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REDUCING GREENHOUSE EMISSIONS IN ENERGY-PLUS CONSTRUCTION BASED ON RENEWABLE ENERGY SOURCES IN POLAND

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ABSTRACT

The European Union's decarbonization targets necessitate a rapid transformation of the building sector toward net-zero emissions. This study presents a comprehensive techno-economic and environmental assessment of photovoltaic (PV), wind, and hybrid PV–wind systems for energy-plus buildings in six representative Polish cities: Białystok, Katowice, Lublin, Poznań, Szczecin, and Gdańsk. Using HOMER Pro simulation software, systems were optimized to minimize Levelized Cost of Energy (LCOE) while maximizing renewable fraction. Results indicate that inland cities achieve optimal performance with PV-only systems (LCOE: 0.50–0.60 USD/kWh), whereas coastal cities favor wind-only systems (LCOE: 0.65 USD/kWh) due to higher wind resource availability. Annual greenhouse gas (GHG) reductions range from 89% to 94%, equivalent to 6.5-7.4 tons CO_2 *per building. Sensitivity analysis confirms the significance of capital cost reductions and financing conditions for economic viability. Policy recommendations include targeted incentives, PV-ready building codes, and grid modernization. The findings provide actionable insights for policymakers, investors, and engineers aiming to accelerate renewable integration in Poland's residential sector.*

Keywords: *Energy-plus buildings, photovoltaic, wind energy, hybrid systems, techno-economic analysis, Poland, HOMER Pro, LCOE, greenhouse gas reduction.*

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1. INTRODUCTION

The building sector is a major contributor to global greenhouse gas (GHG) emissions, responsible for about 36% of final energy consumption and 37% of energy-related CO_2 emissions (Lu & Lai, 2020). To address this, the concept of *energy-plus buildings*—which generate more energy annually than they consume—has gained prominence as a pathway toward achieving the European Union's (EU) climate neutrality objective by 2050 (PLGBC, 2021). These buildings typically integrate on-site renewable generation, such as photovoltaic (PV) panels and small-scale wind systems, with advanced efficiency measures to achieve a positive net energy balance (Prisikar, 2018; Zhang et al., 2018).

In Poland, however, the transition to low-carbon buildings faces unique challenges. More than 70% of the country's electricity is still produced from coal (Igliński et al., 2023), making building-sector decarbonization both urgent and impactful. Policy instruments such as the updated net-billing system for prosumers have reshaped the economics of distributed renewable generation, creating both opportunities and uncertainties for households and enterprises (Igliński et al., 2023; PLGBC, 2021). While earlier studies have examined the technical potential of PV in Poland (Igliński et al., 2023) and assessed regional wind resources (KAPE, 2021), there remains a gap in integrated, building-level techno-economic and environmental assessments that account for seasonal variability, life-cycle carbon impacts, and policy context (Jackson, 2020; Garlík, 2022).

This study addresses that gap by:

i. Analyzing PV, wind, and hybrid PV–wind configurations across multiple climatic zones in Poland.

ii. Quantifying the levelized cost of energy (LCOE), renewable fraction, and GHG reduction potential.

iii. Conducting sensitivity analyses to evaluate the impacts of capital costs, financing rates, and resource variability.

iv. Linking findings to policy, with recommendations aligned to Poland’s *Energy Policy until 2040* and the EU’s *Whole Life Carbon Roadmap for 2050*.

2. REVIEW OF LITERATURE

Globally, energy-plus buildings have been successfully demonstrated in diverse climates. In Germany, Voss and Musall (2011) showed that combining high-efficiency photovoltaic

(PV) systems with advanced insulation can achieve net-positive building performance. In Denmark, Lund et al. (2015) emphasized the complementarity of solar and wind resources, particularly in coastal regions, for achieving reliable renewable energy supply. In the Netherlands, retrofitting projects have achieved near-zero energy performance through PV integration and demand-side management (Zhang et al., 2018).

In Central and Eastern Europe, however, research remains limited. Krajnc and Domjan (2011) reported that PV payback periods in Slovenia are highly sensitive to feed-in tariff structures. In Hungary, Kiss et al. (2020) found that hybrid PV–wind systems improve supply stability despite higher capital costs. In Poland, Paska et al. (2012) analyzed PV economics under the former net-metering regime and found favorable returns, although recent policy reforms have lengthened payback periods (Igliński et al., 2023).

