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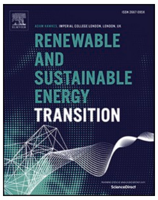

Full-length article

Spatial heterogeneity in deployment and upscaling of wind power in Swedish municipalities

Yodefia Rahmad [a,*], Fredrik Hedenus [a], Jessica Jewell [a,b,c], Vadim Vinichenko [a]

[a] *Division of Physical Resource Theory, Department of Space, Earth and Environment, Chalmers University of Technology, Gothenburg, Sweden*
[b] *Centre for Climate and Energy Transformation, Department of Geography, University of Bergen, Bergen, Norway*
[c] *Advancing Systems Analysis, International Institute for Applied Systems Analysis, Laxenburg, Austria*

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ABSTRACT

Deployment of new onshore wind power faces challenges due to growing resistance, prompting increased interest in the development of effective deployment strategies. One approach is to examine historical deployment to identify factors shaping its distribution within a country. Current literature presents inconsistent results and lacks theoretically grounded approaches. This study enhanced the methodology for analyzing subnational wind deployment in two ways. First, techno-economic, socio-technical, and political perspectives from national energy transition literature were employed to identify relevant deployment mechanisms. Second, the approach differentiated between small-scale and large-scale wind power to avoid conflating results from obsolete technologies. The method is piloted in Sweden where wind deployment varied significantly despite nationwide policies. Findings from Sweden suggest that subnational heterogeneity of wind deployment at the municipality level is not primarily determined by techno-economic factors, but also by socio-technical and political variables. Deployment mechanisms also evolved over time, possibly due to technological upscaling. Small-scale wind power (≤1.5 MW) leveraged agricultural land and accumulated local experience, while large-scale wind power (>1.5 MW) is correlated with political variables such as siting policy and voter turnout. Municipalities with the highest large-scale deployment typically have extensive forest cover, low population density and wind speeds within a lower median range relative to the national median. Findings from Sweden can inform hypotheses for evaluation in other countries and future research can extend the proposed analytical framework to different national contexts.

1. Introduction

The deployment of wind power must accelerate to meet climate goals [1,2] and policy-targets like the European Union's RePowerEU plan in response to the Russo-Ukrainian war [3,4]. However, both the siting and overall deployment of new wind power projects poses a challenge due to growing resistance [5,6,7,8,9], which has led to increasing focus among investors and policymakers on developing effective deployment strategies. Examining historical wind power installations can provide valuable insights into the factors that have influenced its distribution within a country.

Despite nationwide policy instruments, wind power deployment exhibits spatial heterogeneity within countries [10,11,12,13,14,15,16]. Resource potential and site selection studies, as well as many modelling studies, often consider wind speed and land scarcity as key factors in determining allocation of wind deployment within countries [17,18,19], primarily due to the strong correlation between wind speed and profitability. Empirical studies has sought to establish relationships between deployment level and factors such as wind speed [14], realizable potential for wind power in terms of capacity or electricity generation [11,13], and land availability [20,11,14,12]. However, the findings present a lack of consensus. Lauf, et al. [14] found wind speed to be positively correlated with installed wind capacity in German districts, but not in Swedish municipalities. Staid and Guikema [20] conducted an analysis on suitable areas, defined as those with a minimum capacity factor of 30 %, and found a correlation with the total installed capacity of wind power in US states. Conversely, Frantál & Nováková [11] and Gutiérrez-Pedrero, et al. [13] found no correlation between realizable wind potential and deployment level in Czechia and Spain, respectively.

It is evident that different subnational regions can exhibit markedly different deployment levels, despite similar wind speed [10,14]. Consequently, studies have explored other influences apart from wind

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* Corresponding author.
E-mail address: yodefia@chalmers.se (Y. Rahmad).

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speed such as forest cover [11], cropland cover [11,16,20], or population density [11,16,10,14,13]. Frantál & Nováková [11] did not find any effect of forest cover on wind deployment in Czechia, while Staid & Guikema [20] found cropland to be correlated with installed capacity of wind power in US states. Ek, et al. [10] and Lauf, et al. [14] also found population density to be a positive estimator for total installed capacity of wind power in Swedish municipalities and German districts. A number of studies have also investigated the effects of socio-political factors on deployment. Both Ek, et al. [10] and Lauf, et al. [14] considered land use policy in their analysis and the results were conflicting. Goetzke & Rave [12] found that the share of green party votes in state elections has positive explanatory power on wind deployment in German states, but such correlation was not found for Czechian districts [11]. While various technical and socio-political factors have been studied in relation to wind power deployment, the results are inconsistent and vary across different regions and contexts.

Current literature has yet to provide clarity on the limited significance of wind speed and, more importantly, on the other factors that may supersede its importance. Inconsistent results related to wind speed may stem from using average wind speed as a predictor of deployment level which can underestimate the impact of wind speed at the regional level. For example, an inland region and a coastal region may share the same average wind speed, but the coastal region includes a small area adjacent to the sea with high wind speeds and significant deployment. Another reason may be the lack of theoretically grounded discussions on mechanisms influencing heterogeneity of wind deployment. Studies seldom provide explicit hypotheses regarding the variables analyzed in their studies, making it difficult to interpret findings and consistently compare different studies. Lastly, advancement of wind technology may also affect deployment mechanisms and contribute to inconsistencies in previous studies. Despite the rapid increase in rotor diameter, turbine height, unit capacity and wind park size over the last few decades [21,22], studies have treated wind power as a uniform technology. Accounting for technological changes is crucial, as different turbine scales may rely on distinct deployment mechanisms. Neglecting this consideration can lead to conflated results by integrating findings from outdated technologies, particularly given the ongoing trend of increasing turbine size [23,24].

This study improved the methodology for analyzing subnational heterogeneity of wind power in two ways. First, it utilized the three perspectives on the mechanisms underlying national energy transition: techno-economic, socio-technical, and political perspectives [25]. This approach diverges from previous studies, which predominantly centered on techno-economic variables such as resource availability and population density, with only sporadic inclusion of socio-political variables. It also provides a theoretically grounded evaluation of the empirical relationship between wind speed and wind deployment while also investigating other potentially more influential mechanisms. Additionally, the regional aggregation of wind speed is refined to better represent resource distribution rather than only using averages. Second, this study differentiated the analysis between various scales of wind power. This approach accounts for the evolving characteristics of wind technology and enables the examination of the hypothesis that deployment mechanisms change in part due to a change in the technology.

The improved methodology is piloted in Sweden, which presents an interesting case of subnational deployment of onshore wind power. Sweden is notable for its rapid growth in wind power globally [2] and possesses a substantial history of wind deployment at varying scales over the past 30 years. This study contributed to the ongoing policy debate in Sweden on wind power deployment and how to enable the country to achieve its 100 % fossil-free goal [26,27], as there are uncertainties about where future wind expansions will occur due to increasing resistance in various regions [28,29,30].

The paper is organized as follows: Section 2 outlines the theoretical frameworks used in this study. Section 3 describes the methods implemented. Section 4 presents the results of the analysis. Section 5 provides a discussion of the findings, addressing their implications and limitations. Finally, Section 6 concludes the paper with summarizing insights.

2. Theoretical framework

2.1. *Mechanisms of energy transition*

The deployment of renewable energy sources such as wind power at the subnational level constitutes an integral component of the broader national energy transition. A theoretically grounded framework linking deployment to energy transition literature is essential for improving the analysis of subnational wind deployment. This study employs the three perspectives on the mechanisms underlying energy transition proposed by Cherp, et al. [25]: techno-economic, socio-technical, and political perspectives. These perspectives stem from distinct systems which co-evolve during the course of an energy transition and are studied by different disciplines. Initially developed to examine changes in the state of a national energy system, the framework has predominantly been applied to that purpose [31,32], rather than to study deployment of individual energy technologies. Nevertheless, elements of this framework can provide an organizing principle to identify relevant mechanisms. The framework is operationalized in this study by deriving variables to evaluate from each system perspective and tailoring them to the context of Swedish wind deployment, as elaborated in Section 3.

The techno-economic perspective focuses on the shape of energy systems as defined by the actual physical flows of energy and the markets where they are traded. Mechanisms in the techno-economic system encompass technical and economic aspects of energy resources, demand, and the infrastructure for extraction, transportation, conversion, and use of energy. Examples of subnational variables derived from these mechanisms are wind speed, land area, and electricity prices.

The socio-technical perspective examines the societal and technological aspects of energy transition. This view focuses on the emergence and diffusion of specific technologies used in energy transition, as well as mechanisms related to innovation systems. Examples of subnational variables derived from these mechanisms are experiences with wind power and other energy technologies.

The political perspective focuses on the impact of energy policies and political actions on the energy transition. This includes mechanisms influenced by state goals in energy and climate change, political interests of different actors, as well as relevant institutions and their capacities in doing energy transition. Examples of subnational variables derived from these mechanisms are electoral participation and support for Green Party in municipal election.

2.2. *Technological upscaling*

The long-standing deployment of wind power has led to significant technological advancement that can potentially alter its deployment mechanism. One key development is the global trend towards larger unit size. This includes longer blades, higher hubs, and higher rated capacity [23,24]. As the rotor diameter increases, the swept area also increases. A larger swept area allows wind turbines of a certain rated capacity to generate the same power from lower wind speeds. Thus, previously uneconomical sites with less favorable wind conditions have become more accessible. At the same time, the cost of the technology has also decreased [33]. Another consideration is that the larger size of wind turbines could lead to greater visibility, potentially resulting in lower social acceptance [34,35,36]. However, the use of taller hubs is also enabling wind power installations in forested areas.

In relation to the dynamics between changing unit size and deployment level, Wilson [37] characterized technological upscaling as an increase in unit capacities and in the number of units built. The initial phase of deployment is characterized by a formative phase, marked by irregular capacity additions that predominantly come from the installation of smaller-scale units. Once the formative phase has ended and a dominant design is established, deployment occurs through upscaling: a steady increase in the number of units accompanied by a significant rise in unit capacity. Eventually, the increase in unit size levels off, and deployment proceeds with a large number of larger-scale units. While the length and timing vary, upscaling has been consistently found in diffusion of several energy technologies globally or in their core regions [37].

Given the anticipated continuation of unit size increases [23,24] and the ongoing expansion of wind power in different countries, it is crucial to comprehend how deployment mechanisms evolve in response to upscaling. The phases of deployment defined by Wilson [37] are employed to evaluate how upscaling can make the analysis of subnational wind power deployment sensitive to the period of observation. This sensitivity may contribute to the inconsistencies observed in existing literature, as studies span different timeframes. To the knowledge of the authors, no previous research has explored the effect of upscaling on deployment mechanisms. Thus, this study also contributes empirical evidence to the discourse on the implications of technological upscaling.

