapted to combust bioCNG. Under the current legal conditions of the Electro-mobility Law, biomethane-powered and electric-powered buses are treated as zero-emission (EU, 2022). By the end of 2025, 30% of the fleet must consist of low- and zero-emission vehicles. This creates an opportunity to meet these requirements cheaper than investing in electric vehicles. However, such savings were not the focus of this analysis.

5.3. Financial projections based on a survey of professional energy forecasters

Now we elaborate on profitability projections derived from electricity (EE) and natural gas (NG) price forecasts. These forecasts were gathered through a self-administered online survey among professional energy forecasters in Poland. The price calculation paths are illustrated in Figure 5. Clearly, the prediction intervals – traditionally plotted in red, hence nicknamed 'rivers of blood' (Dowd, 2007) – fan out as the forecast horizon increases. This indicates an increase in price uncertainty for longer horizons as perceived by professional energy forecasters. The latter is particularly visible for NG prices, see the right panel in Figure 5, where in the year 2035 the maximum price (light blue color) exceeds 300 EUR/MWh, while the 90th percentile (upper bound of the 80% PI; shade darker) reaches ca. 150 EUR/MWh and the 80th percentile (another shade darker) only ca. 100 EUR/MWh. However, the state guarantee for the sale prices of EE and NG (Polish Government, 2023a) is a promising policy intervention. For EE the state guarantee is rather below the median price path obtained from the forecasters. On the other hand, it is considerably higher than the median for NG. This reduces the volatility risks of prices, especially in the NG sale.

The price paths of each individual respondent were then used as input to calculate EBIDTA for all four scenarios using Eqs. (1), (2), and (3). Bootstrap sampling of entire paths ensures that the temporal dependence structure is preserved (Maciejowska, 2022; Narajewski and Ziel, 2020). Furthermore, in order to retain the dependency between electricity and natural gas prices projected by individual respondents, in the CNG scenarios the EE and NG price paths are sampled jointly from the 18 available pairs of paths. On the other hand, in the CHP scenarios, only electricity price projections are required and thus all 24

