12th INTERNATIONAL SCIENTIFIC CONFERENCE
RURAL DEVELOPMENT 2025
RESILIENCE TO GLOBAL CHANGE
1-3rd October, 2025, Vytautas Magnus University Agriculture Academy, Lithuania

VYTAUTAS MAGNUS UNIVERSITY AGRICULTURE ACADEMY

Proceedings of the 12th International Scientific Conference Rural Development 2025

Edited by assoc. prof. dr. Judita Černiauskienė

ISSN 2345-0916 (Online)

Article DOI: https://doi.org/10.15544/RD.2025.024

# IMPACT OF URBAN EXPANSION ON WIND ENERGY POTENTIAL IN RURAL REGIONS OF LITHUANIA

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Wind energy is one of the main renewable sources in Lithuania. Rural regions are suitable for wind farms due to open landscapes, good wind conditions and low settlement density. Previous research focused on climate change, but the effect of urbanisation was rarely analysed. This study evaluates how different urban growth rates change wind characteristics and electricity generation. The analysis used wind speed observations from 22 meteorological stations (1990–2020). These data were combined with projections from seven global circulation models under three Representative Concentration Pathway (RCP) scenarios: RCP2.6 (minimal emissions), RCP4.5 (medium emissions, current policies trajectory), RCP8.5 (high emissions). Urbanisation was represented by three growth rates: slow (200 years), moderate (100 years) and fast (50 years). They correspond to increasing surface roughness and turbulence. Wind speeds were calculated for hub heights of 100 m and 150 m. Two turbine types were considered: Enercon E-112 and E-126. Energy yield was estimated for a 25-year turbine lifetime. The results show that climate change has only a small impact. Wind speed decreases by less than 8%, and electricity generation declines only slightly. Urbanisation has a much stronger effect. Energy yield falls by 28–32% under slow expansion, by 39–45% under moderate expansion, and by more than 50% under fast growth. Coastal regions remain the most productive, but inland areas are more vulnerable. Higher turbines increase output, but they cannot compensate for roughness. Assessments that ignore urbanisation tend to overestimate long-term wind energy potential. Including land-use change gives more realistic information for rural development, energy planning and spatial policy in Lithuania.

***Keywords***: *wind energy, urbanisation, rural regions, Lithuania, renewable energy potential*

## INTRODUCTION

In recent decades, global electricity demand and supply have undergone major transformations. From reliance on fossil fuels in the 20th century, the energy sector is increasingly shifting towards renewable sources, driven by climate change concerns, environmental regulations, and technological progress(Halder et al., 2020; Pata et al., 2023). Among renewables, wind energy has emerged as a key contributor to the decarbonisation of power systems. In the European Union (EU), installed wind capacity has increased from less than 3 GW in 2000 to over 220 GW by 2020, supplying around 15% of total electricity generation (Bórawski et al., 2020; Tobin et al., 2015; Wasilczuk et al., 2025). This expansion has significantly reduced greenhouse gas (GHG) emissions and strengthened energy security. Globally, wind power capacity exceeded 700 GW by 2020 and is projected to more than double by 2040, becoming a central pillar of carbon-neutral energy strategies.

Lithuania has also experienced a rapid transformation. Since the early 2000s, the country has shifted from strong dependence on fossil fuels to increasing reliance on renewable sources, with wind energy playing a central role. By 2020, more than 500 MW of wind power had been installed, covering approximately 18% of national electricity production (Marčiukaitis et al., 2016; Sliogeriene, 2014). Future strategies include ambitious targets to reach 45% renewables by 2030, supported by both onshore and offshore wind projects (Ministry of Energy of the Republic of Lithuania, 2022; Statistics Lithuania, 2024). Nevertheless, wind farm development in Lithuania is spatially constrained by environmental protection zones, military areas, and settlement buffers, which limit the technically available land for new projects.

Wind energy potential is not static. It depends on both climatic and land-use factors. According to the Intergovernmental Panel on Climate Change (IPCC), climate change may modify wind patterns, but projected changes in Europe are generally modest, ranging from –6% to +8% by the end of the century under different Representative Concentration Pathways (RCPs) (Jung & Schindler, 2021; Collins et. al., 2013; Zhang et. al., 2018). In contrast, urbanisation introduces significant uncertainty. Expanding settlements alter surface roughness, increase turbulence, and may substantially reduce wind speed and turbine efficiency (Farhat et al., 2025; Lv et al., 2022; Theeuwes et al., 2019).