3. Methods

This study employed three different methods to identify factors influencing spatial heterogeneity of wind deployment in Sweden. First, a descriptive analysis of the development and spatial distribution of wind power in the country was conducted using latest database of Swedish wind power until as recent as 2022. Second, variables derived from the mechanisms of national energy transition were evaluated. Relevant deployment mechanisms for different scales of wind power in Swedish municipalities were identified using statistical analysis. Lastly, the statistical results were supplemented with identification of common characteristics found in municipalities with the highest level of wind deployment of large-scale wind power.

3.1. Overview of Swedish onshore wind

A descriptive analysis was conducted to gain a general overview of how wind power has been deployed in Sweden over the years. The analysis was based on data from the Swedish wind power database [38], which contains information such as project status and timeline, locations, numbers of units within a single project, and turbine specifications. This study focuses on onshore wind power installations constructed during the period spanning from January 1990 to August 2022. Wind turbines which have been dismantled were included, as they are still counted towards the total amount of wind deployment in the municipalities during the period of observation. Some wind power must be excluded from the analysis due to incomplete information, such as missing installation dates or rated capacity. The number of turbines and total capacity of wind power examined are shown in Appendix A.

The analysis accounts for the evolution of wind power characteristics in Sweden, particularly due to unit upscaling, by distinguishing between small- and large-scale wind power installations. This distinction is crucial to test the hypothesis that different scales of wind power rely upon distinct deployment mechanisms. The definition of small-scale wind power refers to units with a capacity of 1.5 MW or less, which are the smaller scale units deployed before the upscaling phase defined by Wilson [37]. Large-scale wind power refers to units with a capacity greater than 1.5 MW and are deployed during the upscaling phase, which explains their larger capacity. This scale delineation is established specifically for Sweden, as there is a notable transition at unit capacity of 1.5 MW, with no turbines below this capacity constructed in the country since 2016. Many turbines sized 1.5 MW and larger are still being installed, and the maximum turbine size continues to grow. This threshold is not indicative of the largest turbines available on the market; rather, it serves as a demarcation in Swedish wind power to differentiate between outdated technologies, which are no longer deployed, and those that continue to be built today.

3.2. Statistical analysis

3.2.1. Specification of statistical model

Once an overview of how wind power has historically been deployed in Sweden was obtained, statistical analyses were conducted to identify factors that may contribute to the heterogeneity of wind deployment across the country. Linear regression, a statistical technique, is frequently employed to analyze the implementation of wind power at the subnational level [11,13,15,16,39]. This method involves modeling the relationship between a dependent variable, the outcome of interest, and one or more independent variables, which are the predictors or factors influencing the outcome. Linear regression assumes this relationship to be linear. However, when total installed capacity of wind power is used as the dependent variable, linear regression may not render an accurate relationship between the dependent and independent variables [40,41]. This is because many regions within a country never “take-off” in wind deployment, resulting in a very low to zero total installed capacity. In combination with observations of other regions with high amount of installed capacity, linear regression will result in biased and inconsistent estimates [41]. Cragg double-hurdle model [40] has been used in similar studies [10,14] to address the issue of numerous zeros in the observations. The model is able to account for a dependent variable with a lower (or upper) bound that is found in a sizable number of observations is required to address this issue [40]. In this study, the lower bound is the take-off threshold for wind deployment.

The Cragg double-hurdle model was used to test the hypothesis regarding factors influencing wind deployment in Swedish municipalities. Decision-making processes, including the right to veto wind power projects, typically occur at municipal level. Additionally, variability in wind power deployment between municipalities is suitable for statistical analysis, and most of the data required for such analysis are readily available. The dependent variable used in the analysis is total installed capacity at the municipal level in 2022. In other words, it is the cumulative installed capacity of all wind turbines constructed in each municipality from 1990 to 2022. The deployment of small-scale and large-scale wind power were modeled separately to avoid conflating the effects of the variables tested. The Cragg double hurdle model operates in two parts. The first part determines the probability of a municipality to take-off in wind deployment. The second part is a truncated linear regression, which focuses only on a portion of the full sample, specifically including only municipalities that passed the take-off threshold. The latter part of the model serves as the main statistical model and forms the basis for the analysis of this study. Municipal take-off thresholds for small-scale and large-scale wind power were defined as 1.5 MW and 10 MW in total installed capacity by 2022, respectively. Appendix B provides a flowchart illustrating the statistical analysis.

3.2.2. Deriving variables from mechanisms of national energy transition

The independent variables are derived from different system perspectives of national energy transition proposed by Cherp, et al. [25]. Relevant hypotheses were formulated for the case of Swedish onshore wind deployment and where appropriate, differentiated between small-scale and large-scale wind power. A summary of the variable derivation is available on Table 1. See Appendix C for the complete list of variables used in the statistical model, along with their definition, source, and descriptive statistics. Results of a multicollinearity test for the variables used in the statistical models are shown in Appendix D.

From the techno-economic perspective, variables such as wind speed, land area, types of land cover, presence of protected areas, and electricity price areas were evaluated. Power generated by wind power depends heavily on wind speed, suggesting higher deployment in municipalities with favorable wind resources. However, previous studies on Spain [13] and Germany [14] have yielded inconsistent results. Wind speed can vary significantly within large municipalities, necessitating an

Table 1
Independent variables derived from national energy transition perspectives.

System perspectives in national energy transition from Cherp, et al. [25]	Independent variables	
Techno-economic perspective *Physical flow energy; processes and actors in utilization of the energy; market dynamics*	↑ Wind speed ↑ Land area ↑ Agricultural land ↑ Forest cover ↑ Electricity price	↓ Protected area ↓ Population density
Socio-technical perspective *Emerging technology as a social phenomenon; technological diffusion and experience*	↑ Years since take-off ↑ Small-scale wind power	↓ Hydropower capacity ↓ Employment rate ↓ Population density
Political perspective *Impact of energy policies and political actions*	↑ Prioritized area for wind power ↑ Votes for Green Party	↓ Voter turnout

↑ indicates positive correlation hypothesis, ↓ indicates negative correlation hypothesis.

improved method for aggregating wind resource measurements. Consequently, this study employs the average of the top 90th percentile of wind speeds at 100 m hub height within each municipality as a more representative metric. Additionally, wind speed measurements from areas above 1000 m in elevation were excluded. Due to technical challenges associated with erecting wind turbines at higher elevations, this exclusion rule was also applied to other geographical or land-use variables.

Municipalities with larger land size are hypothesized to have higher deployment level, as shown before for Germany [12], US [20], and Sweden [10]. However, different land types may affect small and large-scale deployment differently. Agricultural land provides open land with little obstructions and flat terrain which are beneficial for smaller turbines with lower hub height. A high share of agricultural land use may then influence deployment of wind power positively, as demonstrated for China [16] and US [20]. This analysis included the percentage of municipal land area used for agricultural purposes and expected a positive correlation with the total installed capacity of small-scale wind power.

Large-scale wind turbines, due to their higher hub heights, can potentially be installed in forested areas. However, in the analysis of Swedish municipalities, the percentage of municipal land area covered by forests exhibits a negative correlation with agricultural land. This arises from the geographical distribution of land use in Sweden, where municipalities with extensive forest cover, typically located in the north, generally lack substantial agricultural land, while southern agrarian municipalities tend to have fewer forested area. Therefore, the forest variable was excluded from the statistical model to avoid collinearity (see Appendix D for the multicollinearity test). However, it is still included in the characterization of municipalities with the highest wind deployment, as discussed in Section 3.3.

Wind turbines may not be permitted to be constructed in various categories of protected areas. Despite statistical results from previous study [14], empirical site-level study reveals wind turbines are often constructed in protected areas [42], likely because these areas are protected for purposes which are not at risk of being affected by wind power. The share of municipal areas under strict nature reserve category in the World Database on Protected Areas (WDPA) are examined in the analysis and expected to demonstrate a negative correlation with the level of wind deployment.

Sweden has four electricity price areas. Small-scale wind power was predominantly constructed during earlier periods, when economic incentives may be less prevalent, resulting in a more diverse distribution that was not necessarily confined to municipalities within high-price areas. In contrast, large-scale wind power projects developed more recently, in an environment of reduced economic support, are likely to be more susceptible to the influence of these price areas. In recent years, the southern price areas (SE3 and SE4) have experienced higher electricity prices due to increased demand and the decommissioning of nuclear power plants. Conversely, the northern price regions (SE1 and SE2) exhibit a concentration of electricity generation, predominantly from hydropower.

From the socio-technical perspective, municipalities' experience in deploying wind power was measured. Findings from earlier studies have shown how longer experience in wind deployment results in a higher level of deployment [10,20] due to accumulation of institutional experience [10], infrastructure readiness [12], or economies of scale [12]. Years since take-off is included in the statistical model, which is the number of years since municipalities passed take-off threshold given in Section 3.2.1 and expected to have a positive effect on the amount of capacity installed today. This study also investigated the potential influence of prior small-scale wind power deployment on subsequent large-scale wind power implementation. The analysis aims to determine whether the same municipalities engage in both small- and large-scale wind power development, or if there exists a continuous learning or developmental process across varying scales of wind deployment.

According to a case study on why municipalities reject wind deployment in Sweden [8], previous negative experiences with the expansion of hydropower have led to a negative perception to development of wind power. There were concerns about companies from outside the community taking advantage of local resources [8]. This hypothesis is tested in the statistical model by including the total installed capacity of hydropower in each municipality. Contrastingly, wind power projects may be perceived as potential job opportunities, making them particularly appealing for regions with high unemployment rates. Previous studies have consistently found a positive correlation between the unemployment rate and level of wind power deployment [11,14,12,39]. The share of gainfully employed individuals (following International Labor Organization's definition [43]) within a municipality is included to investigate if it is negatively correlated with wind deployment.

From the political perspective, the influence of policies on wind power deployment in Swedish municipalities was measured, such as the designation of national areas of interest for wind power. Since 2008, the Swedish Energy Agency with recommendations from regional government has identified areas to prioritize for wind power development [44], which were mostly based on suitable geophysical conditions. The hypothesis suggests a correlation between these prioritized areas and higher wind deployment. Since these areas are not legally binding and the common geophysical criteria constituting them are controlled in the statistical model, they can be considered as proxies for supportive policies for wind deployment. This correlation is particularly anticipated for large-scale wind deployment, as they have been introduced more recently where siting support may be more relevant due to increasing public opposition [28,29,30]. Nonetheless, previous studies on wind deployment in Sweden found contradictory results [10,14].