From a policy perspective, the European Union’s Energy Performance of Buildings Directive (EPBD) mandates nearly zero-energy building (nZEB) standards for all new construction by 2030 (European Commission, 2020). Poland’s *Energy Policy until 2040* (PEP2040) identifies renewable integration as a strategic priority but continues to face challenges related to grid infrastructure and regulatory barriers (Ministry of Climate and Environment, 2021). On the technology side, global PV module prices have fallen by more than 80% over the past decade (International Renewable Energy Agency [IRENA], 2021), making small-scale PV increasingly viable even in moderate climates. While Poland’s coastal regions benefit from high wind potential, restrictive siting rules—particularly the “10H” regulation—have limited deployment (Ministry of Climate and Environment, 2021).

Key gaps in the literature include:

- A lack of integrated PV–wind assessments at the building level in Poland.
- Limited evaluation of seasonal variability on renewable fraction and levelized cost of energy (LCOE).
- Weak linkage between technical results and actionable policy recommendations.

This study seeks to address these gaps through detailed simulation modeling, comparative analysis, and policy-oriented recommendations.

3. RESEARCH METHODOLOGY

3.1 Study Area

Six Polish cities were selected to represent the country’s climatic diversity: inland locations (Białystok, Katowice, Lublin, and Poznań) and coastal locations (Szczecin and Gdańsk). Inland sites are characterized by moderate solar irradiance (3.0–3.4 kWh/m²/day) and relatively low wind speeds (3.5–4.5 m/s at 50 m hub height), whereas coastal sites exhibit higher wind speeds (>6.5 m/s) with comparable solar potential (KAPE, 2021).

3.2 Data Sources

Meteorological data, including global horizontal irradiance (GHI), wind speed, and temperature, were obtained from the

NASA POWER Data Access Viewer (NASA, 2023). Load profiles were developed using household energy consumption data from the Polish Central Statistical Office (Statistics Poland, 2022), which were further adjusted to represent an energy-plus building with passive design features.

Economic parameters were obtained from market data and cost benchmarks published by the International Renewable Energy Agency (IRENA, 2021). The Polish grid emission factor was assumed at 820 gCO_2/kWh, consistent with national averages for coal-dominated electricity generation (Igliński et al., 2023). Figure 1 illustrates the overall energy simulation framework, which integrates photovoltaic (PV) modules and wind turbines. Economic parameters were sourced from market data and IRENA cost benchmarks. The Polish grid emission factor was set at 820 gCO_2/kWh.

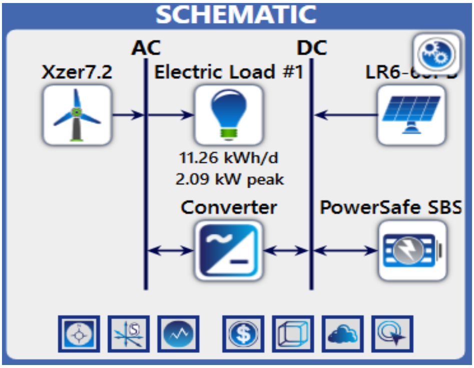

Figure 1. Energy simulation diagram approach

3.3 System Configurations

Three configurations were modeled: PV-only, wind-only, and hybrid PV-wind. In Table 1, technical and cost parameters are shown for PV and wind because hybrid approaches were not economical.

Table 1. technical and economical parameters for PV and WT systems

Parameter	PV	Wind
Rated capacity (kW)	5	5
CAPEX (USD/kW)	1,200	1,800
Replacement cost (USD)	600	1,200
O&M cost (USD/year)	25	60
Lifetime (years)	25	20
Efficiency (%)	19	–

Source: The authors' own work.

3.4 Simulation Tool

HOMER Pro was used for hourly simulation over one year. LCOE was calculated as:

$$LCOE = \frac{\mathrm{NPC} \times CRF}{E_{\mathrm{annual}}}$$

Where NPC is net present cost, CRF is capital recovery factor, and E_{annual} is annual generation (Lambert et al., 2006).

3.5 Sensitivity Analysis

Capital cost, discount rate, and resource variability were varied to assess robustness.

4. RESULTS AND DISCUSSION

4.1 Overview of Simulation Outcomes

Simulation results revealed strong geographic differentiation in optimal renewable configurations. Inland cities—Białystok, Katowice, Lublin, and Poznań—consistently favored PV-only systems, achieving levelized costs of energy (LCOEs) between 0.500 and 0.600 USD/kWh (shown in Figure 2). In contrast, coastal cities—Szczecin and Gdańsk—favored wind-only systems, with LCOEs as low as

