THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Diffusion of onshore wind power: Technological upscaling and national adoption patterns

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Cover image by Author. Description: A black and white image of 2 MW wind turbine in Fjärås, Sweden.

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Abstract

Understanding the mechanisms driving onshore wind power deployment is essential for accelerating national growth to meet climate mitigation targets. The global nature of the wind turbine market influences how the technology diffuses across countries. Recent adopters may be able to leverage turbine technology that has matured elsewhere, allowing them to "leapfrog" ahead and accelerate their expansion. Global development in wind technology, such as increasing turbine capacity, can also reshape country-level deployment patterns by altering site requirements. At the same time, siting of new wind projects faces challenges from growing public and political resistance.

A significant gap exists in the literature on how advancements in wind technology, particularly turbine upscaling, disseminate across countries and affect national growth. Global developments in wind parks also remain understudied, despite their relevance since turbines are rarely installed in isolation. Studies on subnational variations in wind deployment have also overlooked the effect of turbine upscaling and lack a theoretical framework for identifying allocation mechanisms. This thesis situates these research gaps within the broader technological diffusion literature and addresses them through findings presented in the appended publications.

Paper II investigates how global turbine upscaling influences national deployment using wind power data from 28 countries. The findings reveal that the mass customization of turbine technology enables late adopters to access the latest generation of larger turbines directly from the global market, bypassing earlier smaller models. However, the advantage of turbine upscaling alone cannot accelerate growth. Project-level analysis shows that wind park sizes follow no consistent global trends but instead correlate with national factors such as public participation in decision-making and population distribution.

Paper I examines the drivers behind uneven subnational distribution of onshore wind deployment, focusing on Swedish municipalities as a case study. The analysis employs a theoretically grounded framework combining techno-economic, socio-technical, and political perspectives from energy transition literature. The findings show that deployment patterns evolved alongside turbine upscaling and diffusion stages. In the early formative phase, small-scale wind power emerged in municipalities that had agricultural land and prior wind deployment experience. As large-scale wind installations became more common, political factors such as supportive siting policies and high voter participation grew in importance.

Keywords*: Onshore wind power, technological diffusion, spatial heterogeneity, technological upscaling, renewable deployment*

List of Publications

Paper I

Rahmad, Y., Hedenus, F., Jewell, J., Vinichenko, V. (2025) Spatial heterogeneity in deployment and upscaling of wind power in Swedish municipalities. *Renewable and Sustainable Energy Transition.* https://doi.org/10.1016/j.rset.2025.100104

Paper II

Rahmad, Y., Hedenus, F. Leapfrogging in onshore wind power: Analyzing the effect of turbine upscaling on national adoption patterns. *Manuscript.*

Author contributions

Paper I

Conceptualization: **Y.R.**, F.H., J.J., V.V.; *Methodology*: **Y.R.**, F.H., J.J., V.V.; *Data curation and formal analysis*: **Y.R.**; *Writing – original draft*: **Y.R.**; *Writing – review and editing*: F.H., J.J., V.V.; *Supervision*: F.H., J.J.

Paper II

Conceptualization: **Y.R.**, F.H.; *Methodology*: **Y.R.**, F.H.; *Data curation and formal analysis*: **Y.R.**; *Writing – original draft*: **Y.R.**; *Writing – review and editing*: F.H.; *Supervision*: F.H.

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And to my parents & Henrik, I could try my best to write how thankful I am for your presence in my life, though I doubt words large enough exist to do so.

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1. Introduction

The deployment of renewable energy technologies plays a crucial role in achieving climate change mitigation targets, as highlighted in the IPCC's Sixth Assessment Report [1, 2]. Onshore wind power constitutes a critical component of this transition. As of 2024, global onshore wind installations reach a total of 1047 GW, representing the second most significant source of renewable electricity generation worldwide, surpassed only by hydropower [3]. However, many countries are still falling short of their climate goals due to, among others, slow deployment of onshore wind [4, 5]. In order to accelerate national growth of onshore wind, understanding the mechanisms driving its expansion and the associated challenges is essential.

Wind technology has evolved significantly since its inception. Since Scottish engineer James Blyth built the first electricity-generating wind machine in 1887 [6], the technology has matured through continuous refinement into today's typical three-bladed design [7]. Its adoption has spread far beyond the early utility-scale pioneers like Denmark and Germany [8, 9]. In recent decades, costs have fallen significantly due to various factors such as learning in manufacturing processes, economies of scale, and advances in materials and other parts of the turbine technologies [10, 11]. Ongoing research and development efforts continue to yield improvements such as larger unit capacity and rotor size, a trend expected to continue [12, 7, 13].

The wind turbine industry has evolved into a globalized market [14]. Global technological advancements thus directly influence wind power adoption across nations, carrying few implications for wind deployment mechanisms. First, countries that have only recently begun deploying wind power can leverage turbine technology that has matured elsewhere, a concept known as technological "leapfrogging" [15, 16, 17]. This offers late-adopting countries an opportunity to accelerate their wind deployment by building on the accumulated knowledge of earlier adopters. Although previous studies have examined evidence of leapfrogging in terms of faster wind power deployment [5, 18], the current literature has not fully illuminated the mechanisms through which late adopters can capitalize on global technological progress. Second, country-level deployment patterns, including subnational spatial distribution, can also be impacted by development in turbine technology, such as turbine upscaling. The growing turbine sizes may necessitate changes in their placement, driven by both technical requirements and non-technical ones such as social acceptance [12]. Yet existing research on subnational variation in wind deployment has not adequately accounted for such technological evolution when analyzing the mechanisms shaping subnational deployment pattern [19, 20, 21, 22, 23, 24, 25].

Concurrently, as wind installations multiply and shift toward larger turbines and wind parks [7, 26, 12], wind power is pushed into closer contact with broader segments of society. As a result, siting issues for new projects intensify, impeding expansion across different countries. Beyond growing public opposition [27, 28, 29, 30, 31], complex permitting process [32, 33, 34, 35] and the politicization of renewable deployment [36, 37, 38, 39] have also contributed to this challenge. One way to develop an effective deployment strategy under these constraints is to examine the spatial distribution of past deployments within countries and disentangle the mechanisms shaping it. However, existing empirical studies on subnational variations in wind deployment show diverging results and often lack theoretical foundations when investigating potential deployment mechanisms [19, 20, 21, 22, 23, 24, 25]. The literature has yet to adequately clarify which factors beyond wind resources drive deployment patterns and could inform decisions about viable locations for future wind development.

While these mechanisms have been the subject of previous technological diffusion studies on onshore wind [5, 18, 40, 22, 23, 24, 25, 19], important knowledge gaps remain. Current literature has not fully explored how the rapid evolution of wind technology, particularly increasing turbine sizes, affects adoption patterns. The mechanism by which technological development penetrates the market has not been clearly outlined, especially regarding effects on national growth rates and subnational heterogeneity. Moreover, current research lacks a theoretical framework for understanding mechanisms influencing deployment at the subnational level. This thesis addresses these gaps by investigating two research questions:

Research Question 1: *How does global technological development of onshore wind power affect national deployment?*

This question is examined in Paper II through a comprehensive analysis of wind power deployment patterns across 28 countries from 1980 to 2023. The study traces the global technological development of turbines, with particular attention to unit upscaling, and identifies how it may influence turbine adoption patterns in different countries. The analysis evaluates technological characteristics, including design complexity and standardization, and their subsequent impact on global market structure. It then measures national growth rates to determine whether turbine upscaling can accelerate growth for late adopters compared to early adopters. Additionally, wind park development was analyzed to determine whether global trends in park sizes mirror the upscaling pattern seen in turbines and to examine how this relates to national growth.

Research Question 2: *What are the mechanisms shaping the spatial heterogeneity in onshore wind deployment within a country?*

This question is investigated in Paper I through an analysis of historical wind power deployment across Swedish municipalities from 1990 to 2022. The study employs techno-economic, socio-technical, and political system perspectives from national energy transition literature [41] to identify theoretically grounded subnational deployment mechanisms. The analysis also evaluates how these mechanisms evolve over time, both due to technological changes like turbine upscaling and the shifting phases of diffusion.