A high number of votes for the Green Party may be indicative of a voter base that places importance on environmental concerns. Therefore, a positive correlation with deployment of renewable energy technologies such as wind power is expected. Although other parties in Sweden may also publicly support or oppose wind power, their stances vary across regions and time, making it challenging to draw general conclusions. Green Party is often referenced in similar studies due to their relatively consistent environmental focus, such as findings from Czechia [11] and Germany [12] that found positive correlation with wind deployment. The share of votes for the Green Party in municipal elections was averaged over a 10-year period preceding the expansion of each scale of wind power in Sweden.

Contrastingly, higher voter turnout rates may correlate with lower wind deployment. Voter turnout serves as an indicator of citizen engagement in democratic processes [45]. It may reflect the likelihood of the public voicing their opinions on local development, such as opposition to new wind power projects. Support for Green party and voter turnout are hypothesized to have stronger effects on deployment of large-scale wind power, as they were built later where social acceptance might pose a greater challenge compared to earlier deployment.

The last factor considered is population density, which impacts the deployment of wind power through multiple system perspectives. High population density can hinder wind deployment due to competing land use and proximity to residential zones or other densely populated areas, making it a resource availability issue within the techno-economic domain. Additionally, higher population density can lead to an increased probability of opposition due to a larger number of individuals being affected. This is a socio-technical interest as it involves technology's interaction with society. Population density is hypothesized to have negative correlation with total installed wind capacity. However, previous studies have shown mixed results for numerous countries [10,11,13,14,16].

3.3. Characterization of municipalities with highest deployment

To complement the statistical analysis, this study characterized high deploying municipalities by identifying common characteristics which set them apart from the rest of the country. Certain variables may not exhibit significant correlation when compared to the entire population in a statistical model but are nevertheless consistently found in smaller number of special cases, such as those with highest amount of total installed capacity. While qualitative case studies similarly focus their analysis on a select few municipalities [8,46,47], their findings are seldom generalizable to the entire country because the factors discussed are often unique to each case. The characterization approach employed here ensures that findings from high deployment cases can be directly compared against other municipalities.

The analysis is limited to large-scale wind power, as they are expected to dominate future wind development. Municipalities within the 90th percentile of total installed capacity of large-scale wind power in 2022 were evaluated. Fig. 1 highlights the selected high deployment municipalities used in the analysis compared to other municipalities. The high deployment municipalities were then mapped against municipal-level characteristics previously utilized in the statistical model, summarized in Appendix C.

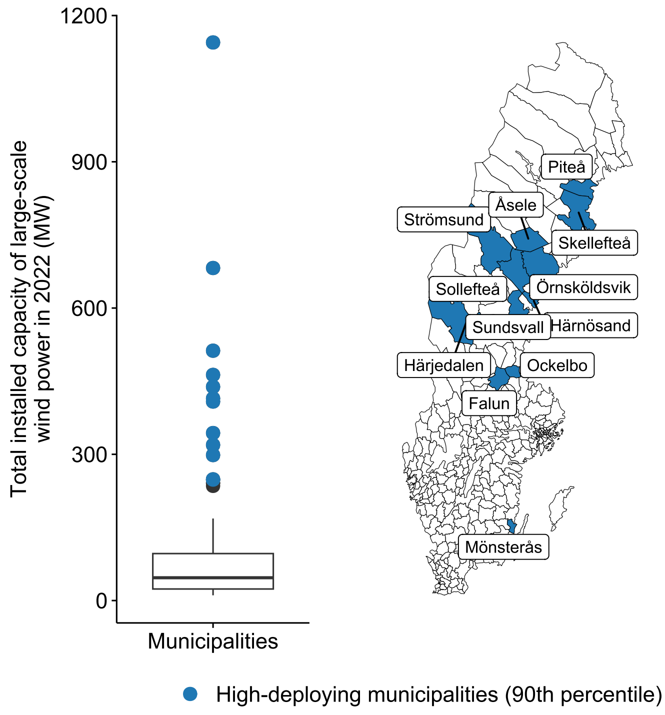

Fig. 1. Distribution of total installed capacity of large-scale wind power in Swedish municipalities.

4. Results

4.1. Deployment of onshore wind power in Sweden from 1990 to 2022

Over the past three decades, Sweden has seen a significant increase in onshore wind power deployment, as illustrated in Fig. 2. The average capacity of newly installed turbines has been steadily rising since 1990. The number of turbines installed annually has also shown consistent growth, with a sharp increase occurring from 2007 onwards, when construction of larger wind parks began. Between 1990 and 2008, the average capacity of additional turbines installed rose from under 200 kW to 1.6 MW, with <100 new turbines installed each year. During this period, the average wind park consisted of fewer than 5 turbines. The average capacity of new turbines has since then increased to over 6 MW in 2022, with annual installations generally exceeding 100 turbines. As of 2022, an average wind park includes 35 turbines.

Small-scale wind power, defined in this study as turbines with capacity of 1.5 MW or less, are no longer constructed since 2016. Conversely, large-scale wind power, consisting of turbines with capacity exceeding 1.5 MW, has continued to expand since its steady growth began around 2007, coinciding with the sharp increase in number of turbines installed annually.

There is noticeable spatial heterogeneity in the deployment of wind power across Sweden's four electricity price areas. Fig. 3A shows the additional installed capacity across different electricity price areas in Sweden, illustrating the annual spatial distribution of new turbine installations. Small-scale wind power was initially built mainly in southern Sweden, overlapping with the electricity price areas SE3 and SE4 (Stockholm and Malmö). Subsequently, small-scale wind power development expanded to the northern price areas SE1 and SE2 (Luleå and Sundsvall), albeit not to the extent of the growth in the south at the time. The concentration of electricity demand in SE3 and SE4 could potentially explain the initial focus on wind deployment in these regions. However, electricity prices were relatively uniform across all electricity price areas until around 2019, when southern areas began experiencing higher prices compared to northern parts of the country.

Deployment of large-scale wind power followed a similar pattern, commencing in the southern price areas SE3 and SE4 before moving to the northern price areas SE1 and SE2. However, a notable distinction has emerged in recent years, with significant growth of large-scale wind power in northern price areas surpassing that of the southern regions. Nevertheless, the continuing deployment in the south suggests that this northward shift cannot be attributed solely to land scarcity in the south. This observation is further supported by Fig. 3B, which illustrates that the growth of both small-scale and large-scale wind power in Sweden follow the expected S-shaped curve characteristic of technological diffusion. The growth of large-scale wind power in terms of total installed capacity in both southern and northern regions has not yet reached saturation.

Significant variations also exist among municipalities, with a few having high wind deployment while many have not built turbines of any size at all, see Fig. 4. Municipalities with the highest deployment level currently have a total installed capacity of 58 MW for small-scale wind power, primarily in coastal areas of southern Sweden. Large-scale wind power reaches up to a total of 1 GW in a few northern municipalities.

Some municipalities have built either small-scale or large-scale wind power exclusively, while others have built both sizes or none at all. This variation forms the basis of the investigation of factors influencing deployment level in Swedish municipalities detailed in Sections 4.2 and 4.3. Additionally, the capacity density of Swedish municipalities is compared against municipalities in few other countries in EU with

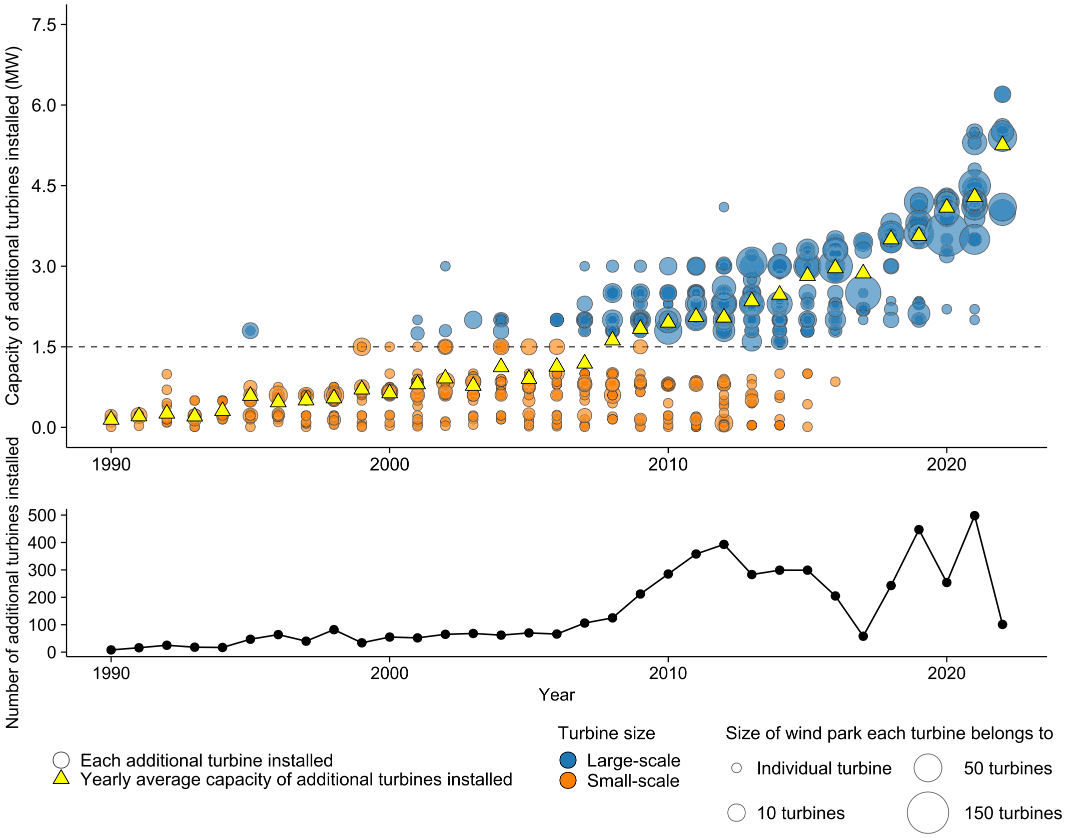

Fig. 2. Onshore wind turbines installed in Sweden from 1990 to 2022.