Previous studies have shown difficulties in modelling wind resources in urbanised landscapes, with discrepancies between observed and predicted values often reaching 30–45% (Reja et al., 2022; Tasneem et al., 2020; Toja-Silva et al., 2018). The combined impact of urban growth and climate change on long-term wind energy potential in rural regions has received little scientific attention.

Although climate-related changes in European wind resources are generally moderate, recent reviews emphasise a more substantial methodological gap: long-term wind assessments rarely account for land-use evolution and the associated increase in surface roughness, despite evidence that these factors substantially modify wind speed and turbulence over time (Jung & Schindler, 2022; Reja et al., 2022). Most studies examine climate change in isolation and treat urbanisation as a fixed boundary condition, without quantifying how expanding rural settlements may gradually reduce wind speeds and alter turbine performance. No previous research has integrated dynamic roughness evolution with bias-corrected climate projections to evaluate long-term wind energy potential in Lithuania or comparable regions. By addressing this omission, the present study provides a novel combined assessment that clarifies the relative importance of climate change and urban expansion for future wind availability and electricity generation.

This study integrates both climate and land-use dynamics into wind resource modelling, using bias correction of Global Circulation Models (GCM) data and dynamic surface roughness parameterisation. While climate change impacts have been widely analysed, the role of urban growth in reshaping rural wind resources has rarely been addressed, and no studies so far have combined both factors in the Lithuanian context. The aim of this research is to assess the impact of urban expansion on long-term wind energy potential in rural regions of Lithuania, considering different climate change scenarios. To achieve this aim, three objectives were formulated: first, to analyse historical wind speed data (1990–2020) and project future changes under RCP2.6, RCP4.5, and RCP8.5 scenarios; second, to evaluate how different urban expansion rates (slow, moderate, fast) influence surface roughness, wind characteristics, and electricity generation; and third, to compare the relative significance of climate change and urban expansion for future wind energy deployment in rural Lithuania.

## RESEARCH METHODS

Wind speed observations from 22 meteorological stations in Lithuania (1990–2020) were used as a baseline for model validation. Meteorological station data were analysed at point scale without spatial interpolation, ensuring consistency between observed and modelled series. Future changes (2006–2100) were assessed using seven global circulation models (GCMs): MPI-ESM-LR, HadGem2-ES, IPSL-CM5A-MR, CNRM-CM3, CSIRO-MK3, CanESM2, MIROC-ESM under three Representative Concentration Pathways: RCP2.6, RCP4.5, and RCP8.5. Bias correction was applied by comparing model outputs with historical observations, and the most reliable models were selected using root mean square error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE) indicators (Jung & Schindler, 2025; Wu et al., 2021). From the seven GCMs tested, only those with the lowest RMSE, MAE and MAPE values were retained for future projections, while less accurate models were excluded from scenario analysis. Quantile mapping was applied as the main bias correction method to adjust both mean values and distribution tails, ensuring consistency with the observed daily wind speed series.

In this study, urbanisation is defined as settlement expansion that modifies land cover, increases surface roughness length ($z_0$), and intensifies turbulence in the atmospheric boundary layer (Battisti et al., 2018; Theeuwes et al., 2019). Unlike most wind energy assessments, which usually account only for climate change, here land-use change was explicitly integrated into wind resource modelling. This represents the main novelty of the research.

Wind speeds were recalculated from the reference height (10 m) to turbine hub heights (100 m, 150 m) using the logarithmic wind profile:

$$v(Z) = v(Z_r) \cdot \frac{\ln\left(\frac{Z}{z_0}\right)}{\ln\left(\frac{Z_r}{z_0}\right)} \quad (1)$$

where $v(Z)$ is wind speed at hub height $Z$, m/s; $v(Z_r)$ is wind speed at reference height (10 m), m/s (Tobin et al., 2015); and $z_0$, m, is surface roughness length determined by land-use type (Andújar-Maqueda et al., 2025; Theeuwes et al., 2019).

Three urbanisation scenarios were modelled:

Slow growth (200 years): settlements expand gradually; $z_0$ remains close to rural values (0.03–0.1 m) (Battisti et al., 2018).

Moderate growth (100 years): suburbanisation accelerates; $z_0$ increases to 0.3–0.5 m (Theeuwes et al., 2019).