This thesis focuses on onshore wind power while contributing to both its specific domain and the broader field of technological diffusion. It offers three contributions. First, it demonstrates how global technological evolution such as unit upscaling affect adoption patterns both at national and subnational levels. Second, it establishes a theoretically robust framework for identifying the determinants of subnational heterogeneity in technological deployment by drawing on system perspectives from national energy transition literature. Third, it presents a novel methodological approach to examine technological diffusion by analyzing deployment patterns at the project-level (such as wind power parks) rather than solely at the core technology level (such as the wind turbines).

The remainder of this thesis commences with Chapter 2, which presents an overview of technological diffusion literature to locate the existing knowledge gaps within the field and demonstrate how the aforementioned contributions address them. The ensuing chapters present the studies conducted to address said gaps: Chapter 3 highlights the methods employed, while Chapter 4 summarizes the results, discussions and directions for future research[1]. Lastly, Chapter 5 concludes with key insights from this thesis.

[1] For comprehensive details about the methodologies and findings, readers should refer to the complete Papers I and II.

2. Technological diffusion

2.1 Overview of the research field

Understanding how technologies diffuse is critical for examining future energy systems and identifying key factors that shape them. For example, integrated assessment models incorporate multiple variables related to energy, population, economy, and environment, using both historical data and extrapolated forecasts to simulate how different pathways might unfold from these inputs [42, 43, 44, 45]. Energy system modeling offers a similar analytical approach but with different system boundaries. It focuses on evaluating various permutations of energy supply and use configurations across different sectors, such as building scenarios to evaluate potential policy impacts or optimizing energy systems under resource limitations and climate mitigation goals [46, 47, 48]. A complementary approach to these forward-looking analyses involves examining historical developments within energy systems. Empirical analysis of past energy technology deployment patterns can shed light on key questions around diffusion processes: What were the historical deployment rates of various technologies? How did spatial diffusion occur? What conditions and mechanisms facilitated these deployment patterns? At least some of the answers to these questions are, in essence, what is pursued in this thesis, situating the conducted studies within the field of technological diffusion research. They can also be utilized to inform policymaking as well as provide empirically grounded modelling inputs, particularly given the significant role anticipated for future deployment of low carbon technologies in addressing climate challenges.

The analysis of historical technological diffusion represents an established field of research, with origins tracing to as early as the 1900s [49]. A central concept in early technological diffusion research was the uptake of innovations over time. Ryan and Gross's [50] seminal research on hybrid seed corn adoption patterns among Iowa farmers established the paradigm for diffusion research [51]. Their analysis revealed that adoption rates exhibited an S-shaped curve temporally. Subsequently, Griliches [52] applied an S-shaped logistic growth function to the same case of hybrid corn adoption, establishing three fundamental diffusion parameters that maintain relevance even today: the point of origin, the slope indicating diffusion speed, and the diffusion ceiling representing long-run equilibrium. Shortly after, Mansfield [53] studied innovation diffusion across different firms within coal, iron and steel, railroads, and brewing industries, and found evidence that adoption probability increased with existing users and decreased with investment costs. Rogers [51] further developed the field by establishing a classification system for adoption rates across population segments, ranging from early adopters to laggards. Kee [49] argued that the original work of Rogers [51] published in 1962 was “the key publication that turned scattered diffusion research in various discipline into a systematic body of work”.

The literature has advanced through increasingly sophisticated methodologies and novel operationalization of the technological diffusion concepts**.** Diverse ways of evaluating technological uptake have been introduced [54, 55, 56, 57, 58, 59, 60, 49]. Marchetti [61] was among the earliest to continue the tradition of fitting technological adoption data to the logistic function. He compared the time required for automobiles to reach specific market penetration levels (for example, from 10% to 90%) in different countries and found that countries achieved these levels more quickly over time. Grübler and Nakićenović [62] adopted a similar approach and found consistent findings, focusing on various U.S. infrastructures and specifically examining how new technology replaced old systems. Many subsequent studies also used this approach of measuring diffusion through market penetration rates [63, 64].

More recent research has expanded to investigate the relationship between diffusion and technological improvement over time [65], as well as the correlation between unit upscaling and adoption of the technology [66]. Comin and Hobjin [67] examined the temporal gap between technological invention and their adoption across different countries. Other methodologies gaining more popularity include analyzing patent distributions across different countries [68] and tracking academic citation patterns [69]. Beyond quantitative assessments, new theoretical frameworks have also emerged [70, 71, 72, 73, 74]. For example, the technology innovation system approach examines the actors, networks, and institutions that facilitate technological diffusion [75, 76], while the multi-level perspective analyzes diffusion through sociotechnical transitions across niche, regime, and landscape levels [77].

The spatial dimension of technological diffusion represents another significant area of research, extensively studied across various geographical scales. Hägerstrand's [78] seminal work introduced a model of innovation diffusion that emphasizes contagion-like mechanisms dependent on spatial proximity and communication networks. Similarly, the Bass model [79] adopted the contagion model and developed it further by making behavioral assumptions explicit. It distinguishes between two types of adopters: innovators who adopt technology independently, and imitators whose adoption decisions are influenced by others. Other models that integrate both temporal and spatial aspects of technological diffusion have also been proposed [80, 81]. Subsequent research has documented how technology spreads between adjacent regions, both at regional [82, 83, 84] and international levels [85, 86]. A subset of these are empirical studies trying to understand what factors influence spatial heterogeneity in diffusion, particularly within a country [87, 84, 88, 19, 25]. Geographic distance itself has also been examined as a determinant of technological diffusion patterns [89, 90].

Technological diffusion research methodologies and frameworks continue to be employed across numerous fields in contemporary research. For example, diffusion patterns in telecommunications [91], biomedical technologies [82], agricultural technologies [92], and educational technologies [93]. Within the energy sector, diffusion of conventional fossil-based generation [94, 95], renewable energy technologies [96, 97, 4], nuclear power [4, 95], and various low-carbon transition technologies [60, 98, 99]. This thesis engages with and contributes to this research field by identifying mechanisms of technological growth at both the national level and its spatial distribution within countries, as discussed further in the following sections.

2.2 Characterizing phases of technological diffusion

Studies on technological growth within the diffusion literature have identified four sequential phases: the *formative phase*, *accelerating phase*, *stable growth phase*, and *stagnation phase* [5, 4, 99]. These phases move along the S-curve of technological diffusion, illustrated in Figure 1. Technologies undergo numerous modifications and refinements as they evolve toward a dominant design in the formative phase [100, 66]. The formative phase is also marked by sporadic growth spurts from early pioneering projects and ends with the formation of a sociotechnical system that can sustain a more stable growth of the technology outside their initial market niche [101]. This point is known as "take off" and it ushers in the ensuing phase of diffusion referred to as the accelerating phase. Adoption of technology accelerates due to positive feedback in profitability and technological learning [101]. Deployment accelerates until it passes the inflection point on the S-curve and enters the quasi-linear stable growth phase. Political or social resistance often emerges at this point, such as oppositions against further wind development many countries currently face [27, 29, 30, 31, 38, 39]. Additionally, deployment may also begin to encounter geophysical constraints. Growth eventually decelerates, leading to the stagnation phase, where technology uptake plateaus. Understanding these distinct phases and where countries fall within them provides insights into technological growth patterns. For example, it can help identify the key mechanisms driving each phase (explored in Paper I) and determine the most appropriate metrics for comparing countries at different stages of diffusion (explored in Paper II).