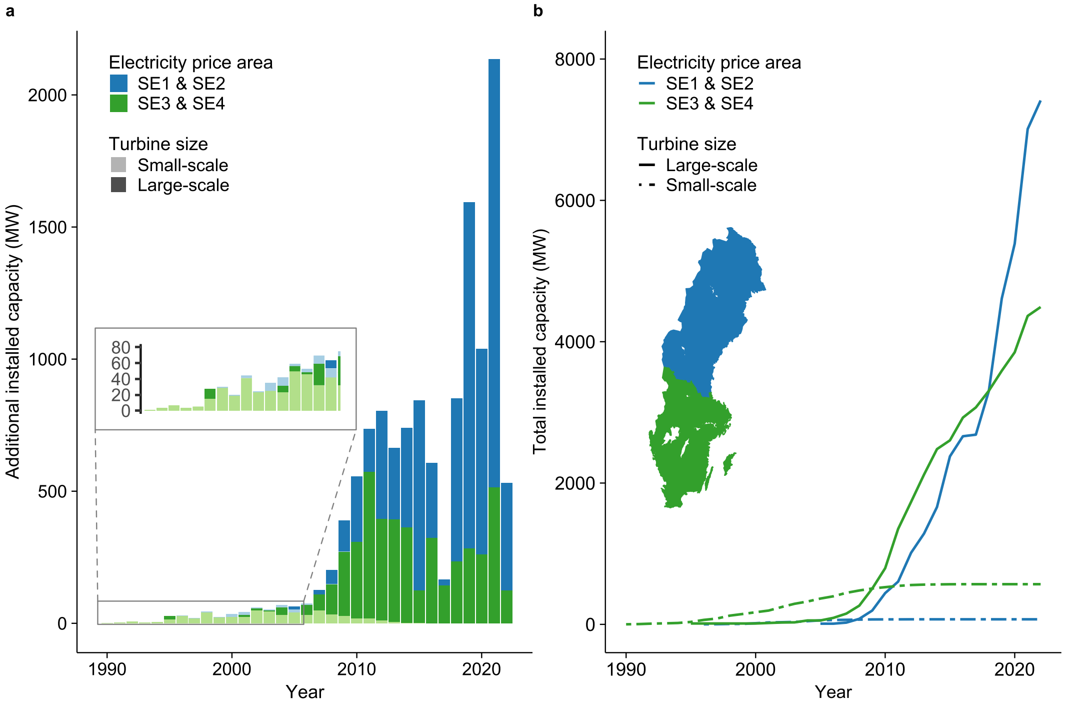

Fig. 3. Installed wind power capacity across Swedish electricity price areas in terms of (a) additional installed capacity and (b) total installed capacity.

similar level of onshore wind deployment using data from Hedenus, et al. [42], as illustrated in Fig. 5. Swedish municipalities generally have lower density levels, with some outliers comparable to countries with intensive deployment such as Germany and Denmark. This comparison is notable given that these two countries typically have higher population density than Sweden. The relatively low utilization of land observed in the majority of municipalities suggests that the expansion into new municipalities is unlikely to be propelled by increasing land constraints.

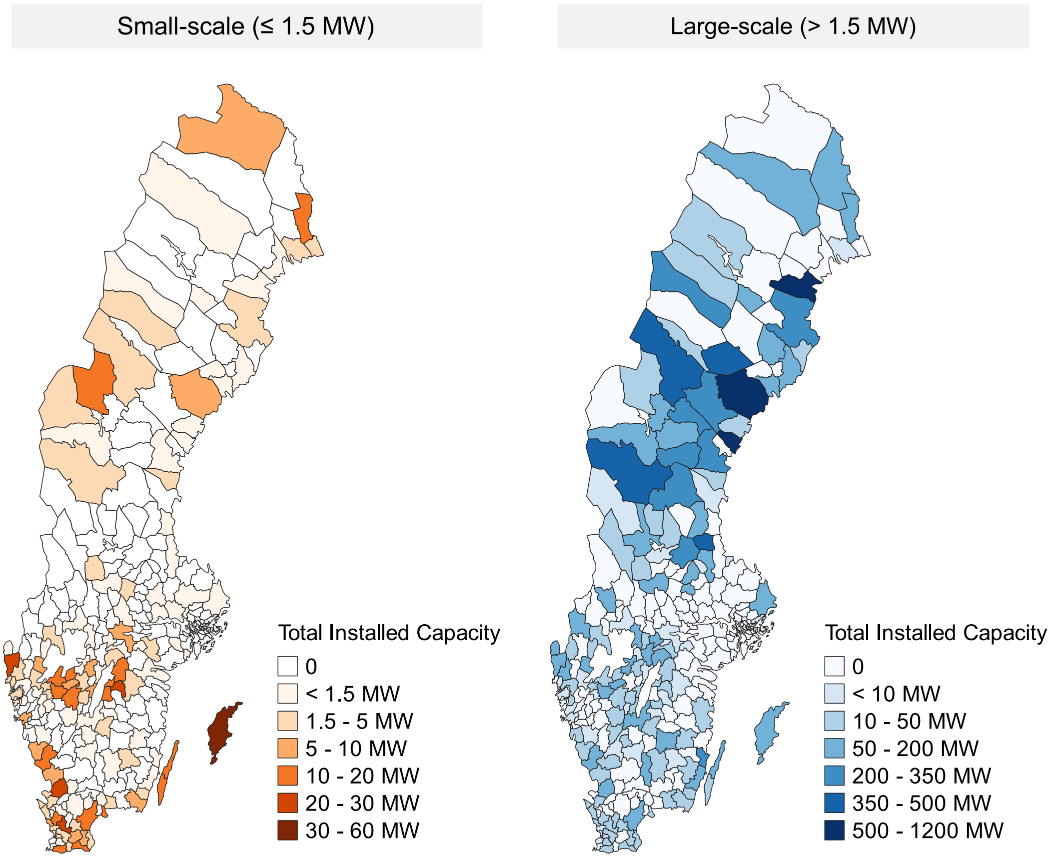

Fig. 4. Map of small-scale and large-scale onshore wind power in Sweden in 2022.

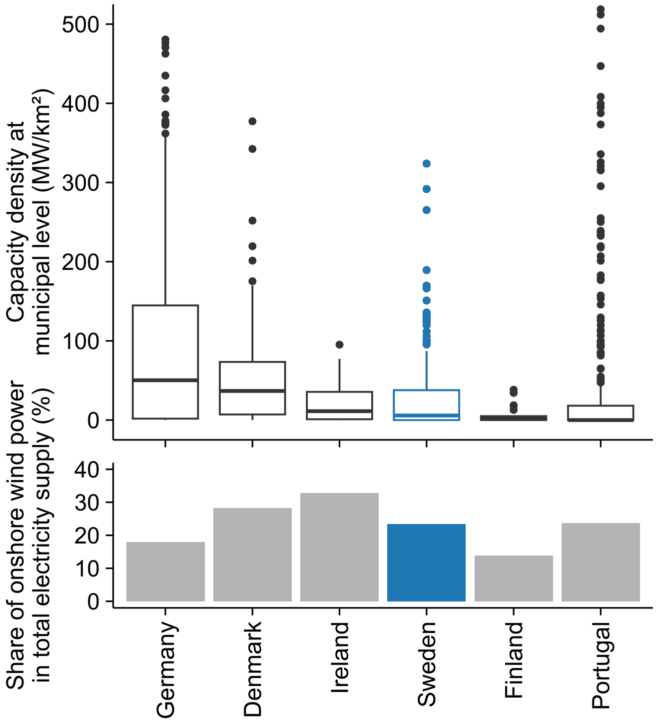

Fig. 5. Capacity density of onshore wind power at the municipal level (or equivalent) in select countries in EU.

4.2. Statistical analysis of spatial heterogeneity of wind deployment in Sweden

Statistical analysis was conducted for wind deployment in Swedish municipalities to test the hypotheses regarding factors that could contribute to its heterogeneity. Different outcomes for small- and large-scale wind power were observed, indicating distinct mechanisms at play for each scale. Table 2 reports the result and diagnostics for small-scale and large-scale wind power in Swedish municipalities. Additional result for take-off probability is available on Appendix E. Multiple model iterations were also run to identify which variables are consistently significant across various specifications, as detailed in Appendix F. The significance levels shown on Table 2 remain consistent across most alternative models tested.

No significant correlation was observed between wind speed or electricity price area and the deployment of either small-scale or large-scale wind power at the municipal level. Few other variables rooting from the techno-economic perspective were found to correlate with deployment of wind power in Sweden. Municipalities with larger land area below 1000 m in elevation deployed more small-scale wind power, but not large-scale wind power. As the hypotheses suggested, a positive correlation between a high share of agricultural land use and the installed capacity was found for small-scale wind power, but not for large-scale.

From the socio-technical system perspective, the number of years since take-off is positively correlated with installed capacity of small-scale wind power, but not with large-scale wind power. The other factor that was intended to reflect experience for municipalities with large-scale wind power, namely the number of small-scale wind power installed, did not demonstrate any significant correlation. Neither gainful employment rate nor support for hydropower was found to be correlated with wind deployment in Swedish municipalities.

Table 2
Results for truncated linear regression on wind deployment in Swedish municipalities.

	Independent variables	**Dependent variable**: Total installed capacity in 2022	
		Small-scale	Large-scale
Techno-economic variables	Wind Speed	−0.875	−208
		(0.878)	(0.209)
	Land Area	26.2**	406
		(0.00778)	(0.0592)
	Agricultural Land Use	14.3**	−563
		(0.00813)	(0.147)
	Strict Nature Reserve	−12.8	−144
		(0.240)	(0.457)
	Electricity Price Area[1]		
	SE4 (Malmö)	21.2	321
		(0.374)	(0.540)
	SE3 (Stockholm)	43.9	−438
		(0.0838)	(0.243)
	SE2 (Sundsvall)	5.61	367
		(0.829)	(0.226)
Socio-technical variables	Population Density	−35.9	−3670
		(0.253)	(0.373)
	Years Since Take-off	21.4**	99.4
		(0.00877)	(0.298)
	Small-scale Wind Power	–	148
			(0.139)
	Hydropower	−6.57	−18.8
		(0.688)	(0.657)
	Gainful Employment Rate	−8.72	−212
		(0.141)	(0.150)
Political variables	Prioritized Area	−1.50	143*
		(0.767)	(0.0309)
	Voter Turnout	−5.24	349*
		(0.279)	(0.0224)
	Support for Green Party	−2.02	108
		(0.649)	(0.323)
	Constant	*−75.1**	*−2340*
		(0.0419)	*(0.112)*
	Model diagnostics		
	Number of observations[2]	75	122
	Log-likelihood[3]	−283	−737
	R-squared[3]	0.259	0.146

** $p < 0.01$.
* $p < 0.05$
Values are standardized estimated coefficients with p-value in parentheses
[1] Estimated coefficients are relative to the reference group SE1 (Luleå).
[2] Sample size after truncation due to take-off threshold.
[3] Diagnostics refer to the complete Cragg double-hurdle model.