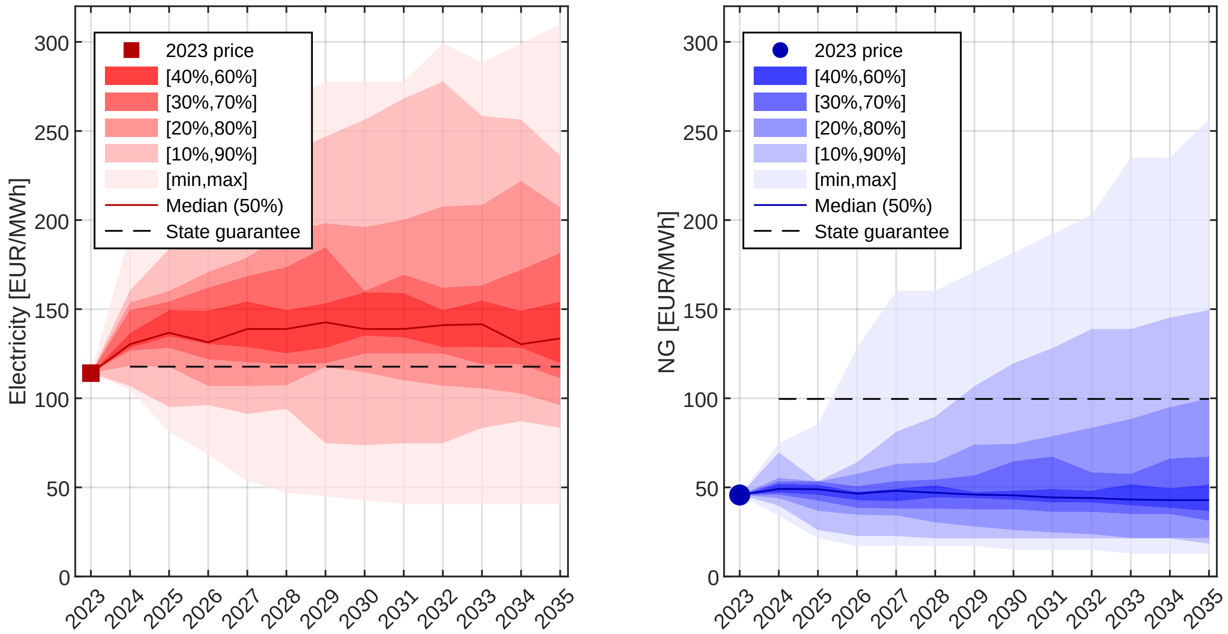

Figure 5: Fan charts of wholesale electricity (*left*) and natural gas (NG; *right*) prices in EUR/MWh for the years 2024-2035 from the conducted survey of professional energy forecasters. For the year 2023, the actual average is shown (red square, blue circle).

EE price paths can be used. Note that unlike Serafin et al. (2022), we do not use copulas to model the multidimensional and temporal dependence structure, as this would require a larger number of responses for calibration.

The calculated EBIDTA values for scenarios WetCHP and WetCNG are illustrated in the left panel of Figure 6, and for DryCHP and DryCNG in the right panel. We use overlapping fan charts to compare the projections for the years 2024-2035. Clearly, the projections show that scenarios WetCNG and DryCNG are riskier in the longer term – the lower blue shaded areas are below the corresponding red shaded areas. For example, in 2035 there is a 10% chance (10th percentile) that the EBIDTA for the WetCNG will will not exceed 2.50 million EUR, while for the WetCHP there is a 10% chance that the EBIDTA will not exceed 3.31 million EUR. At the same time, it is potentially more profitable – the upper blue shaded areas are above the corresponding red shaded areas. For example, the 90th percentile EBIDTA for the WetCNG is 6.84 million EUR, while it is only 5.76 million EUR for the WetCHP in 2035. As noted earlier, WetCNG has a higher initial investment (CAPEX). However, the analysis using the 2022 values (see Section 4.3) suggested this difference could be recovered in just over a year. The projected NG and EE prices in Figure 5 further reinforce this possibility. Additionally, it can be seen that the for the DryCHP and DryCNG scenarios, the projections are lower than that of WetCHP and WetCNG, respectively. However, the risk related to DryCHP or DryCNG would be much higher than WetCHP or WetCNG, respectively, because of considerably higher CAPEX, see Table 3. It would require almost 5 years in scenario DryCNG just to recover the additional CAPEX compared to WetCNG; this is without considering the cost of capital.

Due to the risk of price fluctuations, Poland has introduced state-guaranteed prices for a period of 15 years, for facilities that recover energy from waste: 551 PLN/MWh for electricity and 466.2 PLN/MWh for natural gas, see the red and blue dashed lines in Fig. 5. This significantly reduces the risk for WetCHP and