Fast growth (50 years): dense urban sprawl dominates; $z_0$ exceeds 1.0 m, representing strong roughness effects (Roth, 2000; Theeuwes et al., 2019).

The wind speed at the desired hub height in a changing urbanised environment, accounting for turbulence intensity, can be calculated using the equation derived by the author for this study:

$$v(Z) = v(Z_r) \cdot \left( \frac{\ln\left(\frac{Z}{z_0 + n \cdot z_{0d}}\right)}{\ln\left(\frac{Z_r}{z_0 + n \cdot z_{0d}}\right)} \right) \cdot \left( 1 + \frac{k}{\ln\left(\frac{Z}{z_0 + n \cdot z_{0d}}\right)} \right) \quad (2)$$

where $v(Z_r)$ – known wind speed at the reference height $Z_r$, m/s; $n$ – number of days since the beginning of urbanisation; $Z$ – new hub height, m; $z_0$ – initial roughness length, m; $z_{0d}$ – daily change of roughness length, m.

For this study, the daily roughness increments were defined as $z_{0d}$ = 1.05×10⁻⁵ m (slow), 2.11×10⁻⁵ m (moderate), and 4.22×10⁻⁵ m (fast growth), based on urbanisation growth rates. The turbulence adjustment coefficient $k$ (dimensionless) was calibrated using observed differences between urban and rural station pairs, with typical values ranging from 0.05 to 0.15. The turbulence adjustment coefficient k was validated by comparing urban and rural station pairs, providing confidence that Equation (2) realistically reflects the impact of settlement growth.

Equation (2) combines the logarithmic wind profile (Theeuwes et al., 2019; Tobin et al., 2015) with a dynamic roughness parameterisation (Battisti et al., 2018; Roth, 2000). Its novelty lies in explicitly linking urban growth rates with wind resource estimation.

Wind speed distributions were fitted with the Weibull function (Jung & Schindler, 2025; Roth, 2000). Weibull parameters shape (p) and scale (c) were estimated using the maximum likelihood method, which ensures stable results across both historical and projected datasets. Energy yield was calculated for two modern turbines (Enercon E-112 and E-126) using manufacturer power curves, with their key technical specifications (rated power, rotor diameter, hub height, and cut-in/cut-out wind speeds) summarised in Table 1. Manufacturer power curves were obtained directly from technical specifications, ensuring realistic turbine performance estimates. Production was estimated for a 25-year turbine lifetime.

**Table 1.** Technical specification of wind turbines used in the study (https://www.thewindpower.net).

| Turbine model | Rated power, MW | Rotor diameter, m | Hub height, m | Cut-in speed, m/s | Cut-out speed, m/s |
|---|---|---|---|---|---|
| Enercon E-112 | 4.5 | 112 | 100 | 3.0 | 25.0 |
| Enercon E-126 | 7.5 | 126 | 150 | 3.0 | 25.0 |

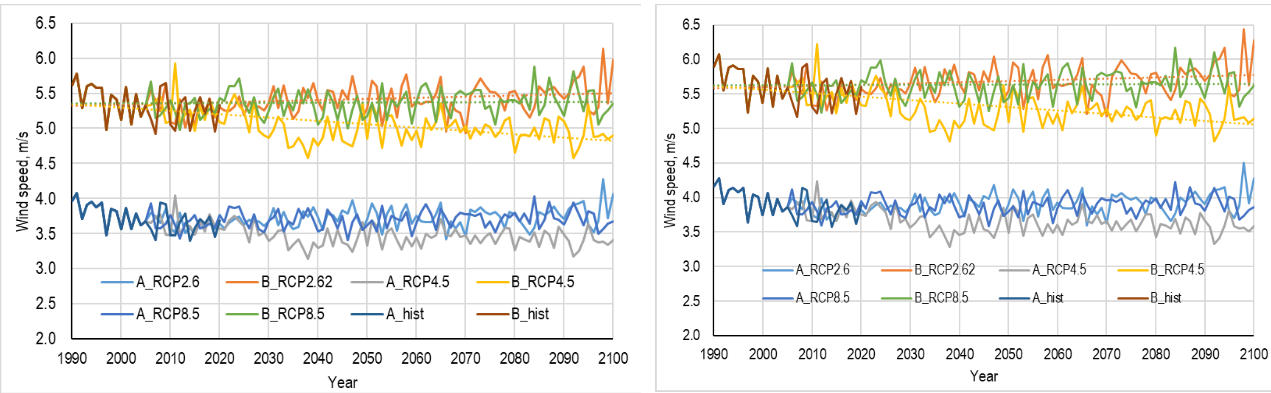
Wind farm layouts were simulated as 4×4 arrays with spacing of 8 rotor diameters (8D), assuming 90% efficiency (Roth, 2000). The 90% wind farm efficiency factor was adopted from empirical studies of wake losses in medium-sized European wind farms (Martin et al., 2020). Uncertainty was addressed by comparing the spread of results across GCMs and RCP scenarios, and presenting ensemble means together with the range of variation. Unfavourable wind days ($v < 3$ m/s or $v > 25$ m/s) were calculated to assess operational reliability (Jung & Schindler, 2022). Unfavourable days were calculated from daily mean wind speed values rather than hourly data, which provides conservative but robust estimates.