Lastly, the political variables of prioritized area and voter turnout have demonstrated positive correlations with deployment level of large-scale wind power, but not small-scale. The positive effect of voter turnout contradicts the initial hypothesis. The other political factor, which is the share of votes for Green Party in the municipal election, did not appear to have any effect on deployment of wind power.

A full model without distinguishing between wind power scales was also run, with results available in Appendix E. The model revealed statistically significant positive correlations between total installed wind power capacity in Swedish municipalities and land area, prioritized area, and voter turnout.

4.3. *Characterization of municipalities with highest deployment of large-scale wind power*

The statistical analysis on wind deployment in Swedish municipalities was complemented with identification of shared traits among municipalities with the highest level of wind deployment. The analysis focused on municipalities within the top 90th percentile in total installed capacity of large-scale wind power. Characteristics of these municipalities were compared with all Swedish municipalities, as shown in Fig. 6.

Municipalities with the highest large-scale wind deployment possess a median range (IQR) of total land area that is higher than the rest of the country, aligning with the statistical result showing a positive correlation between land area and large-scale wind deployment. Findings on land cover also reinforce the statistical results, as these municipalities have a lower median range of agricultural land use and consequently higher for forest cover compared to others. Municipalities with high deployment also have a larger share of the prioritized area compared to the rest of the country.

The median range for wind speed in municipalities with high deployment is actually lower than the country's median. The population density also has a much lower median range. Although these variables do not demonstrate statistical correlation, they appear to be significant characteristics unique to municipalities with the most extensive deployment of large-scale wind power.

Municipalities with the highest deployment of wind power are also home to some of the country's largest hydropower capacities. These are concentrated in electricity price area SE2 (Sundsvall), around the northern region of Sweden. Most of these municipalities only started to adopt wind power around 2010, a relatively recent development and not much earlier compared to other municipalities.

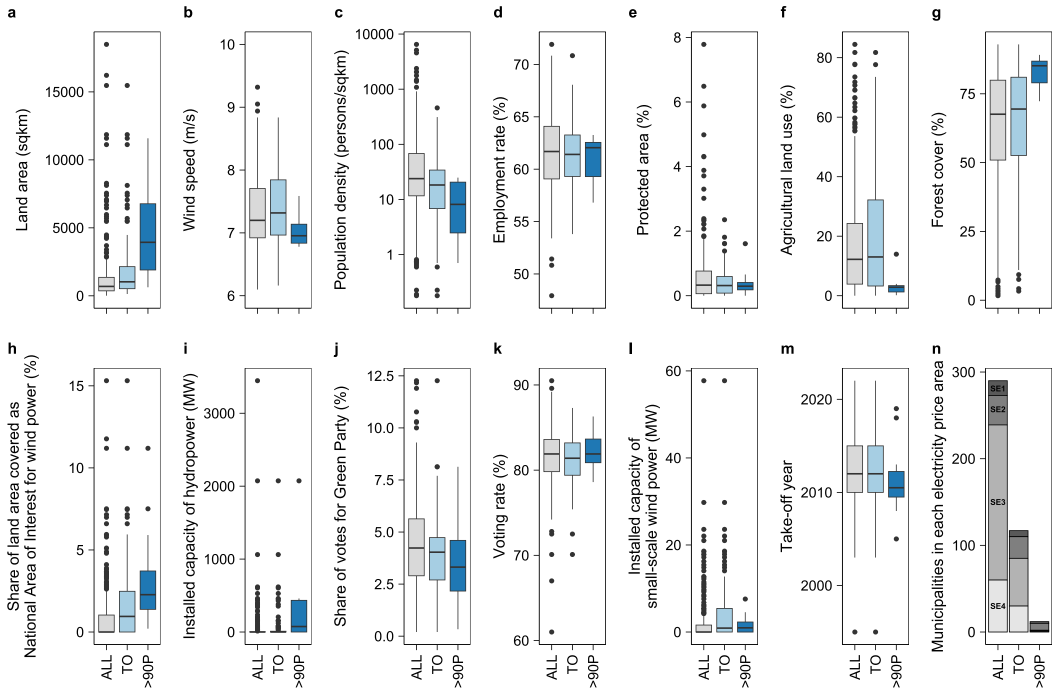

Fig. 6. Characteristics of municipalities with high deployment of large-scale wind power. "*All*" refers to values for all municipalities, "*TO*" refers to values for municipalities with total installed capacity of large-scale wind power ≥10 MW, "*>90P*" refers to values for municipalities within 90th percentile of total installed capacity of large-scale wind power.

5. Discussion

5.1. Factors influencing spatial heterogeneity of wind deployment in Sweden

This study has examined factors derived from energy transition mechanism that potentially correlate with wind deployment across Swedish municipalities beyond resource availability. Additionally, the concept of upscaling from Wilson [37] was applied to identify potential shifts in dominant deployment mechanisms due to change in the scale of the technology. While Wilson's analysis for wind power was confined to Denmark as the technology's core region [37], findings from this study demonstrated that the upscaling pattern is consistent for national level deployment in Sweden. During the formative phase of deployment, prior to around 2007, growth occurred mainly through additions of smaller-scale wind power, defined in this study as those with capacity below 1.5 MW. Following this phase, upscaling ensued, characterized by a sharp increase in unit size concurrent with a rise in the number of additional turbines installed annually. This phase ushered in the installations of large-scale wind power, defined in this study as those with capacity above 1.5 MW.

Differences emerge in the factors influencing deployment of small-scale and large-scale wind power, supporting the proposition to examine wind deployment as two separate subcategories, rather than viewing it as a homogeneous phenomenon as previous studies have done [10,14]. While the scale threshold is admittedly arbitrary, it is specifically defined to serve the case of Swedish wind power, where small-scale wind power installations ceased after 2016. This distinction in scale helps prevent the conflation of results for technologies that are becoming less relevant for future deployment.

The full model results in Appendix E further supports this finding as only variables significant for large-scale deployment are significant in the full model, with the addition of land area showing a positive correlation with deployment. This is expected, as large-scale wind power dominates the overall fleet. The divergent results from the small-scale model, which mainly covers the earlier period of Swedish wind deployment, may indicate that mechanisms change over time. It is, however, challenging to disentangle the effects attributable to scale itself from those related to the progression of the diffusion phase or simply the different period of deployment. Nevertheless, these findings and their implications are discussed both in terms of upscaling and changing phases of diffusion where applicable. This calls for caution when analyzing countries that may be undergoing upscaling or are still in the early stages of diffusion.

The analysis reveals a limited influence of techno-economic factors on deployment of wind power at the municipal level. No significant correlation between wind deployment in Swedish municipalities with wind speed was observed, even when the precision of the variable is improved by only considering highest 90th percentile of wind speed in each municipality. Municipalities with highest large-scale deployment actually have wind speeds within a lower median range relative to the national median. The 90th percentile of wind speed in these municipalities also does not fall below 6.7 m/s, which aligns with historical turbine siting data showing that sites with average wind speeds below 6 m/s are seldom utilized in Europe and the US [42]. Electricity price areas also showed no correlation with municipal deployment levels.

Small-scale wind power is correlated with municipalities with more agricultural land, corroborating previous studies [16,20], but this does not apply to large-scale wind power. This pattern may explain the initial concentration of wind power development in the agrarian southern Sweden before its subsequent diffusion across the country. However, as Fig. 3A shows, large-scale wind power also surged in the northern part of the country, where forested areas dominate rather than agricultural land. While forest cover was excluded from the statistical model due to its collinearity with agricultural land, municipalities with the highest level of large-scale wind deployment have substantial forest cover, underscoring the critical role of forests for significant large-scale wind power growth. This connection may stem from the use of taller turbine hubs in modern larger turbines, allowing for placement in forests far from populated areas, which may reduce public opposition [48].

While population density may impact wind deployment as previous studies suggested [13,14], this is not the case for Sweden, likely due to its generally low population density (descriptive statistics in Appendix C). There may also be an optimal range of population size that favors wind development, which may contribute to the inconsistent results found even for the same country [10,14]. A certain level of population density can provide readily available infrastructures to support the construction and operation of the turbines and thereby reducing costs. Oppositions to wind power can also come from both large cities and small villages. Nevertheless, the pattern of low population density in municipalities with high deployment of large-scale wind power suggests that land-intensive projects are more feasible in sparsely populated areas.

From the socio-technical perspective, longer deployment period is associated to higher deployment of small-scale wind power, highlighting the value of experience with the technology and local network development, especially during the earlier formative phase of technological diffusion [37,49]. In contrast, the deployment of large-scale wind power did not demonstrate a correlation with prior experience within the municipality. The emergence of large-scale wind power coincided with a later stage of diffusion, during which the new sociotechnical regime had likely developed sufficiently to facilitate expansion [50] independent of local networks and experience. Consequently, this phase did not necessitate the accumulation of experience, resulting in a less localized pattern of expansion. The sporadic installation pattern of large-scale wind power is evidenced by the presence of larger wind parks, as illustrated in Fig. 2. This pattern results in abrupt increases in wind capacity within municipalities hosting only a limited number of wind parks.

Ek, et al. [10] and Lauf, et al. [14] also identified a positive correlation between experience and wind power deployment, though the methodology in these studies involved categorizing deployment periods into prior to and after certain year. This approach bears more similarity to assessing the correlation between total installed capacity of small-scale and large-scale wind power in the current model, which yielded no significant results. The present study corroborates the finding that municipalities with extensive wind power experience tend to increase wind power installations. However, measuring experience through the duration of wind power deployment in each municipality offers more nuanced insights into experience effects, compared to using an arbitrary time threshold. Experience significantly influences small-scale deployments, aligning with Ek, et al. [10] and Lauf, et al. [14], but diverges for large-scale deployment likely due to their focus on the periods of prevalent small-scale installations (2006 to 2009 and 2008 to 2012 respectively).