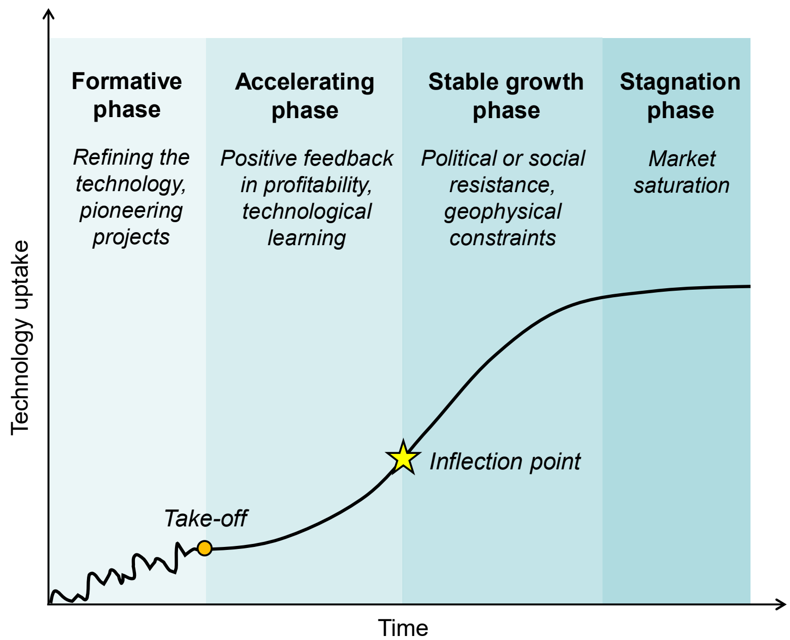

Figure 1 Phases along the S-curve of technological diffusion

The relationship between industrial-level and unit-level growth during technological diffusion has also been demonstrated by Wilson [66]. Industrial-level growth refers to the increase in cumulative production, whereas unit-level growth, or upscaling, pertains to the upscaling of average or maximum unit size. In the context of energy technology, unit size usually corresponds to capacity. Although Wilson [66] categorizes upscaling as a distinct phase of technological diffusion, it can alternatively be seen as a growth mechanism, whereby increased unit capacities facilitate diffusion in parallel with unit additions. Once a dominant design emerges, larger unit sizes become desirable as technologies can exploit economies of scale to reduce costs. However, market demand and engineering constraints ultimately limit upscaling potential. The former constraint implies that technologies with homogeneous applications and thus can be standardized particularly benefit from unit upscaling [66]. Cost reductions can also occur through industry-level growth as experience with the technology accumulates, commonly represented by the learning rate [102, 103]. Observing unit upscaling can aid in revealing valuable perspectives on how technological changes affect both deployment patterns within countries (explored in Paper I) and national growth over time (explored in Paper II).

2.3 Technological leapfrogging

A strand of the diffusion literature places special emphasis on the benefits of accumulated technological learning over time and its impact on deployment. One conceptualization of this is technological leapfrogging, which refers to the implementation of an advanced technology in an area where its predecessors were not previously deployed [15, 16, 17]. This is not a novel concept, with its origins tracing back to Gerschenkron's idea of latecomer's advantage in economic development, where latecomers benefit from access to the latest technology and can utilize new institutional models different from historical precedents [104]. The term "leapfrogging" itself has a multitude of interpretations. Some scholars examined it in terms of innovation cycles [105, 106], where latecomers jump ahead to lead certain industrial sectors [107, 108, 109, 110]. Others studied how developing countries might follow economic (and environmental) trajectories that avoid the pollution-intensive routes previously taken by developed nations [111, 112, 113, 114]. However, the definition of interest here concerns how countries that adopt technology later can gain an advantage by leveraging the global technological advances made by the time they implement it.

Previous studies have explored how late-adopting countries adopt mature technologies without participating in their development, effectively "leapfrogging" over earlier, riskier, and costlier stages of technological evolution. The literature that explicitly distinguishes itself as the leapfrogging subfield of research consists mostly of narrow-scope investigations examining implementation of specific technologies in novel contexts. Examples include biofuel use in Brazil [15], renewable electricity technologies in Chinese urban low-carbon development [115], solar energy in sub-Saharan Africa [116], and mobile telephones in countries that never developed extensive landline networks [117]. Another major research focus evaluates how various modes of technology transfer, such as foreign direct investment and licensing agreements, have enabled late-adopting countries to catch up with early-adopters in adoption of different technologies [118, 119, 120, 121, 122].

The broader technological diffusion literature has evaluated leapfrogging by measuring technological growth rates, expecting late adopters to show faster adoption rates than early adopters. However, evidence supporting this hypothesis remains scant. While some studies have found that newer markets show shorter diffusion times (measured as the time for market share to grow, for example from 10% to 90%) [61, 63, 123], these markets ultimately reached lower saturation levels. Gosens, et al. [18] found that late adopters successfully accelerated domestic market growth for wind and PV power. Yet Cherp, et al. [5], using a more robust metric of maximum growth rates in capacity or generation, discovered that countries with later wind and solar PV adoption did not actually exhibit higher maximum growth rates than early adopters. Other attempts to quantify leapfrogging, such as comparing increases in unit size, have similarly found no evidence of faster unit upscaling among late adopters [40].

The lack of evidence of faster growth in late-adopting countries is often attributed to inadequate country-specific adoption contexts. Cherp, et al. [5] argued that the benefits of global learning were offset by the same unfavorable socio-economic and political conditions that caused the delay in initial adoption. Wilson and Grübler [63] explained that while cross-country spillover can accelerate the process, it cannot eliminate the need for developing local conditions and institutions that support technology diffusion. This development is gained through cumulative experimentation and learning with the technology. Wilson [66] emphasized the importance of a formative phase in building essential knowledge and institutions through experience, which leapfrogging attempts to bypass. These findings align with what the leapfrogging literature identifies as requirements for successful technological leapfrogging, such as technical capabilities [17, 124], experience with the technology [125], and institutional capacity [15, 126].

While previous studies have explored the national characteristics that can potentially limit leapfrogging, less attention has been given to explaining how technological development spreads across countries and benefits late adopters. Understanding this process requires analyzing technological characteristics to understand global industry and market formation. Yet such analysis first needs a clear map of the technology's global evolution, a discussion also missing from studies comparing early and late adopters' growth patterns. Understanding these mechanisms could better explain both the limitations of leapfrogging and why late adopters struggle to grow technologies faster than early adopters (explored in Paper II).

2.4 Spatial heterogeneity of technological deployment

The spatial dimension is a crucial aspect of how technologies spread and thus makes up a significant part of the literature. At the international level, spatial studies commonly investigate how technology spreads between countries. Some studies explore spillover effects, examining how technologies diffuse through geographical proximity [85, 86, 127, 128] and various means of cross-country transfer of technologies like trade [129, 118, 130, 131]. Other research compares diffusion patterns across countries over time, analyzing how technological adoption is influenced by country-specific characteristics such as policies [132, 133, 134], socioeconomic conditions [135, 136, 137], and local culture [138, 139].

While cross-country studies illuminate the mechanisms of global technology diffusion, subnational analysis can reveal equally valuable information on how technologies are deployed within largely similar sociopolitical environments. These local-level insights can directly inform national policies to optimize future technology deployment. Analyses of subnational heterogeneity have been explored for various energy technologies, from fossil-based power plants [140, 141] to variable renewables such as solar PV [87, 84, 88] and wind power [19, 25]. Most of these studies analyzed subnational distribution patterns by comparing installed capacity figures across provinces, cities, or equivalent regions within a country. Others focused on acceptance rates by examining project approvals [142, 143], particularly for renewable energy projects that face public oppositions [144, 145]. The aims of heterogeneity studies vary, ranging from investigating regional acceptance variations [142, 143], land use patterns [23, 146], sociodemographic characteristics of affected populations [147, 148], regional policy effects [149, 150, 151], to empirical parameters for modelling site selection [152, 153]. Few studies have also investigated the temporal dynamics of spatial diffusion, exploring how technologies spread geographically and analyzing spillover effects between neighboring regions [84, 154].

Although the research foci in this literature appear scattered, they ultimately investigate different facets of the mechanisms shaping heterogeneity in deployment of certain technologies within countries. Their divergent objectives, however, have led to inconsistencies in approach, particularly in the theoretical foundations they engage with. This is especially apparent in cross-sectional studies that typically employ statistical analysis to identify correlations between deployment level and various variables of interest. Due to differing research agendas, variables representing potential mechanisms tested in one study may be absent in another, even when measuring the same outcome such as total installed capacity at similar level of regional disaggregation. This creates issues with omitted variables, making findings from different studies difficult to compare, even for the same technology. The problem is compounded when studies fail to state clear hypotheses, let alone provide theoretically grounded justifications for their choice of variables.