## RESEARCH RESULTS

### Wind speed changes under climate scenarios

The first research objective was to analyse historical wind speed changes and evaluate projections under three climate scenarios. Figure 1a) presents the mean wind speed at 100 m hub height. Historical observations from 1990–2020 reveal a moderate decline of ~0.2–0.3 m/s in inland regions, equal to 5–10% of baseline values. Coastal sites recorded smaller decreases, about 0.1–0.2 m/s, reflecting the stabilising effect of the Baltic Sea.

Projected changes under RCP2.6, RCP4.5, and RCP8.5 confirm that climate change alone does not strongly alter wind resources. By the end of the 21st century, the largest reduction occurs under RCP4.5, with inland speeds dropping from 3.7 m/s to ~3.4 m/s. RCP2.6 suggests partial recovery after 2070, returning values close to the 1990s baseline. RCP8.5 shows almost no long-term change. These results prove that climate change is not a decisive factor for wind resources in Lithuania, as variations remain within ±8%.




a b

**Figure 1.** Windiness in the historical period (1990–2020) and future (until 2100) under three climate scenarios (RCP2.6, RCP4.5, RCP8.5) at heights of (a) 100 m and (b) 150 m in the central (A) and coastal (B) regions

Figure 1b) shows results at 150 m hub height. The same trends are observed, but average speeds are consistently 0.3–0.4 m/s higher than at 100 m. This difference means up to 15% more energy potential, indicating that turbine height is a more important driver of production change than climate trajectories. Thus, the first objective is fulfilled: climate change causes only minor variations in wind speed, while technological parameters such as hub height play a stronger role in energy potential. Bias correction reduced model errors (RMSE, MAE) to below 5%, increasing the reliability of climate projections. Differences between RCP scenarios were statistically insignificant, as their uncertainty ranges overlapped.

**Impact of urban expansion on wind characteristics and energy yield**

The second objective was to determine how different urbanisation rates influence wind characteristics and electricity generation. Figure 2 shows the number of unfavourable wind days per year. At 100 m height, inland regions experience ~90 days annually when wind speed is outside the operational range (<3 m/s or >25 m/s), compared to only ~27 days at the coast. Raising the hub to 150 m reduces unfavourable days by 15–20%. For example, central Lithuania improves from ~90 to ~72 days. This demonstrates that taller towers improve reliability, but also that inland regions remain far less stable than the coast.

Figure 3a illustrates annual energy yield for an Enercon E-112 turbine at 100 m. Historical records show a long-term decline: at the coast, production fell from ~460 MWh/year in the early 1990s to ~350 MWh/year by 2020, while inland production decreased from ~150 to ~100 MWh/year. Future projections confirm that climate scenarios alone cause <8% additional change. However, when urbanisation effects are included, reductions become much stronger. Under moderate settlement growth, inland turbine output drops below 100 MWh/year by mid-century, while coastal output declines toward ~300 MWh/year.

Figure 3b shows the corresponding energy yield at 150 m hub height. Compared to 100 m, higher turbines substantially increase absolute production in both inland and coastal regions, but the relative impact of urbanisation remains similar. Even at 150 m, moderate and fast urban expansion leads to pronounced long-term losses, confirming that increased hub height improves yield but cannot offset the effects of growing surface roughness.