The lack of correlation between total installed capacity of small-scale and large-scale wind power negates the hypothesis that municipalities deplete their land from earlier small-scale wind power deployment, necessitating later large-scale wind power deployment elsewhere, as this scenario would result in a negative correlation. The persistent growth of large-scale wind power in the southern municipalities aligns with this observation. These findings, coupled with the lack of statistical correlation between municipal area and large-scale wind power deployment, as well as low land utilization rate compared to other EU countries with comparable wind penetration levels, collectively suggest that land scarcity is not a significant factor influencing wind power deployment across Swedish municipalities.

The negative effect of hydropower on wind power observed in case studies [8] is not applicable nationwide. Adverse perceptions of wind turbines linked to poor experiences with hydropower are based on limited interviews with municipal decision-makers, which evidently is not representative of all hydropower municipalities. The absence of correlation between employment rate and wind power deployment in Swedish municipalities contrasts with findings from other countries [11,12,14,39]. A study on wind power proposal approval suggests that employment may be more pertinent for project-specific analyses [51]. Furthermore, interviews with municipal decision-makers indicate that employment opportunities are a more compelling factor in favoring new wind development in northern municipalities, especially in rural areas [8]. However, statistical analysis at the municipal level refuted these observations.

From a political perspective, the presence of prioritized areas for wind power show a significant correlation with large-scale wind power deployment, but not with small-scale installations. The introduction of these areas in 2008 coincided with the rise of large-scale projects and the decline of small-scale deployment. Discrepancy from Lauf et al.'s [14] findings may be due to their dataset ending in 2012, when small-scale wind power still dominated. Since Lauf et al. [14] found a correlation between wind speed and wind power deployment, they suggested that prioritized areas mainly serve to disseminate information about favorable resource locations, rather than as land use designations. However, the present analysis shows no statistical significance for wind speed in either small-scale or large-scale models. The positive correlation with prioritized areas likely reflects the presence of these designated zones rather than wind resources. Although not legally binding, this correlation suggests that wind power developers find municipalities with a large share of prioritized areas favorable for development, potentially highlighting the importance of supportive siting policies.

Voter turnout showed a positive correlation with large-scale wind projects deployment. High voter turnout may instead suggest less opposition to government initiatives like wind power investment, due to higher satisfaction with democratic processes [52]. This finding is consistent with a recent study on public acceptance of wind power in Sweden, which indicate that respondents with greater trust in governments and politicians are more inclined to support new wind power developments [53]. Interestingly, the share of votes for Green Party to municipal election is not correlated with deployment, contrasting findings from other countries [12,11] as well as individual acceptance of wind power in Sweden [53]. It is possible that the party prioritizes other local environmental concerns or voters may lack awareness regarding the municipal government's role in such decisions [54].

As large-scale wind power deployment progresses through later stages of technological diffusion, political variables may become increasingly relevant. This shift could be attributed to growing social resistance, which intensifies as wind power installations become more widespread and visible. On the other hand, the increasing unit size may also contribute to this trend, as larger turbines potentially affect more people and attract greater public attention.

5.2. Limitations and future studies

This study is subject to several limitations. Firstly, the analysis was conducted at the municipal level rather than at the exact site of turbine installation. This approach presents challenges in incorporating site-specific variables, such as grid availability and investment cost. However, there is no strong evidence to suggest consistent cost differences between municipalities beyond those accounted for by infrastructure readiness, which this study attempted to address using population density as a proxy. In general, the relevance of cost and grid availability variations is more pertinent at the site-level analysis. Caution is also needed when interpreting land use-related variables, such as land cover and prioritized areas, as the aggregation of these variables at the municipal level may not accurately reflect the characteristics of specific wind power installation sites. Future research could address these limitations by conducting analyses at a higher spatial resolution.

Secondly, this study has excluded offshore wind power from the analysis. Although the majority of wind power installations in Sweden are currently land-based, instances of public opposition to offshore wind have been documented [8]. However, offshore wind is subject to a different regulatory framework compared to its onshore counterpart, and its overall local impact is smaller. Therefore, offshore wind necessitates a separate analysis.

Thirdly, the approach of averaging political variables over multiple elections represents an attempt to capture the general political sentiment in the municipality. For a project-level analysis, it would be more relevant to examine which parties held the majority when specific projects were approved or rejected. However, such an analysis falls outside the scope of this study.

Lastly, the variables utilized in the analysis specific to Sweden may not be directly applicable to other countries, but they can still inform hypotheses for evaluation in other countries. Such a comparative analysis can enable consistent evaluations across nations on which aspects—techno-economic, socio-technical, or political—are most influential under different national settings, while aiding the identification of universal mechanisms and those that are context-specific.

6. Conclusion

Allocation of wind deployment across Swedish municipalities is not primarily determined by techno-economic factors. Higher wind speed is not correlated with higher deployment level, and the low land utilization rate and lack of correlation between early and later wind power deployment illustrate that expansion into new areas is not driven solely by increasing land constraints. Instead, subnational heterogeneity in Swedish wind power is also shaped by a set of socio-technical and political criteria. In light of these findings, studies on resource potential and feasible wind power siting could be enhanced by incorporating these additional factors into their methodologies.

Small-scale wind power was deployed earlier, during the formative phase of technological diffusion, in municipalities with agricultural land and accumulated experience in wind deployment. This highlights the socio-technical factor at play. When large-scale wind power installations became dominant more recently, supportive siting policy and voter turnout indicating high satisfaction with the democratic process gained importance. This shift underscores the significance of political factors in addressing resistance during the later stages of technological diffusion. Additionally, municipalities with the highest amount of large-scale wind power are typically forested municipalities with low population density, potentially to mitigate public opposition. These municipalities also have wind speeds within a lower median range relative to the national median.

These findings stem from the improved methodology for analyzing subnational heterogeneity of wind deployment, integrating a theoretically grounded approach using perspectives from national energy transition literature. The measure of wind resources at the regional level was also enhanced, moving beyond the use of averages employed in previous studies. The effect of technological upscaling on deployment was accounted for by introducing a scale-specific analysis. Given the distinct deployment mechanisms between small-scale and large-scale wind power, formulating effective deployment strategies necessitates a careful consideration of relevant changes in the technological characteristics.

While the mechanisms identified for Sweden may not be generalizable to countries with significantly different deployment contexts, they can nevertheless inform hypotheses for evaluation using similar analytical framework in other countries. The study also illustrated how deployment mechanisms evolve over time potentially due to changes in technological characteristic and diffusion phases. This suggests that countries may need to continually adjust their strategies to support wind growth based on current deployment context, especially under the conditions of continuing technological and socio-political innovation.

CRediT authorship contribution statement

Yodefia Rahmad: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Fredrik Hedenus:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Jessica Jewell:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Vadim Vinichenko:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Data used from Swedish wind power database

Table A.1

Table A.1
Summary of data used from Swedish wind power database [38].

	Number of turbines	Total capacity
All constructed onshore wind power (January 1990 – August 2022)	5050	–
Wind power with missing installation date	57	0.33 MW from 16 wind turbines, capacities of the remaining turbines are missing
Wind power with missing unit capacity	38	Capacities of the remaining turbines are unknown
Wind power used in the analysis		
Installed	4825	12,482 MW
Dismantled	130	63 MW
Total	4955	12,545 MW

Appendix B. Flowchart of the statistical analysis

Fig. B.1

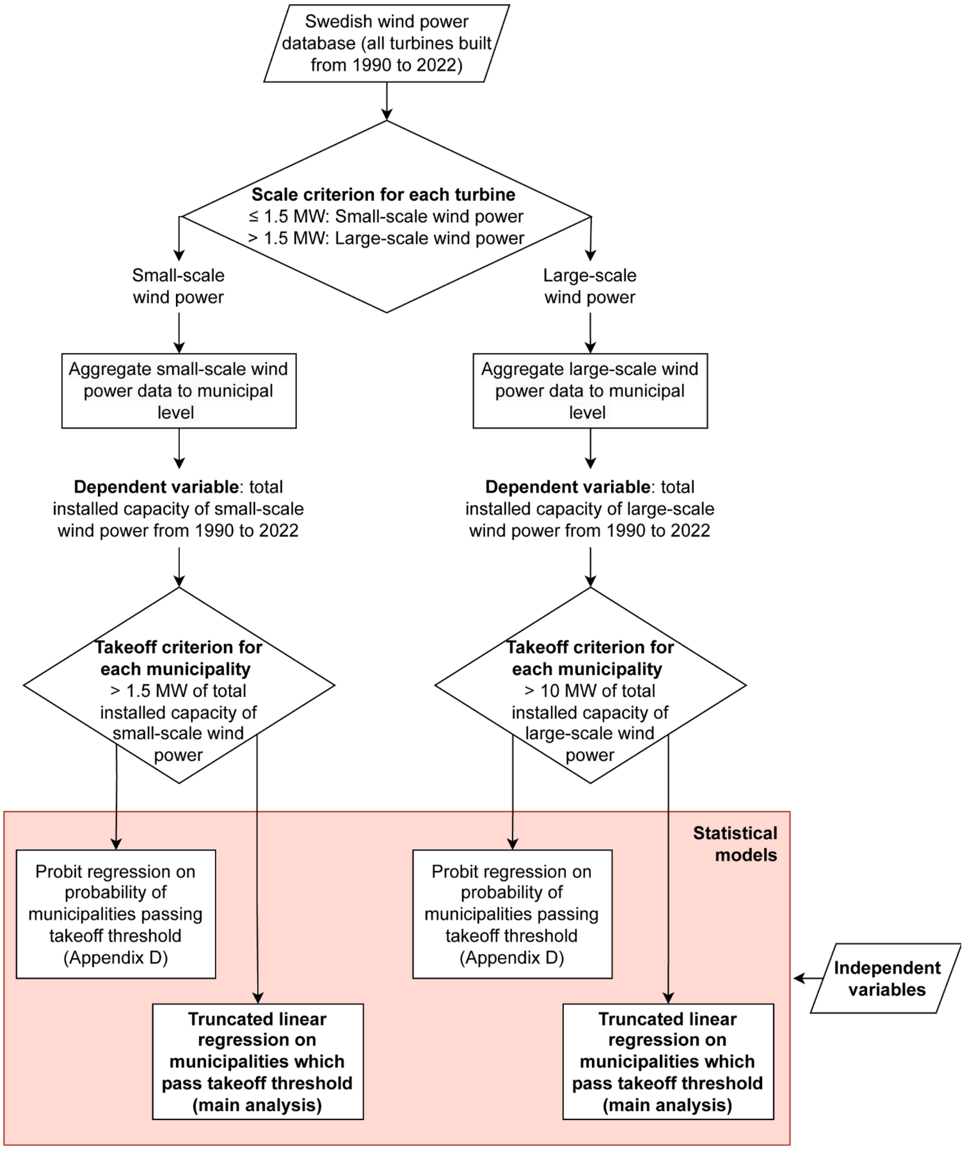

Fig. B.1. Flowchart of the statistical analysis.