For example, numerous studies have examined how and why wind power deployment varies within countries [19, 20, 25, 24, 23, 21, 155]. While resource potential studies emphasize wind speed and land availability as key deployment factors [156, 157, 158], empirical studies show inconsistent findings [20, 25, 24, 23, 150], with regions showing different deployment levels despite similar wind speeds. Research has explored additional factors like land cover [20, 23, 155, 150], population density [20, 23, 155, 24, 19], and socio-political variables such as employment rate and green party votes [25, 23, 20, 22]. However, these variables too lack consensus across regions, with studies testing different sets of variables without clear theoretical foundations. Without a consistent framework, it becomes challenging to determine whether mixed results in the literature reflect genuine variations in local mechanisms across countries or merely arise from methodological differences. Therefore, a theoretically grounded framework serving as a consistent systemic lens can improve examination of subnational technology diffusion (explored in Paper I).

3. Methodology

3.1 Evaluating the effect of global technological development of onshore wind power on national adoption patterns

The effect of global technological development on national adoption patterns of onshore wind power is evaluated through deployment of the technology in 28 countries, explored in detail in Paper II. These countries represent around 86% of current global wind generation. The analysis is mainly based on a commercial dataset from *The Wind Power* [159] containing comprehensive information on global wind power parks built from 1980 to 2023, including location, number of turbines in each park, total park capacity, turbine capacity, type, and manufacturer, as well as its operational year.

The analysis of global technological development in onshore wind power follows three steps. The first is to investigate the evolution of turbine technology across a four-decade period. The primary technological parameter under investigation is turbine capacity. Larger generator capacities allow each unit to produce more electricity from wind energy, making this an important indicator of advancement in turbine technology. The actual turbine output is also influenced by specific power, or the ratio of a turbine's generator capacity to its blades' swept area. However, in most cases, manufacturers aim to maintain optimal load curves by keeping generating capacity and rotor size proportional [26]. Therefore, developments in turbine capacity typically occur in parallel with advancements in rotor size. Additionally, unit upscaling itself serves as a mechanism of diffusion [66], occurring alongside unit additions. As a dominant design emerges, larger unit sizes become more attractive since technologies can leverage economies of scale to lower costs.

The second step explores how technological advancement affects national adoption, with particular focus on evidence of technological leapfrogging in onshore wind deployment. Two forms of leapfrogging are examined: The first analyzes the global diffusion of technology, specifically how state-of-the-art turbines penetrate the market, and whether late adopters face delays in accessing new turbines or can bypass obsolete technologies entirely. Technological characteristics such as design complexity and standardization [160] are employed to explain findings from this analysis. The second measures national growth across different countries to test whether turbine upscaling has enabled late adopters to deploy wind power more rapidly than early adopters.

A robust growth metric is required to evaluate and compare national growth of onshore wind. Diffusion studies often rely on diffusion time (the period from market entry to saturation) as a growth measure [63, 18, 161]. However, this approach is problematic for currently expanding technologies like wind power, where countries are at varying deployment stages and saturation levels remain unclear [5]. Cherp, et al. [5] proposed a more robust growth metric which can better account for technologies' current deployment phases. The metric captures growth at the inflection point of the S-curve where maximum observed growth rate G occurs. Maximum growth is typically measured as annual additions to total installed capacity or generation. For countries still in the accelerating phase before the inflection point, the growth is calculated using the three-year average annual growth rate instead.

The unit of measure use in this thesis are annual total installed capacity and total number of turbines. This dual approach allows for examination of national growth independent of unit capacity evolution, as capacity measurements alone may not accurately represent installation patterns due to turbine upscaling. The measurements are distinguished as follows: maximum growth in total capacity addition is defined as *capacity growth*, while maximum growth in total number of turbines is termed *unit growth*. Both metrics are normalized to total electricity supply to enable cross-country comparisons across different electricity system sizes. Annual data commencing from the national take-off point of onshore wind is used, defined as the conclusion of the formative phase when onshore wind generation achieves 1% of total electricity supply. These metrics are illustrated along the S-curve in Figure 2.

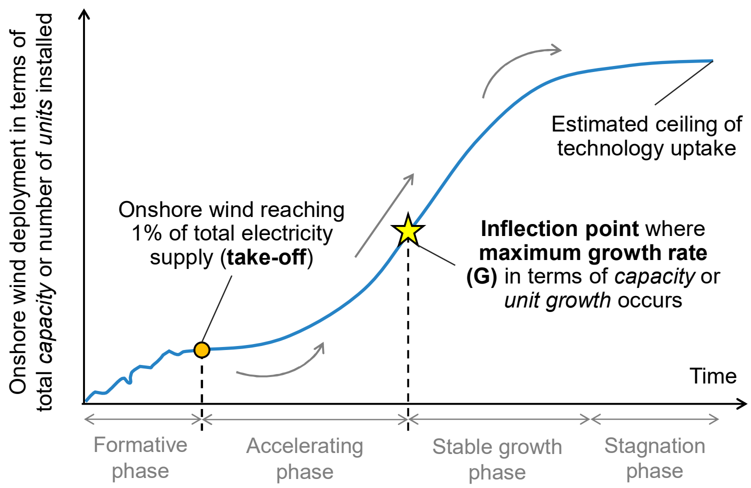

Figure 2 S-curve of wind power diffusion with relevant metrics

The third approach examines development at the wind park level rather than individual turbines. This novel perspective on understanding wind power diffusion carries increasing relevance as most turbines are now built in parks rather than in isolation. The analysis begins by comparing global trends to country-level trends. While growth rates and turbine technology have been argued to be able to benefit from leapfrogging effects, this phenomenon remains unexplored in the context of wind park development. Consequently, this analysis explores potential evidence of global "learning" in wind park construction, measured in terms of trends in park sizes.

Additionally, possible country-specific determinants of wind park sizes are explored using linear regression with median park size as dependent variable. Three national variables are examined: system size (measured by total electricity supply or land area), land availability (measured via population distribution coefficient similar to Gini coefficient), and decision-making processes (measured through participatory democracy index or government quality). The hypotheses posit larger system size to correlate with the need of larger parks, concentrated populations leave more land available for larger parks away from residential areas, and higher public participation may lead to smaller park sizes due to increased public opposition against larger wind parks.

3.2 Identifying mechanisms of subnational deployment of wind power

The identification of mechanisms of subnational technology deployment are illustrated through the case of onshore wind power in Sweden, explored in detail in Paper I. The analysis drew on data from the Swedish wind power database *Vindbrukskollen* [162], which contains information on project status, timeline, locations, number of units per project, and turbine specifications. Onshore wind power installed from January 1990 to August 2022 were examined. Prior to identifying the deployment mechanisms, a descriptive analysis was carried out to gain a general overview of how wind power has been deployed in Sweden over the last 30 years.

The analysis of deployment mechanisms follows a three-step method. First, the installed wind turbines in Sweden are divided into small-scale and large-scale categories to account for the evolution of wind power characteristics, particularly due to unit upscaling. This distinction is crucial for testing the hypothesis that deployment mechanisms evolve with technological advancement, resulting in different scales of wind power relying on distinct deployment mechanisms. Small-scale wind power refers to units with a capacity of 1.5 MW or less, the smaller units deployed before the upscaling phase defined by Wilson [66]. Large-scale wind power refers to units exceeding 1.5 MW capacity, deployed during the upscaling phase. This threshold does not indicate the largest turbines available on the market; rather, it serves as a demarcation specifically in the context of Swedish wind power between outdated technologies no longer being deployed and those that continue to be built today.

Second, a theoretically grounded framework for identifying potential mechanisms shaping subnational heterogeneity is developed. This study borrows from the perspectives underlying energy transition proposed by Cherp, et al. [41]: techno-economic, socio-technical, and political perspectives. These perspectives originate from distinct systems that co-evolve throughout a national energy transition and are studied by different disciplines. This framework is particularly relevant because the deployment of energy technologies, especially renewable energy technologies, at the subnational level forms an integral component of broader national energy transitions. 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. The socio-technical perspective examines the societal and technological aspects of energy transition. The political perspective focuses on the impact of energy policies and political actions on the energy transition.