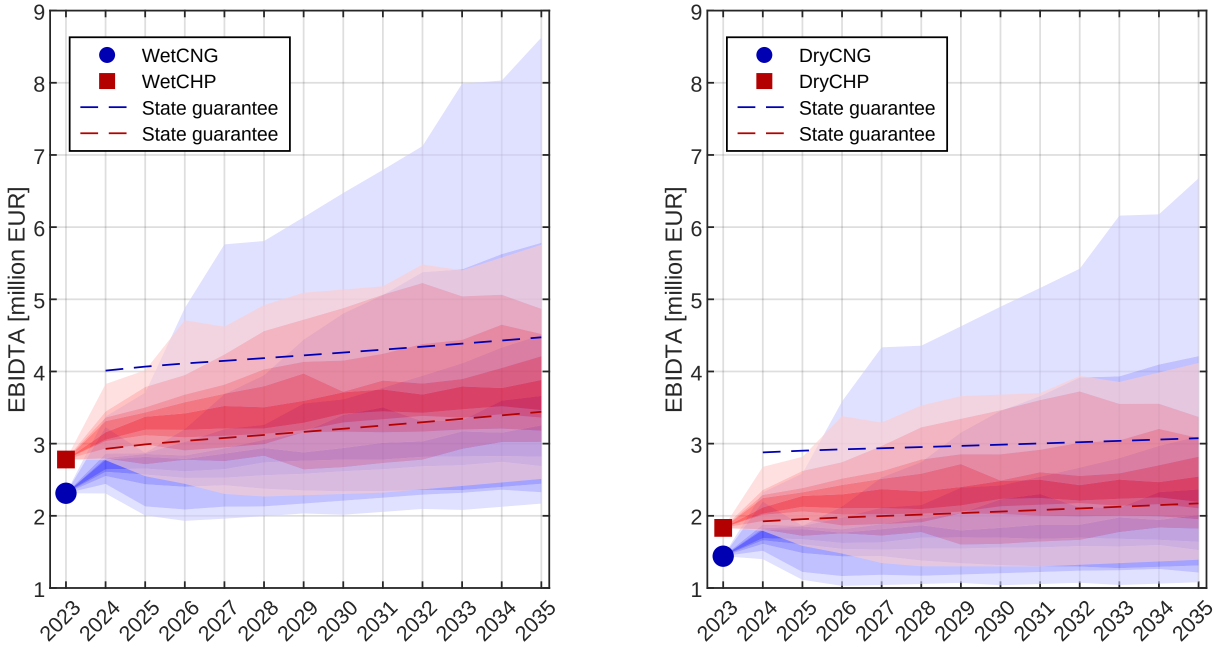

Figure 6: Fan charts of the EBIDTA projections for the four considered scenarios: two for wet (WetCHP and WetCNG; *left*) and two for dry fermentation (DryCHP and DryCNG; *right*). Note that the CHP scenarios (red) use 24 electricity price paths from the conducted survey of professional energy forecasters, while the CNG scenarios (blue) use 18 pairs of electricity and NG price paths.

WetCNG scenarios, while increasing financial viability and profitability. As can be clearly seen in Figure 6, the EBIDTA calculated based on the state guarantee is more lucrative for WetCNG as compared to WetCHP. Therefore, this guarantee incentivizes the construction of biogas plants for energy and material recovery, with particular focus on the WetCNG scenario.

5.4. Practical insights for scenario implementation

In order to manage the growing amount of waste, new projects are currently in various stages of implementation in Poland. However, the key informants highlighted several challenges that hinder the process. One such important case was from the large municipality of Wrocław in southwestern Poland, where the project was suspended at the stage of environmental clearance, citing citizen concerns. This signifies the need to assess social acceptance, further adding to the work of Moreau et al. (2017). Failure to involve the community can lead to protests, delays, and suspension. This project, which was planned to use the WetCHP scenario, was held back due to lack of community awareness of the potential impacts of implementation in their vicinity, and national and local elections further complicated the case. To avoid such setbacks, it is essential to prioritize social acceptance and open communication with the public is essential. Based on the insights from the key informants, we formulated a concise action plan for implementing the scenarios considered in study, see Table 4.

Table 4: Action plan for implementation scenario(s)

1.	Advocate for regulations and incentives at local and national levels that support the development and implementation of anaerobic digestion plants with energy recovery.
2.	Identify potential sites for biogas plants, such as landfills or treatment facilities, perform cost-benefit analysis to determine the most appropriate scenario, and conduct feasibility studies, including social acceptance analysis, to determine the best locations for these facilities.
3.	Develop partnerships with waste management companies, municipalities, and local communities to collect and process the selective kitchen waste needed for the biogas plants.
4.	Implement the selected fermentation scenario (e.g., WetCNG for 72% energy recovery from biogas).
5.	Monitor the production of biogas and digestate, as well as the financial gain, energy savings, and reduction of landfill waste.
6.	Continuously evaluate and optimize the efficiency and profitability of the biogas plants through use of emerging technologies, and data collection and analysis.
7.	Disseminate information about the success and benefits of this approach to other municipalities and encourage the replication of this model.
8.	Identify, highlight and mitigate the potential risks and challenges that may arise during the implementation process.
9.	Continuously monitor and implement best available techniques (BATs) for the process and equipment to improve the efficiency and effectiveness of the system.