Appendix C. Variables used in the statistical model

Table C1

Table C.1
Variables used in the statistical model.

Variables	Definition	Source	*Descriptive statistics*				
			N	Mean	SD	Min.	Max.
Dependent Variables							
Take-off of small-scale wind power project[1]	1 if total installed capacity of wind power under 1.5 MW from 1990 to 2022 exceeds 1.5 MW, 0 otherwise	[38]	1 = 75 0 = 215	–	–	–	–
Escalation of small-scale wind power project	Total installed capacity of wind power under 1.5 MW from 1990 to 2022 (MW)	[38]	75	8.02	8.66	1.6	57.7
Take-off of large-scale wind power project[1]	1 if total installed capacity of wind power above 1.5 MW from 1990 to 2022 exceeds 10 MW, 0 otherwise	[38]	1 = 122 0 = 168	–	–	–	–

(*continued on next page*)

Table C.1 (*continued*)

Variables	Definition	Source	*Descriptive statistics*				
			N	Mean	SD	Min.	Max.
Escalation of large-scale wind power project	Total installed capacity of wind power above 1.5 MW from 1990 to 2022 (MW)	[38]	122	96.5	151	10.0	1150
Independent Variables							
Techno-economic variables							
Wind speed	Top 90th percentile of wind speed excluding those within land with elevation $>$ 1000 m (m/s)	[55]	290	7.34	0.61	6.1	9.32
Land area	Log of total land area excluding those with elevation $>$ 1000 m (km^2) in 2019	[56]	290	6.54	1.23	2.02	9.82
Agricultural land use	Share of total land area (%) in 2010	[57]	290	17.8	18.8	0	84.5
Forest cover	Share of total land area (%) in 2010	[57]	290	63.4	22.1	0.693	95.1
Protected Area	Share of total land area under WDPA category IA (Strict Nature Reserve) excluding those within land with elevation $>$ 1000 m (%) in 2019	[58]	290	0.624	0.973	0	7.78
Electricity Price Area[1]	*Dummy variable for Swedish electricity price area*	[38]					
SE1 (Luleå)			1 = 17 0 = 273	–			
SE2 (Sundsvall)			1 = 34 0 = 256				
SE3 (Stockholm)			1 = 179 0 = 111				
SE4 (Malmö)			1 = 60 0 = 230				
Population density	Ppulation density excluding those within land with elevation $>$ 1000 m (persons per km^2) in 2020	[59, 60]	290	165	623	0.180	6490
Socio-technical variables							
Years since take-off	*Number of years since total installed capacity of wind power exceeds take-off threshold in 2022*	[38]					
Small-scale wind power			75	19.9	5.07	10	31
Large-scale wind power			122	9.57	4.51	0	27
Small-scale wind power[2]	Total installed capacity of wind power under 1.5 MW and 5 turbines per project from 1990 to 2022 (MW)	[38]	290	2.21	5.58	0	57.8
Hydropower	Total installed capacity of hydropower (MW) in 2020	[61, 62]	290	55.5	260	0	3450
Gainful employment rate	Share of total population above 16 years old (%) in 2010	[63]	290	61.6	3.73	47.9	71.9
Political variables							
National Area of Interest for Energy Production and Distribution	Share of total land area from National Area of Interest (*områden av riksintresse*) for energy production and distribution (%) in 2014	[64]	290	0.905	1.92	0	15.3
Voter turnout	*Share of eligible voters in municipal election (%)*	[65]					
Small-scale wind power project: Election year 2002			290	78.0	3.45	57.8	87.8
Large-scale wind power project: Election year 2010			290	81.5	3.35	61	90.5
Support for Green Party	*Share of valid votes to municipal election (%)*	[66]					
Small-scale wind power project: Average of elections years 2002, 2006, and 2010			290	3.84	2.19	0.200	23.6
Large-scale wind power project: Average of election years 2010, 2014, and 2018			290	4.43	2.29	0.200	12.3

Appendix D. Multicollinearity test

A multicollinearity test is conducted to ensure the absence of near-linear dependence among independent variables, which can lead to inaccurate regression estimates [67]. Table D1 presents the Pearson's correlation coefficient [68] matrix for each pair of independent variables. A coefficient of 0 indicates no correlation between the pair, while 1 (or −1) signifies perfect positive (or negative) correlation. While there is no universal rule for interpreting values between these extremes, larger absolute values indicate stronger correlations. Coefficients between 0.5 and 0.7 may suggest moderate relationships, while those above 0.7 indicate strong collinearity. The analysis reveals a Pearson correlation coefficient of −0.74 between forest cover and agricultural land, indicating a strong inverse relationship. This finding is corroborated by the variance inflation factor (VIF) analysis presented in Table D2. VIF quantifies the extent to which multicollinearity inflates the variance of a regression coefficient [67]. While values closer to 1 are ideal as it indicates no inflation of variance due to collinearity, those below 10 are generally considered acceptable [67]. A comparison of VIF values before and after the removal of forest cover demonstrates that post-removal, no independent variables exhibit VIF values exceeding 10, and the mean VIF decreases. These results necessitate the exclusion of forest cover as an independent variable from the statistical models.

Table D.1
Pearson correlation coefficient matrix.

	Wind Speed	Land Area	Agricultural Land Use	Forest Cover	Strict Nature Reserve	Population Density	Years Since Take-off (Small-scale)	Years Since Take-off (Large-scale)	Hydropower	Gainful Employment Rate	Prioritized Area	Voter Turnout (2002)	Voter Turnout (2010)
Wind Speed													
Land Area	−0.27												
Agricultural Land Use	0.62	−0.36											
Forest Cover	−0.69	0.58	−0.74										
Strict Nature Reserve	−0.18	−0.12	−0.25	0.04									
Population Density	−0.03	−0.46	−0.06	−0.42	0.28								
Years Since Take-off (Small-scale)	−0.46	−0.03	−0.50	0.38	0.17	0.09							
Years Since Take-off (Large-scale)	−0.12	−0.32	−0.12	−0.03	0.16	0.17	NA[1]						
Hydropower	−0.07	0.34	−0.17	0.08	−0.02	−0.05	0.05	−0.06					
Gainful Employment Rate	0.22	−0.18	0.05	−0.25	0.07	0.19	0.04	0.06	−0.04				
Prioritized Area	−0.11	0.21	−0.17	0.25	−0.07	−0.11	−0.06	−0.35	0.02	−0.03			
Voter Turnout (2002)	0.18	−0.23	0.11	−0.16	−0.02	0.03	0.03	0.09	−0.05	0.53	0.01		
Support for Green Party (2002 - 2010)	0.15	−0.17	0.08	−0.21	0.16	0.25	−0.08	0.13	0.02	0.25	−0.11	0.21	NA[1]
Voter Turnout (2010)	0.21	−0.23	0.13	−0.16	0.01	0.00	0.00	0.06	−0.06	0.59	−0.03	NA[1]	
Support for Green Party (2010 - 2018)	0.26	−0.33	0.14	−0.38	0.21	0.39	−0.02	0.19	0.06	0.42	−0.14	NA[1]	0.32

The electricity price area variable was not included as this method is not applicable to categorical variables. Instead, potential collinearity was assessed using variance inflation factor as shown in Table D.2.

[1] These variables are never used simultaneously.

Table D.2
Variance inflation factor.

	Variance inflation factor			
Independent variables	Small-scale model	Large-scale model	Small-scale model (without forest cover)	Large-scale model (without forest cover)
Wind Speed	6.65	5.56	2.63	3.47
Land Area	3.78	4.00	3.75	3.94
Agricultural Land Use	12.57	15.5	2.82	5.32
Forest Cover	22.82	20.14	–	–
Strict Nature Reserve	1.40	1.3	1.31	1.29
Electricity Price Area[1]				
SE4 (Malmö)	15.07	8.82	9.82	7.41
SE3 (Stockholm)	15.01	9.52	8.80	7.58
SE2 (Sundsvall)	3.97	5.49	3.23	4.21
Population Density	1.99	2.54	1.30	2.03
Years Since Take-off	1.49	1.36	1.47	1.36
Small-scale Wind Power	–	1.93	–	1.88
Hydropower	2.93	1.34	2.77	1.33
Gainful Employment Rate	1.82	1.55	1.75	1.43
Prioritized Area	1.35	1.19	1.28	1.17
Voter Turnout	2.03	1.61	2.02	1.56
Support for Green Party	1.56	1.47	1.48	1.40
Mean VIF	***6.30***	***5.21***	***3.17***	***3.03***

[1] Estimated coefficients are relative to the reference group SE1 (Luleå).

Appendix E. Additional statistical results

Tables E1 and E2

Table E.1
Results for the probability of Swedish municipalities to take-off in wind deployment.

	Independent variables	**Dependent variable:** Binary choice, 1 if municipalities pass take-off threshold[1], 0 otherwise	
		Small-scale	Large-scale
Techno-economic variables	Wind Speed	0.763**	0.0990
		(2.26e-07)	(0.462)
	Land Area	0.607**	0.525**
		(0.000885)	(0.00113)
	Agricultural Land Use	0.780**	0.237
		(1.11e-06)	(0.113)
	Strict Nature Reserve	−0.179	−0.106
		(0.366)	(0.501)
	Electricity Price Area[2]		
	SE4 (Malmö)	−1.03	0.556
		(0.0652)	(0.269)
	SE3 (Stockholm)	−1.06*	0.364
		(0.0270)	(0.410)
	SE2 (Sundsvall)	−0.980*	0.896*
		(0.0438)	(0.0449)
	Population Density	−0.594	−0.223
Socio-technical variables		(0.0754)	(0.613)
	Small-scale Wind Power	−0.201	0.635**
		(0.172)	(0.000731)
	Hydropower	−0.327*	−0.0232
		(0.0292)	(0.816)
	Gainful Employment Rate	0.273**	−0.0319
		(0.00330)	(0.790)
Political variables	Prioritized Area	−0.154	0.504**
		(0.193)	(2.60e-06)
	Voter Turnout	0.209*	0.0484
		(0.0419)	(0.672)
	Support for Green Party	−0.594	−0.151
		(0.0754)	(0.183)
	Constant	*−0.170*	*−0.706*
		(0.703)	*(0.0899)*
	Model diagnostics		
	Number of observations[2]	290	290
	Log-likelihood[3]	−283	−737
	R-squared[3]	0.259	0.146

** $p < 0.01$,.
* $p < 0.05$
Values are standardized estimated coefficients with p-value in parentheses.
[1] Take-off thresholds for small-scale and large-scale wind power are 1.5MW and 10 MW in total installed capacity by 2022 respectively.
[2] Estimated coefficients are relative to the reference group SE1 (Luleå).
[3] Diagnostics refer to the complete Cragg double-hurdle model.