Mechanisms potentially influencing subnational heterogeneity can be identified by deriving variables from each system perspective as shown on Table 1. The potential mechanisms also serve as the hypotheses formulated in this study when the variables are tested in the statistical analysis later. For example, superior wind resources and higher electricity prices may account for greater wind power installation in certain regions. Conversely, elevated population density could explain the limited wind power development observed in other areas. Some mechanisms are suspected to differ between small-scale and large-scale installations. For instance, agricultural land is hypothesized to be more significant for small-scale wind power deployment, as these earlier installations required open spaces due to technological limitations of the period. In contrast, modern turbines with higher hub heights can be built in forests, making forested areas more relevant for large-scale deployments. Furthermore, political variables functioning partly as indicators for acceptance or public support are hypothesized to exert more substantial influence on large-scale wind power deployment, as these larger turbines were installed later when acceptance constituted a more formidable challenge relative to earlier deployment phases.

Table 1 Variables derived from national energy transition perspectives

System perspectives in national energy transition from Cherp, et al. [41]	Variables related to potential mechanisms
Techno-economic perspective *Physical flow energy; processes and actors in utilization of the energy; market dynamics*	↑ Wind resource ↑ Land area Types of land cover (↑ agricultural land, ↑ forest cover, ↓ protected area) ↑ Electricity price
Socio-technical perspective *Emerging technology as a social phenomenon; technological diffusion and experience*	↑ Experience with wind power ↓ Presence of other energy technology ↓ Employment rate ↓ Population density
Political perspective *Impact of energy or environmental policies and political actions*	↑ Prioritized area for wind power development ↑ Votes for Green Party ↓ Voter turnout

↑ indicates positive correlation hypothesis, ↓ indicates negative correlation hypothesis. Please refer to the full Paper I for discussion on the hypotheses used in this study.

Third, statistical analysis is used to identify the significance and nature of the variables as deployment mechanisms. The spatial resolution chosen for Sweden is at the municipality level for several reasons: decision-making processes, including the power to veto wind projects, typically occur at this level; sufficient variability in wind power deployment between municipalities for meaningful statistical analysis; and most required data are readily available at this scale. The dependent variable is the total installed capacity of wind power up until 2022 and the independent variables are those derived from national energy transition perspectives in Table 1. Small-scale and large-scale deployments are modeled separately, with each model including only the total installed capacity of its respective scales. The Cragg double hurdle model [163] was selected for this analysis. The model is essentially a linear model that better fits the data distribution at this level of observation where many zero values exist, thus avoiding the biased estimates that standard linear regression might produce [163, 164]. The Cragg model first accounts for the probability of municipalities reaching a "take-off" point in wind deployment, thereby excluding municipalities with negligible deployment level. The take-off threshold is set at 1.5 MW for small-scale and 10 MW for large-scale wind power in total installed capacity per municipality by 2022. Summary of the statistical model specifications is shown in Table 2.

Table 2 Statistical model specifications

	Small-scale model	**Large-scale model**
Size of turbines included in the analysis	≤ 1.5 MW	> 1.5 MW
Total installed capacity of turbines included in the analysis	640 MW	11904 MW

Model used	Cragg double hurdle model	
Dependent variable	Total installed capacity of wind power ≤ 1.5 MW from 1990 to 2022 in each municipality (MW)	Total installed capacity of wind power > 1.5 MW from 1990 to 2022 in each municipality (MW)
Takeoff threshold for municipalities to be included in the sample	1.5 MW	10 MW
Number of observations	75	122

To complement the statistical analysis, a systematic characterization of municipalities exhibiting exceptional deployment levels was also conducted. The rationale for this approach is that certain variables may not exhibit significant correlation when compared to the entire population in a statistical model but are nevertheless consistently found in a smaller number of special cases, such as those with the highest amount of total installed capacity. The analysis is limited to large-scale wind power, as these installations 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. These high-deployment municipalities were then mapped against municipal-level characteristics previously utilized in the statistical model to enable direct comparison with other municipalities.

4. Results and discussions of present work

4.1 Effects of global onshore wind turbine upscaling on national adoption patterns

The average capacity of onshore wind turbines installed globally has grown steadily over the past 40 years, as shown in Figure 3. This advancement is evident at the *technological frontier*, representing state-of-the-art development in turbine technology for onshore use, which expanded from a modest 100 kW in the early 1980s to reach 7.5 MW testing unit by late 2008. The *deployment frontier*, comprising the largest turbines in commercial use and thus a proxy for market readiness, has also increased in capacity, albeit at a slower pace than the technological frontier. Although larger turbines are projected to be constructed in the coming years [12, 7, 13], the technological frontier has shown limited progress in the last decade. This may be attributed to various factors constraining the feasibility of larger turbines, such as the understanding of wind profiles at higher hub heights, advances in materials science, as well as improvements in aerodynamics and structural dynamics [12, 165].

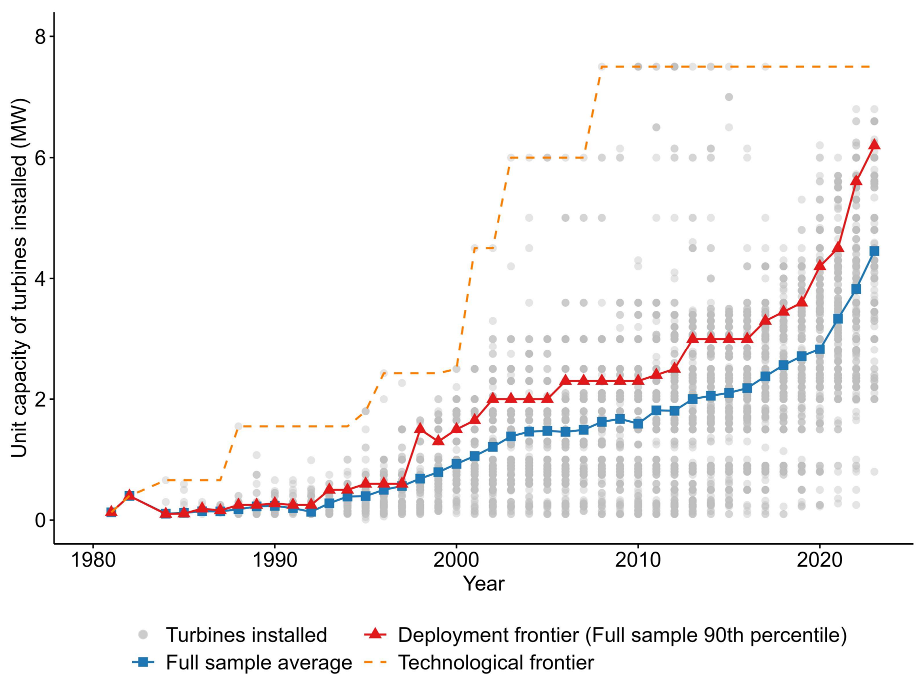

Figure 3 Trends in unit capacity of onshore wind turbines installed globally

While the latest technological developments at the frontier take longer to become market-ready, new generations of turbines with larger unit capacity spread into widespread use much faster, as shown by the average installed turbine size in Figure 3. The adoption of larger turbines is evident across individual countries, as illustrated in Figure 4. Countries follow similar upscaling patterns to the global average, with the latest generation of turbines reaching late adopters almost immediately after becoming market ready. Late-adopting countries can deploy turbines larger than the global average in their take-off year, sometimes even matching the deployment frontier. These late adopters benefit from global turbine upscaling by bypassing older, smaller turbines, demonstrating one form of leapfrogging in onshore wind deployment.