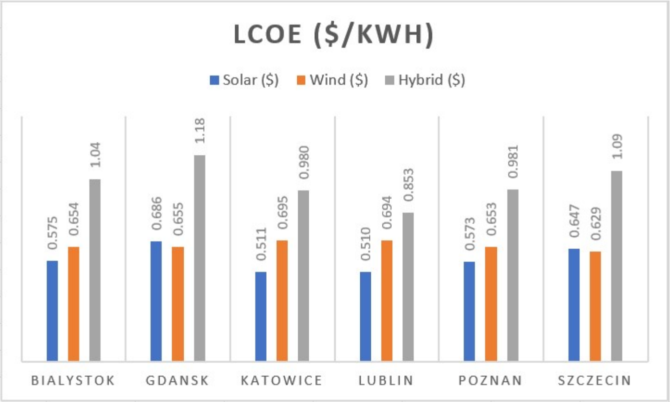

Figure 2. LCOE of the following cities for RES

0.629 USD/kWh, driven by higher wind speeds (>6.5 m/s) and capacity factors exceeding 35%. These outcomes are consistent with prior findings on resource complementarity in northern Europe (Lund et al., 2015; Kiss et al., 2020).

4.2 Techno-Economic Performance

Table 2. the optimal system configuration, LCOE, GHG reduction, and renewable fraction

City	Optimal Technology	LCOE (USD/kWh)	GHG Reduction (%)	Renewable Fraction (%)
Białystok	PV	0.575	90.99	94.32
Katowice	PV	0.511	89.09	93.11
Lublin	PV	0.510	89.07	93.09
Poznań	PV	0.573	90.93	94.29
Szczecin	Wind	0.629	92.98	95.35
Gdańsk	Wind	0.655	93.35	95.84

Source: The authors' own work.

Table 2 summarizes the optimal system configuration, LCOE, GHG reduction, and renewable fraction. These LCOEs are competitive with reported residential PV costs in Germany (~0.850 USD/kWh; IRENA, 2021) and coastal wind in Denmark (~0.600 USD/kWh; Lund et al., 2015).

4.3 Seasonal Energy Generation Profiles

PV systems showed strong seasonal variation, with summer output (May–August) up to three times higher than winter (December–January). Wind systems demonstrated more uniform generation across the year, with peaks in autumn and winter that align with heating loads. Hybrid systems mitigated variability, achieving renewable fractions above 90%, albeit with a slight LCOE increase (~3–5%) due to higher capital costs.

These findings are consistent with the stability benefits of hybrid systems reported by Kiss et al. (2020).

4.4 Environmental Impact

Annual greenhouse gas (GHG) reductions ranged from 89.07% in Lublin to 93.35% in Gdansk, equivalent to 6.5–7.4 tons of CO_2 per building, based on Poland's grid emission factor of 820 gCO_2/kWh (Igliński et al., 2023). Scaling to 100,000 residential units yields annual savings of ~0.7 $MtCO_2$, or ~1.2% of Poland's residential-sector emissions.

4.5 Sensitivity Analysis

- Capital Cost Variation: A 20% reduction in PV capital expenditure (CAPEX) decreased inland LCOE by ~0.015 USD/kWh, narrowing the gap with coastal wind.
- Discount Rate Variation: Raising the discount rate from 6% to 10% increased wind LCOE by ~0.02 USD/kWh due to higher upfront costs.
- Resource Variability: A 10% reduction in wind speed could make PV–wind hybrid systems optimal in Gdańsk.

These trends highlight the importance of financing conditions and resource certainty, consistent with IRENA's (2021) cost sensitivity analyses.

4.6 Comparative Context with EU Benchmarks

Inland PV LCOEs approach German levels (IRENA, 2021), while coastal wind performance is comparable to Denmark (Lund et al., 2015). These results suggest that Poland can achieve EU market parity in distributed renewable generation through targeted incentives and grid modernization.

4.7 Policy Implications

- Targeted Incentives: Inland PV supported through grants or feed-in tariffs; coastal wind enabled through regulatory relaxation of siting restrictions.
- Hybrid Promotion: Recognition of grid stability benefits in remuneration frameworks.
- PV-Ready Building Codes: Mandating structural readiness for rooftop PV could lower retrofit costs by up to 20% (Voss & Musall, 2011).
- Grid Modernization: Upgrading rural and coastal networks to accommodate higher renewable penetration.

5. CONCLUSION

This study confirms that energy-plus buildings in Poland can achieve high renewable fractions and significant GHG reductions through location-specific system optimization. Inland regions benefit most from PV-only configurations, while coastal areas favor wind-only systems. Hybrid PV–wind offers enhanced reliability and seasonal balance, albeit with slightly higher costs. Large-scale deployment could cut residential CO_2 emissions by over 1% annually, contributing to Poland’s PEP2040 and EU Green Deal objectives. Policy measures focusing on incentives, building codes, hybrid recognition, and grid upgrades are recommended to accelerate adoption. Overall, this research confirms that energy-plus buildings, when designed with regional resource conditions in mind, can simultaneously lower energy costs, reduce emissions, and strengthen Poland’s alignment with EU decarbonization pathways.

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