Table E.2
Full model results for the take-off probability and truncated linear regression of wind deployment in Swedish municipalities.

	Independent variables	**Dependent variable**	
		Binary choice, 1 if municipalities pass take-off threshold[1], 0 otherwise	Total installed capacity in 2022
Techno-economic variables	Wind Speed	0.420**	−307
		(0.00104)	(0.0546)
	Land Area	0.734**	661**
		(1.48e-06)	(0.00990)
	Agricultural Land Use	0.443**	187
		(0.00107)	(0.364)
	Strict Nature Reserve	−0.370*	−152
		(0.0299)	(0.405)
	Electricity Price Area[2]		
	SE4 (Malmö)	−0.504	289
		(0.312)	(0.529)
	SE3 (Stockholm)	−0.441	−302
		(0.313)	(0.389)
	SE2 (Sundsvall)	0.0795	547
		(0.869)	(0.0825)
	Population Density	0.125	−3080
Socio-technical variables		(0.509)	(0.176)
	Years Since Take-off	–	99.3
			(0.316)
	Hydropower	−0.165	−21.6
		(0.0998)	(0.629)
	Gainful Employment Rate	−0.0205	−243

(continued on next page)

Table E.2 (*continued*)

	Independent variables	Dependent variable	
		Binary choice, 1 if municipalities pass take-off threshold[1], 0 otherwise	Total installed capacity in 2022
		(0.866)	(0.0788)
Political variables	Prioritized Area	0.782**	198**
		(2.03e-06)	(0.00310)
	Voter Turnout[3]	0.000424	290*
		(0.997)	(0.0146)
	Support for Green Party[3]	−0.0878	90.3
		(0.433)	(0.327)
	Constant	*0.530*	−2260*
		(0.201)	*(0.0211)*
	Model diagnostics		
	Number of observations	290 (155 after truncation)	
	Log-likelihood[4]	−905	
	R-squared[4]	0.123	

** $p < 0.01$,.

* $p < 0.05$

Values are standardized estimated coefficients with p-value in parentheses.

[1] Take-off thresholds for full model is 2 MW in total installed capacity by 2022 respectively.

[2] Estimated coefficients are relative to the reference group SE1 (Luleå).

[3] Election variables from election years 2010, 2014, and 2018 are used (following model specification for deployment of large-scale wind power)

[4] Diagnostics refer to the complete Cragg double-hurdle model.

Appendix F. Alternative model specifications

Tables F1 and F2

Table F.1

Results for truncated linear regression on deployment of small-scale wind power in Swedish municipalities from alternative model specifications.

Independent variables	**Dependent variable:** Total installed capacity of wind power with capacity ≤ 1.5MW in 2022						
	Models						
	(1)	(2)	(3)	(4)	(5)	(6)	Main
Land Area	28.9	33.6	24.3*	23.7**	24.2**	27.3*	26.24**
	(0.167)	(0.175)	(0.0350)	(0.00881)	(0.00800)	(0.0132)	(0.00778)
Wind Speed	10.1	6.51	−4.84	−1.52	−1.21	−1.09	−0.875
	(0.396)	(0.572)	(0.517)	(0.799)	(0.837)	(0.860)	(0.878)
Population Density	−73.4	−59.5	−37.2	−48.6	−47.4	−40.4	−35.9
	(0.338)	(0.385)	(0.334)	(0.165)	(0.169)	(0.257)	(0.253)
Electricity Price Area[2]							
SE4 (Malmö)	65.3	72.2	16.5	10.3	9.38	13.7	21.2
	(0.288)	(0.279)	(0.582)	(0.652)	(0.679)	(0.575)	(0.374)
SE3 (Stockholm)	74.8	91.1	38.7	31.9	30.5	37.6	43.8
	(0.238)	(0.222)	(0.202)	(0.162)	(0.177)	(0.144)	(0.0838)
SE2 (Sundsvall)	−19.7	−11.8	−1.00	−5.03	−0.924	−3.28	5.61
	(0.697)	(0.813)	(0.971)	(0.823)	(0.970)	(0.896)	(0.829)
Years Since Take-off	24.5	31.9	23.1*	22.7**	22.3**	24.0*	21.4**
	(0.109)	(0.126)	(0.0315)	(0.00812)	(0.00800)	(0.0112)	(0.00877)
Prioritized Area	−5.81	−4.80	0.735	−0.660	−0.790	−1.29	−1.50
	(0.558)	(0.624)	(0.877)	(0.892)	(0.871)	(0.804)	(0.767)
Strict Nature Reserve		−33.2	−14.4	−12.3	−12.6	−13.9	−12.8
		(0.273)	(0.321)	(0.269)	(0.254)	(0.242)	(0.240)
Agriculture Land Use			16.7*	14.4**	14.1*	15.0*	14.3**
			(0.0273)	(0.00974)	(0.0103)	(0.0136)	(0.00813)
Gainful Employment Rate				−11.3*	−11.1*	−12.5*	−8.72
				(0.0471)	(0.0474)	(0.0466)	(0.141)
Hydropower					−7.23	−6.46	−6.56
					(0.653)	(0.702)	(0.688)
Support for Green Party						−5.01	−2.02
						(0.2666)	(0.649)
Voter Turnout							−5.24
							(0.279)
Constant	*−133*	*−156*	*−77.0*	*−66.4*	*−65.9*	*−73.6*	−75.1*
	(0.210)	*(0.210)*	*(0.0932)*	*(0.0538)*	*(0.0536)*	*(0.0610)*	*(0.0419)*
Model diagnostics							
Number of observations[2]	75	75	75	75	75	75	75
Log-likelihood[3]	−317	−316	−296	−289	−287	−284	−283
R-squared[3]	0.162	0.170	0.225	0.244	0.248	0.255	0.259

** $p < 0.01$,.

* $p < 0.05$

The analysis begins with a basic model ((1)) incorporating a minimal set of independent variables. Subsequent models ((2) to (6)) systematically introduce additional independent variables, culminating in the primary model specification (Main) used in the analysis. Values are standardized estimated coefficients with p-value in parentheses.

[1] Estimated coefficients are relative to the reference group SE1 (Luleå).

[2] Sample size after truncation due to take-off threshold.

[3] Diagnostics refer to the complete Cragg double-hurdle model.

Table F.2

Results for truncated linear regression on deployment of large-scale wind power in Swedish municipalities from alternative model specifications.

Independent variables	**Dependent variable**: Total installed capacity of wind power with capacity $\leq$ 1.5MW in 2022						
	Models						
	(1)	(2)	(3)	(4)	(5)	(6)	Main
Land Area	938	841	613*	413	357	372	406
	(0.117)	(0.109)	(0.0265)	(0.0667)	(0.0569)	(0.0557)	(0.0592)
Wind Speed	−712	−694	−326	−244	−185	−186	−208
	(0.160)	(0.130)	(0.111)	(0.173)	(0.234)	(0.227)	(0.209)
Population Density	−5190	−4670	−5460	−3030	−2260	−2180	−3670
	(0.433)	(0.443)	(0.203)	(0.437)	(0.498)	(0.507)	(0.373)
Electricity Price Area[2]							
SE4 (Malmö)	370	201	245	341	219	225	321
	(0.711)	(0.828)	(0.667)	(0.534)	(0.650)	(0.638)	(0.540)
SE3 (Stockholm)	−748	−776	−387	−460	−464	−446	−438
	(0.327)	(0.282)	(0.351)	(0.260)	(0.202)	(0.217)	(0.243)
SE2 (Sundsvall)	751	637	505	385	301	314	367
	(0.251)	(0.263)	(0.139)	(0.216)	(0.258)	(0.245)	(0.226)
Years Since Take-off	219	197	88.7	82.8	89.2	87.9	99.4
	(0.245)	(0.244)	(0.375)	(0.406)	(0.330)	(0.331)	(0.298)
Small-scale wind power	206	206	88.6	185	167	162	148
	(0.214)	(0.181)	(0.246)	(0.116)	(0.102)	(0.106)	(0.139)
Prioritized Area	354	314	183*	162*	144*	143*	143*
	(0.0832)	(0.0781)	(0.0284)	(0.0338)	(0.0245)	(0.0241)	(0.0309)
Strict Nature Reserve		−192	13.5	−53.8	−129	−137	−144
		(0.500)	(0.942)	(0.780)	(0.481)	(0.453)	(0.4574)
Voter Turnout			329*	327*	338*	340*	349*
			(0.0387)	(0.0397)	(0.0212)	(0.0191)	(0.0223)
Agriculture Land Use				−648	−589	−571	−563
				(0.142)	(0.124)	(0.130)	(0.147)
Gainful Employment Rate					−151	−161	−212
					(0.237)	(0.221)	(0.150)
Hydropower						−12.5	−18.8
						(0.759)	(0.657)
Support for Green Party							107
							(0.323)
Constant	*−4230*	*−3780*	*−2900*	*−2370*	*−1930*	*−1910*	*−2340*
	(0.199)	*(0.193)*	*(0.0797)*	*(0.107)*	*(0.109)*	*(0.106)*	*(0.112)*
Model diagnostics							
Number of observations[2]	122	122	122	122	122	122	122
Log-likelihood[3]	−746	−745	−743	−739	−738	−738	−737
R-squared[3]	0.136	0.137	0.140	0.144	0.145	0.146	0.147

** $p < 0.01$.

* $p < 0.05$

The analysis begins with a basic model ((1)) incorporating a minimal set of independent variables. Subsequent models ((2) to (6)) systematically introduce additional independent variables, culminating in the primary model specification (Main) used in the analysis. Values are standardized estimated coefficients with p-value in parentheses.

[1] Estimated coefficients are relative to the reference group SE1 (Luleå).

[2] Sample size after truncation due to take-off threshold.

[3] Diagnostics refer to the complete Cragg double-hurdle model.

Data availability

Data will be made available on request.

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