This evidence confirms the second objective: urbanisation significantly increases surface roughness and turbulence, resulting in more unfavourable wind days and lower electricity generation. The effect is especially strong inland, where production potential is already marginal. The strongest increase in unfavourable wind days was observed in central Lithuania, whereas coastal regions remained the most stable due to the Baltic Sea influence.

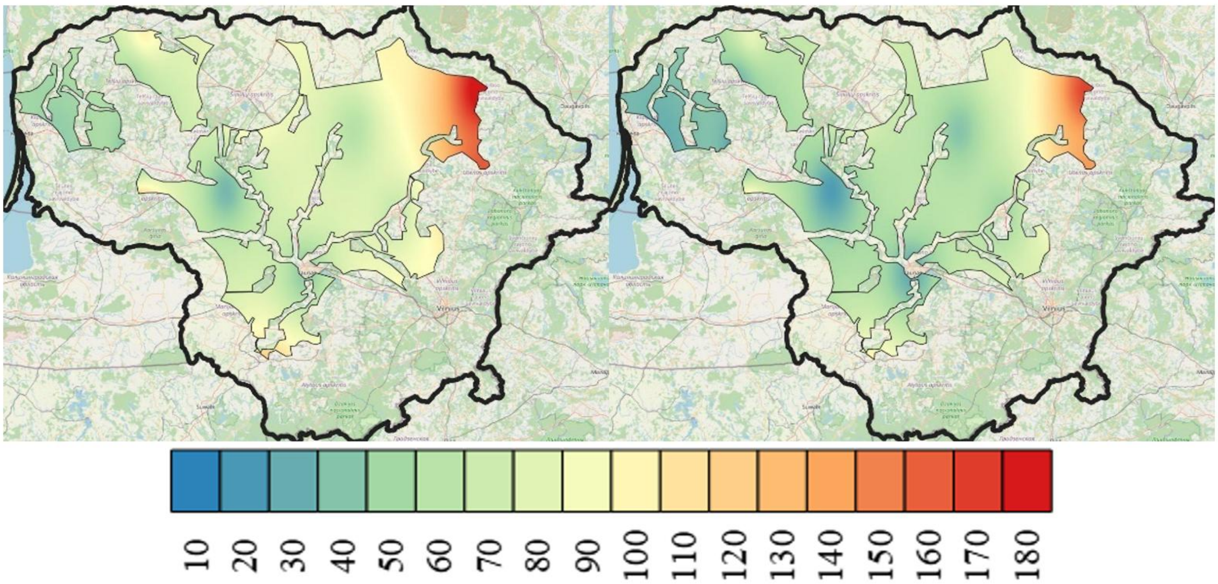
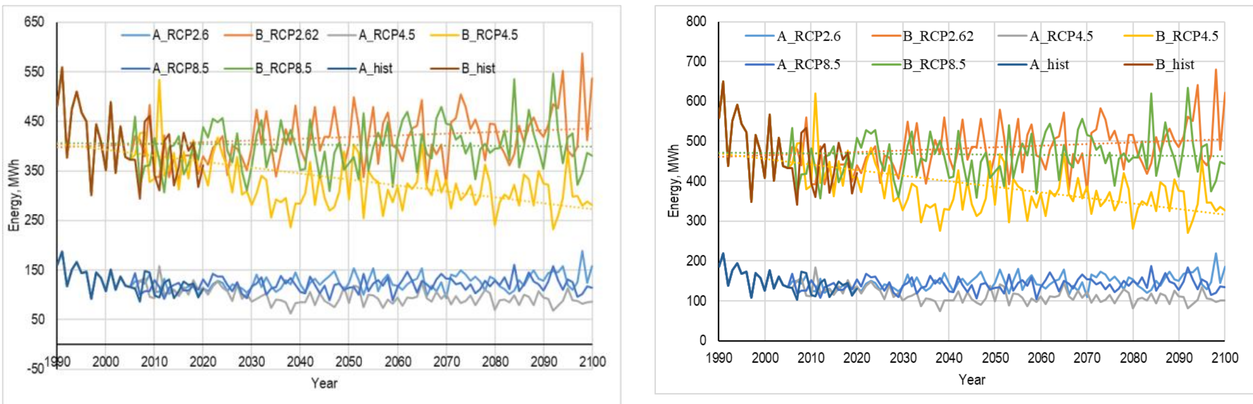



**Figure 2.** Average annual number of days during 1990–2020 when wind speed at 100 m (left) and 150 m (right) is unsuitable (< 3 m/s or > 25 m/s) for wind energy production.