6. Discussion and future perspectives

The fate of humanity rests on our current efforts to protect the environment and conserve dwindling resources (EU, 2022). The common practice of waste management through landfills is discarding a variety of materials, leading to the loss of valuable resources and energy (Chen et al., 2022). This article addresses critical empirical gaps in the literature, aiming to pave the way for a potential shift away from landfills towards anaerobic digestion methods. This transition promises improved profitability and enhanced waste management through a more sustainable and circular economy approach.

The study makes four key contributions. Firstly, a detailed cost-benefit analysis, comparing WetCHP, WetCNG, DryCHP and DryCNG scenarios, indicates that precise data calculations, forecasts, as well as policy interventions support the profitability of WetCNG. What sets this research apart is its utilization of real-world empirical data obtained from key informants. The study's results and detailed procedures furnish practical insights into managing the escalating volumes of municipal waste directed to landfills in a sustainable manner. Furthermore, the utilization of biogas digestate as fertilizer presents a significant opportunity for increasing material recovery of municipal waste. This approach not only reduces the volume of waste sent to landfills but also provides a valuable resource for agriculture, reducing the need for synthetic fertilizers and promoting soil health. However, it is crucial to acknowledge potential risks associated with digestate utilization, such as the presence of heavy metals or microplastics. These risks can be mitigated through careful source separation of waste, pre-treatment processes at the biogas plant, and regular monitoring of digestate quality. By addressing these concerns, the full potential of biogas digestate for material recovery and sustainable waste management can be realized.

Detailed environmental trade-offs of each of these scenarios were beyond the scope of this study, however important to discuss. Wet fermentation achieves higher biogas yields but may result in greater greenhouse gas emissions, particularly during handling and processing stages (Pöschl et al., 2010; Kumar and

Samadder, 2017). Conversely, dry fermentation generally has lower greenhouse gas emissions but requires higher water consumption for effective operation (Ghisellini, 2023). The choice between these methods should align with the specific priorities of the project, such as minimizing emissions or conserving water resources, underscoring the importance of tailoring waste management strategies to local environmental and regulatory conditions. The methodological contributions, encompassing various permutations and combinations, along with specific results, offer valuable insights for comparative case studies and investment evaluations, addressing the literature gap concerning the scarcity of empirical data, especially from a real project.

The second novel contribution of this study is the involvement of energy traders in the process of a long-term evaluation of a project. By anonymously surveying professional forecasters, the study provides realistic forecasts of electricity and natural gas prices from 2024 to 2035, which are generally considered proprietary knowledge and kept secret. These forecasts can help researchers, managers, and policymakers make better decisions about investments. In particular, our study shows that while the WetCNG scenario might seem more profitable initially, it also comes with higher risks over time due to price fluctuations. This means that different municipalities may need different strategies depending on how much financial risk they can handle. So, it is crucial to consider not only inflation but also the expected prices of commodities when planning such investments.

Thirdly, the study provides a comprehensive technical and managerial background for local governments and businesses to sustainably manage municipal waste management. By underscoring the importance of knowledge exchange between the public and private sectors, it provides new avenues for researchers, practitioners, and policymakers to participate in or explore public-private partnerships (Sarmento and Renneboog, 2016). This collaborative approach addresses the challenges associated with material recovery and ensures energy security, a vital geopolitical concern (Blondeel et al., 2021). The paramount goal of establishing a sustainable society through recycling and reusing necessitates collective endeavors.