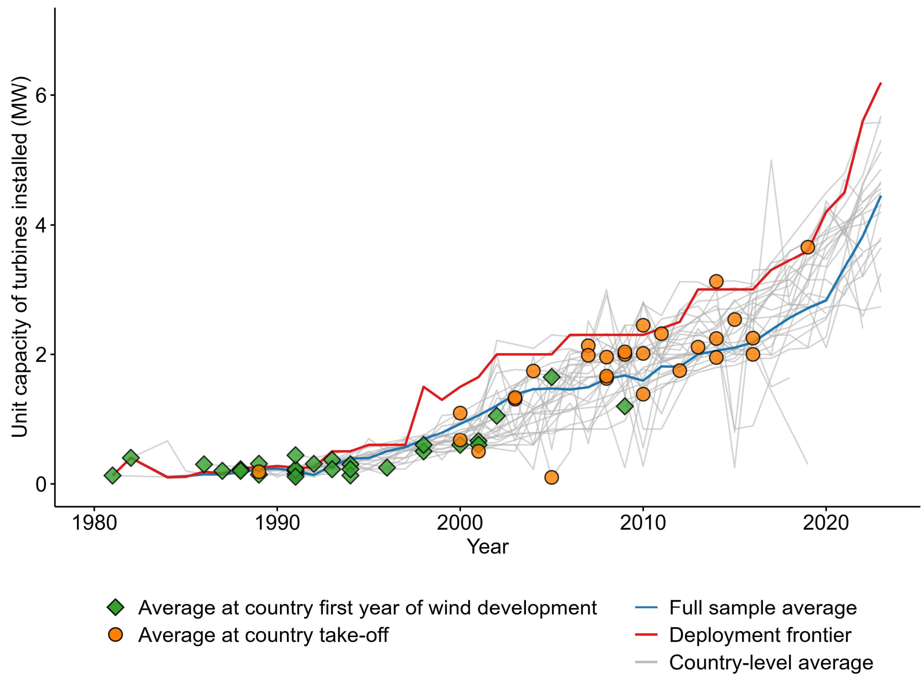

Figure 4 Trends in unit capacity of onshore wind turbines installed globally and at early phase of deployment in different countries

The identified leapfrogging mechanism can be attributed to the characteristics of onshore turbine technology and its resulting market structure. Wind turbines are design-intensive products requiring complex system integration and accumulated technical expertise that is difficult to replicate (compared to simpler technology such as solar PV modules) [160, 166]. This creates high entry barriers [8], resulting in concentration in the industry. In 2019, the top 10 manufacturers produced 90% of global turbines [167]. Turbine manufacturing companies are also concentrated in a few countries: Denmark, Germany, China in recent years, with the United States, Spain, and India playing smaller roles [14, 8]. This geographical clustering emerged partly because early innovation required close user interaction [166], as countries like Denmark and Germany were also early adopters of utility-scale turbines in the 1980s.

Accordingly, most countries either import turbines or manufacture them domestically using imported designs [14, 8, 168]. Some companies have localized production in major markets like India and Brazil [8], though patent analysis shows that research and development activities remain in their country of origin [14]. Companies may also operate manufacturing facilities abroad through licensing or joint ventures [169, 8]. Through such agreements, newcomers like companies in Spain, China, and India benefit from direct knowledge transfer from established players to build their domestic industrial capacity [170, 171, 172]. Nevertheless, these are exceptional cases, as most countries continue to rely on turbine development and often manufacturing from other countries with mature turbine industry.

Beyond the entry barriers created by design complexity, countries rarely pursue localized industry of the turbines for several other reasons. First, countries may not have substantial domestic market or deployment policies to ensure market expansion [166]. Some countries may also lack the necessary skilled workforce or economic resources [168, 166, 173]. Second, the mass-customizable nature of wind turbine technology itself diminishes the need for local manufacturing [160]. Though market segmentation exists, turbine designs are largely standardized and readily available to be installed off-the-shelf, eliminating the need for countries to develop local turbine manufacturing capabilities tailored to their specific market needs.

Nevertheless, late-adopting countries do not demonstrate accelerated growth rates in annual capacity additions, or *capacity growth*. The interplay between capacity growth and unit growth reveals how turbine upscaling affects national wind power growth, as illustrated in Figure 5. The availability of larger turbines means countries can achieve equivalent capacity growth with fewer units, requiring lower unit growth. For example, when normalized to their respective electricity system sizes, Ireland and Portugal began adoption a decade after Denmark but surpassed Danish capacity growth while maintaining lower unit growth. Sweden and Finland later extended this pattern. Although these countries demonstrate successful leapfrogging in terms of faster capacity expansion, most late adopters cluster in the bottom left of Figure 5 with low capacity and unit growth, indicating they are not installing sufficient turbines despite the advantages of larger units. This may highlight other determinants of accelerated growth beyond technological advancement, particularly in the country-specific adoption context [5], such as technical capacity build-up from experience in deploying the technology [63, 40, 125] and favorable political conditions [15, 126, 5].

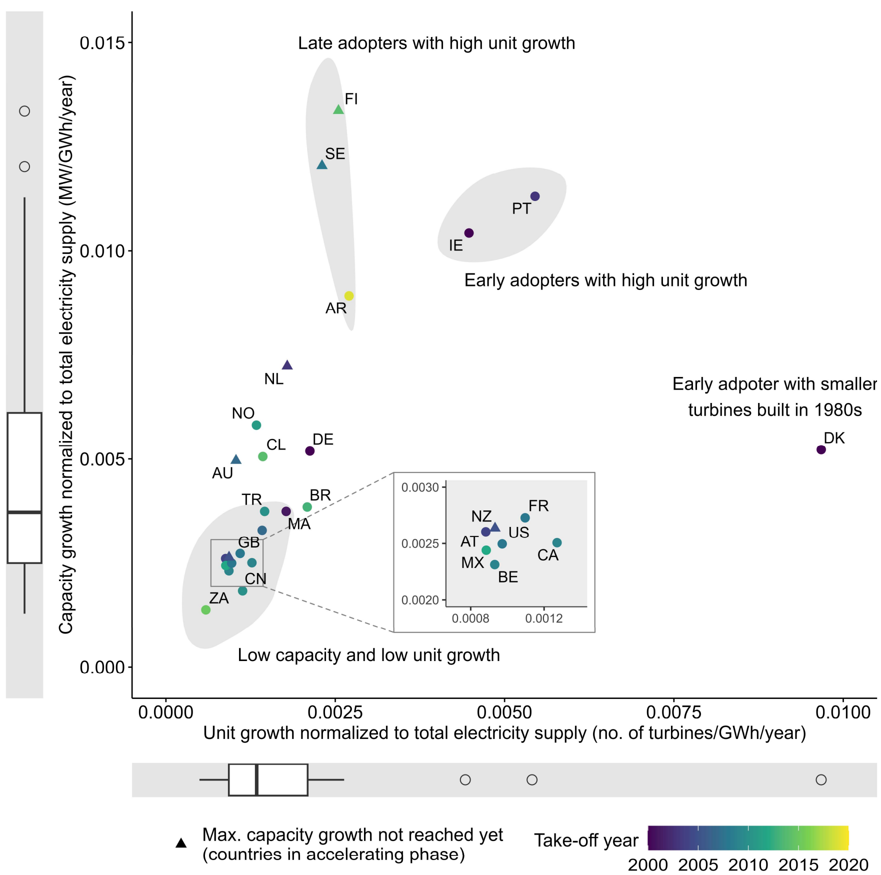

Figure 5 Relationship between two different measures of national wind growth: capacity growth and unit growth. Note that values are normalized to total electricity supply in 2021 to enable cross-country comparison.

Novel analysis of deployment patterns at the wind power park level reveals no correlation between country-level and global trends, indicating limited global learning regarding park size that is analogous to turbine upscaling, as illustrated in Figure 6. The global average number of turbines per park only increased from approximately 3 in 2000 to 8 in 2023, while the average capacity rose from 3 MW to 35 MW per park during the same period. Although an anomalous data point exists from the first large-scale wind park in the United States during the 1980s, the predominant trend remained significantly lower.