**a** **b**

Figure 3. Energy production using the Enercon E-112 turbine in the central (A) part of the country and on the coast (B), during 1990–2020 and projected until 2100 under RCP2.6, RCP4.5, and RCP8.5, at heights of (a) 100 m and (b) 150 m.

**Relative significance of climate change and urbanisation for wind energy potential**

The third objective was to compare the importance of climate change and urbanisation. Figure 4a shows projected electricity generation of the Enercon E-112 turbine at 100 m hub height under combined climate and urbanisation scenarios. The results demonstrate that climate change alone produces only small variations, less than 8% across all RCPs. In contrast, urbanisation causes substantial decreases. Under slow expansion, yields are reduced by about 30%; under moderate expansion, by 40–45%; and under fast expansion, by more than half. The steep downward trajectories of the urbanisation curves confirm that settlement growth is the primary driver of long-term losses.

Figure 4b presents the corresponding results for the Enercon E-126 turbine at 150 m hub height. Despite its larger rotor diameter and higher tower, the same pattern emerges. Climate scenarios again cause only minor shifts, while urbanisation dominates. Under rapid urban growth, production drops by more than 50% compared with the baseline. The higher hub height increases absolute generation, but the relative decline remains almost identical to smaller turbines. This indicates that technological scaling alone cannot compensate for the negative effects of land-use change.

Together, these results confirm the third research objective: climate change is a secondary factor, while urbanisation exerts a dominant, long-term influence on wind energy potential. The comparison of turbine types and hub heights shows that even advanced designs cannot prevent losses if settlement growth is uncontrolled. Therefore, the sustainability of rural wind energy development in Lithuania will depend primarily on land-use planning and regulation of urban expansion. Overall, the effect of urbanisation was found to be approximately 4–6 times stronger than that of climate change. Even larger turbines such as the E-112 and E-126 lose more than half of their potential output under fast urban growth.

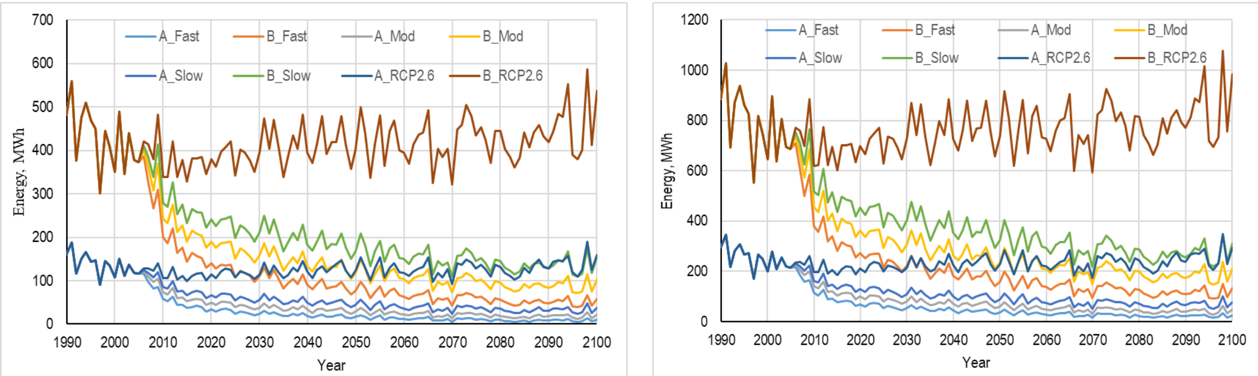



**Figure 4.** Energy production during 1990–2020 and projected until 2100 under the RCP2.6 climate scenario and slow, moderate, and fast urbanisation, in the central (A) part of the country and on the coast (B), using (a) the Enercon E-112 turbine at 100 m height and (b) the Enercon E-126 turbine at 150 m height.

## DISCUSSION

The results of this study address the three main research objectives by comparing the roles of climate change and urbanisation in shaping wind energy potential in Lithuania. The discussion focuses on three issues: (1) the relatively small influence of climate change, (2) the much stronger impact of urbanisation, and (3) the limited capacity of technological improvements to compensate for land-use change.