Finally, The recent introduction of state-guaranteed energy prices in Poland is a promising policy intervention, especially for the CNG scenarios. Such interventions significantly reduce the investment risk, which has a positive impact on the economic viability – a crucial factor for projects of this nature. State guarantees effectively mitigate revenue fluctuations caused by volatile energy markets, ensuring stable returns over the project's operational lifespan. This is particularly impactful for scenarios like WetCNG, which involve higher volatility but offer long-term profitability under stable pricing conditions. Additionally, for Poland to fully realize its biogas potential, it is recommended to include meat in the kitchen waste fraction, following the Danish example for higher biogas yields. To further address barriers to implementation, policies promoting targeted subsidies and tax incentives could mitigate high upfront investment costs. Strengthening regulations on waste segregation, alongside public awareness campaigns, can improve feedstock quality and availability. Moreover, encouraging public-private partnerships (PPPs) would foster collaboration between municipalities and private investors, ensuring shared risks and streamlined project execution. Together, these policy measures can accelerate the adoption of biogas technologies and align waste-to-energy practices with circular economy goals.

From a justice perspective, the energy recovery options explored in this study also have significant social implications. Biogas upgrading to bioCNG, for instance, presents an opportunity to address energy poverty by providing cleaner, affordable energy to underserved communities. The localization of biogas plants within urban areas can support local energy autonomy, reducing dependence on fossil fuels and lowering energy costs, particularly in regions where traditional energy infrastructure is insufficient (Sovacool, 2021). Moreover, ensuring that the transition to bio-based energy recovery includes marginalized communities helps prevent the perpetuation of social inequities that are often associated with conventional energy systems. Enhancing social acceptance is critical to the success of such initiatives and can be achieved through public awareness campaigns, stakeholder consultations, and transparent communication about the environmental and economic benefits of biogas technologies. Early involvement of local communities in decision-making processes can also foster trust and encourage active participation, ensuring long-term acceptance and equitable outcomes. By focusing on community involvement and equitable resource allocation, the CE can play a critical role in achieving both environmental and social justice.

Looking ahead, future research in biogas production and waste management should concentrate on improving the efficiency and profitability of the wet fermentation process. Exploration of alternative feedstocks for biogas production and development of advanced energy recovery technologies, such as upgrading to biomethane, are additional areas of focus to maximize energy recovery and minimize greenhouse gas emissions. The scalability and implementation of biogas production and waste management systems in diverse municipalities and regions, as well as the exploration of supportive policies and regulations for the transition to a circular economy, are also essential. The integration of advanced technologies, such as AI, can play a pivotal role in analyzing and optimizing the biogas production process and waste management. Additionally, researching and developing a framework to understand social acceptance (Wüstenhagen et al., 2007) in waste management projects – both general and municipal-specific – would prove beneficial. This framework could incorporate social life cycle assessment (S-LCA) (Sala et al., 2015) as a key tool to comprehensively assess the social impacts of waste management initiatives throughout their entire lifecycle. This would provide valuable insights into potential social benefits and drawbacks, contributing to a more holistic understanding of social acceptance and facilitating the development of more sustainable and socially responsible waste management practices.

7. Conclusions

The study advocates a shift in waste management, highlighting the inadequacy of traditional landfills in the face of resource scarcity and stringent regulations. By proposing anaerobic digestion for specific waste categories, in particular selectively collected kitchen waste, the research emphasizes energy recovery and environmental impact mitigation. Filling a critical empirical gap, it provides actionable insights for waste management, addressing economic viability as a catalyst for sustainable practices. By evaluating and comparing alternative processes – wet vs dry digestion, cogeneration (CHP) vs upgrading to bioCNG (CNG) – the study provides practical insights based on ongoing project implementation. A novel concept, a survey of professional energy forecasters, provides a market-driven projection of energy prices from 2024 to 2035, contributing to a probabilistic assessment of risk-reward relationships. Importantly, the study also highlights the importance of understanding the social acceptability of such scenarios and policy interventions. In conclusion, this research provides guidance to municipalities and businesses on sustainable waste management, offers practical insights, and contributes to the discourse on implementing innovative practices amidst contemporary environmental and energy transition challenges.

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