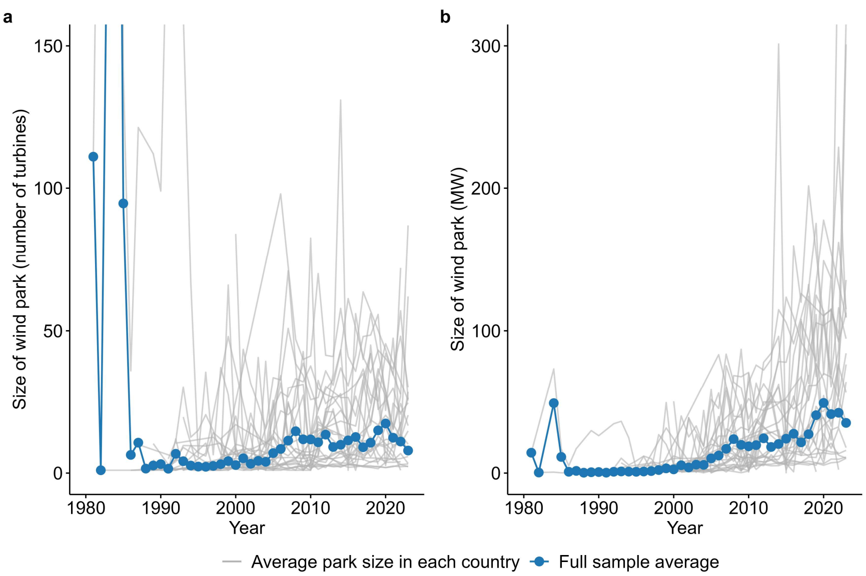

Figure 6 Global and country-level average wind park size in (a) number of turbines and (b) total capacity (MW)

While larger turbine units reduce the need for bigger wind parks, global experience in project management could have led to more large-scale developments, yet this trend is not observable across different countries. Park sizes depend on local context, as supported by results from statistical analysis presented in Table 3. Median park sizes negatively correlate with participatory democracy and government quality indices. Given increasing public resistance to wind power, it is possible that larger parks, which would amplify all the aspects of wind power that the public disapproves of, are more frequently established in countries where populations have limited channels to oppose government decisions. They also positively correlate with population distribution coefficient, as countries with more concentrated populations often have more remote areas suitable for larger parks. Additionally, apart from pioneering projects, local developers, rather than international ones, dominate project development [174]. While developers sometimes undertake wind power projects abroad, this happens less frequently than turbine imports [8].

Table 3 Linear regression models for factors affecting national median park size (in number of turbines)

	Independent variables						
Model	Total electricity supply	Total land area	Population distribution	Quality of Government	Participatory democracy index	GDP per capita	Adjusted R^2
1	NS		NS	**-7.23***		NS	0.489
2		NS	NS	**-7.78****		NS	0.477
3	NS		**6.37****		**-8.45***	NS	0.493
4		NS	**7.63****		**-8.90****	NS	0.513

Dependent variable: Median park size (in number of turbines). Values are standardized estimated coefficient. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, NS $p > 0.05$. Empty cells indicate that the corresponding independent variable was excluded from the model.

However, no clear relationship between wind park sizes and capacity growth is observed. When normalized to total electricity supply, countries with larger parks show lower growth rates, as large parks typically exist in larger countries with concentrated populations and sizable electricity systems. However, countries with low normalized growth rates can also have smaller parks. While the literature in this subject is limited, studies suggest that more granular technologies tend to diffuse faster [175, 176]. However, this pattern is not apparent when viewing smaller wind parks as more "granular" compared to larger, "lumpier" installations. These findings raise questions about optimal scale of wind park projects, especially for late-adopting countries seeking accelerated deployment.

4.2 Spatial heterogeneity of onshore wind deployment in Swedish municipalities

Over the past three decades, Sweden has seen a significant increase in onshore wind power deployment, as illustrated in Figure 7. The average capacity of newly installed turbines and number of turbines installed annually have been steadily rising since 1990. Before 2007, during the formative phase of deployment, growth primarily occurred through small-scale wind power installations (defined as those with capacity below 1.5 MW). Since 2016, turbines with capacity of 1.5 MW or less are no longer built. The subsequent upscaling phase brought a sharp increase in both unit size and annual installation numbers, introducing large-scale wind power (defined as those with capacity above 1.5 MW). This pattern of upscaling aligns with Wilson's analysis [66], though it appears more prolonged as turbines continue to grow in size while annual installation numbers increase.

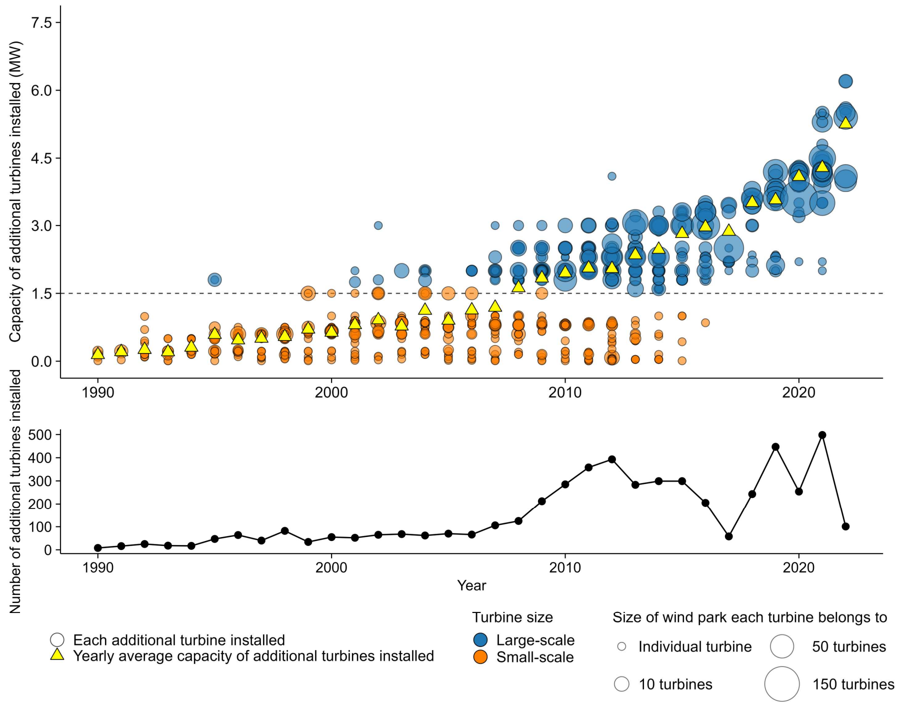

Figure 7 Onshore wind turbines installed in Sweden from 1990 to 2022

The deployment of different-sized wind power installations varies notably across Swedish municipalities, as shown in Figure 8. While some municipalities have exclusively built either small-scale or large-scale wind power, others have implemented both types or none at all. Small-scale wind power installations are concentrated in southern Sweden, particularly in coastal regions, with northern municipalities building them to a lesser extent. Conversely, large-scale wind power installations are predominantly found in the northern part of the country, though some exist in many southern municipalities as well.

Statistical analysis was conducted for wind deployment in Sweden to test hypotheses on factors shaping its heterogeneity. Table 4 reports the results and diagnostics for small-scale and large-scale wind power in Swedish municipalities. 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. Distinguishing between scales can prevent conflating results for technologies that are becoming less relevant for future deployment, especially in the context of turbine technology with its expected continuation of unit upscaling.

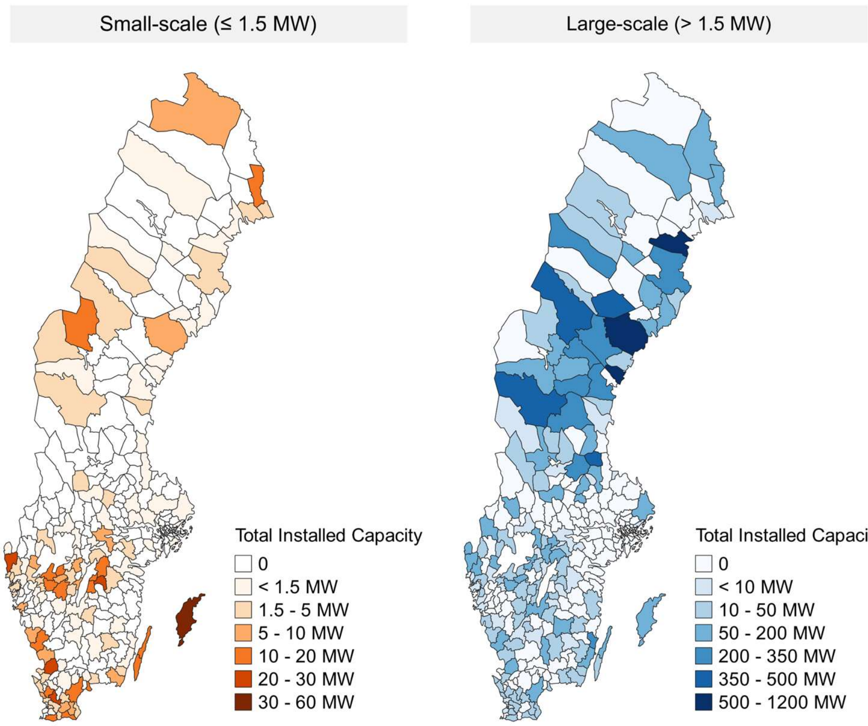

Figure 8 Map of small-scale and large-scale onshore wind power in Sweden in 2022

However, it remains challenging to separate the effects of scale from those related to the progression of the diffusion phase and different deployment periods in this changing mechanism. These findings and their implications are therefore discussed in terms of both upscaling and changing phases of diffusion where relevant. This raises two important cautions: First, the scale threshold used is arbitrary and specific to Sweden and must be adjusted when applying this approach to other cases. Second, careful consideration is needed when analyzing countries that may be undergoing upscaling or are still in the early stages of diffusion.