The analysis demonstrated that changes in mean wind speed under RCP2.6, RCP4.5, and RCP8.5 remain within ±8% by the end of the 21st century. Even in the most unfavourable scenario (RCP4.5), the decrease was less than 0.4 m/s at inland sites. This confirms findings from other regional studies which reported relatively minor impacts of climate change on wind resources in Northern Europe and the Baltic Sea region (Jung & Schindler, 2022; Tobin et al., 2015). While small variations in wind speed can still translate into measurable production changes due to the cubic relationship between wind speed and power, the overall effect remains modest compared to natural inter-annual variability. Therefore, climate change alone is unlikely to pose a critical threat to the long-term development of wind energy in Lithuania. Bias correction reduced GCM errors to below 5%, which increases confidence in the robustness of these projections.

In contrast, urbanisation was found to be a much more powerful driver of change. Settlement growth increases surface roughness and turbulence, significantly reducing effective wind speeds and increasing the number of unfavourable wind days. Inland regions were particularly vulnerable: the number of unfavourable days exceeded 90 per year at 100 m hub height, while along the coast the value remained below 30. These findings confirm that land-use dynamics play a crucial role in modifying boundary-layer flows (Battisti et al., 2018; Theeuwes et al., 2019). This contrast highlights the stabilising role of the Baltic Sea, which buffers coastal sites against both climate and land-use induced changes

The quantitative analysis shows that climate change reduces energy yield by less than 8% in all scenarios, while urbanisation decreases output by 28–32% under slow growth, 39–45% under moderate growth, and more than 50% under fast growth. This means that the effect of urbanisation is approximately 5–6 times stronger than that of climate change.

For example:

At 100 m hub height (Enercon E-112), climate change reduces output by ~6%, while fast urban growth reduces it by ~52%.

At 150 m hub height (Enercon E-126), climate change reduces output by ~7%, while fast urban growth reduces it by ~55%.

Thus, even the most advanced turbine designs cannot compensate for the negative effects of rapid settlement expansion. Urbanisation emerges as the dominant driver of long-term wind energy decline, clearly outweighing the relatively minor influence of climate change (Jung & Schindler, 2022).

These results also explain the spatial differences between inland and coastal zones. Although coastal turbines produce more electricity in absolute terms, inland turbines suffer the greatest relative losses. This confirms earlier studies which showed that inland rural areas are more sensitive to land-use change due to lower baseline wind speeds (Roth, 2000).

The analysis of different hub heights and turbine types (Enercon E-112 and E-126) revealed that technological improvements increase absolute production but cannot offset the negative effects of urbanisation. At 150 m hub height, mean wind speeds are ~0.3–0.4 m/s higher, leading to 10–15% higher electricity production. However, under scenarios of rapid settlement growth, even the largest and tallest turbines lost more than 50% of their baseline output. This confirms that while turbine design is an important factor, it is insufficient to counteract long-term land-use pressures (Theeuwes et al., 2019). Although taller towers increased average generation by 10–15%, this technological advantage was insufficient to offset the stronger negative effects of urban growth.

These findings highlight that sustainable rural wind energy development in Lithuania depends not only on technology or climate but primarily on land-use planning. If settlement expansion is not managed, wind energy potential will decline regardless of turbine advancements.

## CONCLUSIONS

The conclusions reflect the main results of the study. Only the main conclusions based on the results of research are given. Climate change has only a minor effect on wind resources in Lithuania. Projected changes in mean wind speed remain within ±8% by the end of the century, leading to modest reductions in electricity production. Bias correction reduced model errors to below 5%, increasing the reliability of projections. In contrast, urbanisation exerts a much stronger influence, with energy yield decreasing by 28–32% under slow expansion, 39–45% under moderate expansion, and more than 50% under fast expansion. Inland rural regions are particularly vulnerable, while coastal areas remain the most productive in absolute terms, partly due to the stabilising role of the Baltic Sea. Increasing turbine hub height from 100 m to 150 m improves electricity production by 10–15%, yet this technological advantage cannot offset the negative effects of increased surface roughness. Even modern turbines such as the Enercon E-126 lose more than half of their potential output under rapid urbanisation. These results demonstrate that urbanisation is the dominant driver reducing long-term wind energy potential, outweighing the influence of climate change. For Lithuania, sustainable wind energy development will depend on careful land-use planning and the regulation of settlement expansion. Integrating urbanisation scenarios into energy modelling provides a more realistic basis for rural development strategies and energy security.

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