Table 4 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 (0.878)	-208 (0.209)
	Land Area	26.2** (0.00778)	406 (0.0592)
	Agricultural Land Use	14.3** (0.00813)	-563 (0.147)
	Strict Nature Reserve	-12.8 (0.240)	-144 (0.457)
	Electricity Price Area[1]		
	SE4 (Malmö)	21.2 (0.374)	321 (0.540)
	SE3 (Stockholm)	43.9 (0.0838)	-438 (0.243)

	SE2 (Sundsvall)	5.61 (0.829)	367 (0.226)
Socio-technical variables	Population Density	-35.9 (0.253)	-3670 (0.373)
	Years Since Take-off	21.4** (0.00877)	99.4 (0.298)
	Small-scale Wind Power	-	148 (0.139)
	Hydropower	-6.57 (0.688)	-18.8 (0.657)
	Gainful Employment Rate	-8.72 (0.141)	-212 (0.150)
Political variables	Prioritized Area	-1.50 (0.767)	143* (0.0309)
	Voter Turnout	-5.24 (0.279)	349* (0.0224)
	Support for Green Party	-2.02 (0.649)	108 (0.323)
	Constant	*-75.1** *(0.0419)*	*-2340* *(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

Limited influence of techno-economic factors is observed in subnational deployment patterns. Wind speed shows no significant correlation with deployment levels, even when analyzing only the highest 90th percentile measurements. Municipalities with high large-scale deployment have wind speeds in a lower median range compared to the national median yet remained above the 6.7 m/s threshold historically observed in Europe and the US [177]. Electricity price areas demonstrate no correlation with deployment levels, which is expected given the uniformity of prices across areas until 2019 [178]. Agricultural land positively correlates with small-scale wind power, confirming previous studies [155, 150], but municipalities with high large-scale deployment feature substantial forest cover instead, potentially due to taller hubs enabling forest placement away from populated areas [179].

Unlike findings from previous studies [24, 23], population density shows no significant impact on Swedish wind deployment. Instead of a linear relationship, there may be an optimal range of population density that best suits wind deployment by providing necessary infrastructure while minimizing land-use conflicts. 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 periods correlate with higher small-scale wind power deployment, emphasizing the importance of experience and local network development during the earlier phase of technological diffusion [66, 100]. Conversely, large-scale wind power deployment showed no correlation with prior municipal experience. Larger turbines were deployed during a later diffusion stage when the sociotechnical regime had sufficiently developed [101], enabling expansion independent of local networks, resulting in a less localized expansion pattern.

Political variables such as prioritized areas for wind power correlate significantly with large-scale but not small-scale wind deployment. These areas, introduced in 2008, coincided with the rise of large-scale projects. Although Lauf et al. [23] attributed this correlation to favorable wind resources, present analysis controlling for wind speed still finds statistical significance, indicating that the designated zones themselves drive the correlation and the potential importance of supportive siting policies. Voter turnout showed a positive correlation with large-scale wind project deployment. Voter turnout may reflect satisfaction with democratic processes [180], as supported by Swedish survey data showing a connection between trust in government and support for wind power [181].

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.

4.3 Future research

Future research pathways to further understand diffusion of low-carbon technologies can take many forms. The methodological contributions of this thesis, which has been applied to onshore wind, present opportunities for examining other technologies with different design characteristics, standardization opportunities, and development trends. For example, how does technological development spread and affect national adoption of technologies that are either highly standardized (like solar PV) or highly customized (like nuclear power plants)? What types of cross-country learning are more relevant for these technologies? While onshore wind has characteristics such as continuously growing unit capacity, what kinds of technological developments exist in these other technologies that could benefit late adopters? Similar framework from this thesis can be employed to explore these questions.

While this thesis has elucidated the relationship between turbine unit upscaling and national deployment patterns of onshore wind, country-specific determinants require further investigation. Which national characteristics drive the contrasting growth trajectories between countries with rapid capacity expansion and those with slower, staggered development? Beyond differences in policy design, what sociotechnical or political factors enable countries to implement effective policies? How crucial is experience with the technology in developing the necessary technical expertise? A comparative case study of archetypal countries could identify the key influencing factors, while statistical analysis could assess the findings' broader applicability and their interaction with external factors such as global technological progress.

A deeper analysis of wind power park sizes could provide additional insights into project-level deployment patterns. For instance, since park sizes historically show no correlation with national growth, how can countries with limited resources optimize their project planning between investments in large “mega parks” and smaller ones to better stimulate wind growth? This question could be investigated using other types of wind power park data, including financial costs and project development timelines. Additionally, while evidence suggests countries with fewer channels for public opposition tend to have larger parks, what is the precise relationship between park sizes and public acceptance? Do public preferences on park sizes vary across different regional contexts? These questions could be investigated through survey studies or by examining past wind project proposals.

Finally, the framework for analyzing uneven subnational deployment could be expanded to study allocation mechanisms across countries, addressing questions such as: Which mechanisms are universal, and which vary by country? Do these mechanisms evolve predictably over time in response to technological changes or diffusion phases, as observed with Swedish onshore wind? Additionally, higher-resolution spatial analysis could provide a more accurate picture of which demographic groups face impacts from wind installations. This understanding could help reveal the root causes of opposition, leading to better resource assessments and more effective mitigation strategies.

5. Conclusion

Returning to the first research question, this thesis has presented evidence on how technological development affects national deployment. In the case of onshore wind, late-adopting countries benefit from the rapid unit upscaling of turbines. The mass customization feature of turbine technology enables new technological developments to spread quickly through the global market, allowing late adopters to bypass the obsolete versions of the technology. However, late-adopting countries must still deploy more units than they historically have to achieve accelerated growth compared to early adopters. Additionally, park sizes show no global trend analogous to turbine technology adoption. Countries with larger wind parks tend to have limited channel for public opposition and more concentrated populations, yet they do not demonstrate higher growth rates.

Findings from the second research question evince that turbine upscaling has also influenced the mechanisms shaping subnational heterogeneity in wind deployment. For the case of Swedish municipalities, different turbine scales correlate with different deployment mechanisms, which often align with distinct phases of technological diffusion. This pattern becomes evident through the use of a theoretical framework examining techno-economic, sociotechnical, and political perspectives. Wind deployment across Swedish municipalities is not driven primarily by techno-economic factors like wind speed or land availability. Rather, socio-technical and political factors play key roles. Small-scale wind power was deployed earlier, mainly during the formative phase of technological diffusion, in municipalities with agricultural land and accumulated experience in wind deployment. 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. The rising prevalence of the political factors may signal the end of accelerated growth, as public resistance continues to mount.

Though the answers to the research questions pursued in this thesis were specific to onshore wind deployment, they have implications and methodological insights relevant for other low-carbon technologies and the broader technological diffusion literature. First, evidence shows that global technological advancement affects country-level deployment patterns. Understanding a technology's characteristics and its resulting market structure is crucial when assessing deployment mechanisms and potential for technological leapfrogging. These insights are useful when establishing national policies to accelerate deployment in late-adopting countries, such as whether to prioritize domestic industry development prior to adoption. Furthermore, since changes to the technology appear to also influence subnational deployment mechanisms, countries need to continually adjust their strategies to support low-carbon technology growth amid ongoing technological and socio-political innovations. Second, the framework derived from national energy transitions can evaluate subnational deployment in different countries, enabling consistent assessment and distinguishing between country-specific and universal mechanisms. These insights can benefit countries in the early phases of deployment in need of benchmarks for developing siting policies, while also providing empirical parameters for modeling communities. Finally, understanding the relationship between project sizes and capacity expansion can also inform deployment strategies. This knowledge can help countries with limited resources decide whether to focus on large, concentrated investments or smaller, decentralized projects to achieve sustained growth.

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