Energy Economics
Peer-reviewed and accepted version

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Published version:
https://doi.org/10.1016/j.eneco.2022.106208

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Geographic Price Granularity and Investments in Wind Power: Evidence From a Swedish Electricity Market Splitting Reform [*]

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July 25, 2022

Abstract

I evaluate the effect of the 2011 Swedish electricity market splitting reform on the allocation of wind power, exploiting a unique data set of all Swedish applications for wind power since 2003. By comparing investments in each price zone before and after the reform using a difference-in-differences estimator, I find that 18 percent of all projects constructed by large developers after the reform were allocated to the high price zone due to the reform. This effect is not driven by geographic differences in approval rates, suggesting that the estimated effect also captures investors' locational choices. Small, sometimes locally owned developers, did not react to the reform. A likely reason is that the locational choice set of small developers usually only includes one of the price zones. A nearest neighbor matching estimator comparing areas with similar prerequisites for wind power, largely confirms the main DiD results.

Keywords: Electricity market design, zonal market, electricity market integration, spatial price dispersion, wind power, wholesale electricity market, Nord Pool.

JEL: D22, D47, Q21, Q48

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[*] I thank Sven Heim, Björn Tyrefors, Pär Holmberg, Thomas Tangerås, Marcos Demetry, Henrik Hällerfors, two anonymous reviewers, seminar participants at MINES ParisTech CERNA, The 38th Annual USAEE/IAEE North American Virtual Conference, The 2021 Workshop on Industrial Organization at Stockholm School of Economics, Brandenburg University of Technology, and the Research Institute of Industrial Economics for helpful comments and discussions. This research was conducted within the framework of the IFN research program "Sustainable Energy Transition". The author gratefully acknowledges financial support from Energiforsk and the Swedish Energy Agency.

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1 Introduction

Electricity wholesale markets are typically organized as auctions, where market participants submit bids to a power exchange that computes market-clearing prices and quantities. Trade is enabled by transmission lines, with limited capacities. In European electricity markets, the auction design only takes into account a subset of these constraints, ensuring that prices are always uniform at least within certain predefined regions, or *zones*. As a consequence, the transmission system operator (TSO) has to activate succeeding mechanisms after the main auctions to redispatch generation until the physical transmission constraints are met.

Due to the increased share of intermittent generation across the continent, transmission congestion has worsened during the last decade. As noted by Eicke and Schittekatte (2022), EU's zonal pricing model is now challenged by an increasing mismatch between network and generation expansion within existing bidding zones. Efficient congestion management is therefore a central topic of the Clean Energy Package (European Council, 2019), and European regulators examine the potential advantages of splitting countries into multiple price zones (ENTSOE, 2018). The expected short run advantages of such reforms include a more efficient dispatch of existing generation, and in the long run, to provide locational price signals for new generation and consumption.

A central rationale for increasing the number of price zones is that investments in generation are pushed toward areas where the marginal value of production is high, mitigating the need to increase transmission capacity. However, empirical evidence of investment effects following market splitting reforms is missing. One likely reason is that such reforms are rare[1], another is that detailed data on investor behavior is usually scarce. An exception is Sweden, which was split from one to four zones in 2011. In this study, I evaluate the effect on investments in wind power following this reform, exploiting a unique data set on all Swedish wind power applications since 2003. These data contain information about the application date of each project, the owner of the project, whether the project was approved and subsequently realized, as well as a large set of project characteristics. The value of examining application data is emphasized by the fact that lead times are usually several years. Therefore, the immediate effect on investor behavior can only be detected with any degree of precision when also evaluating application data. In addition, the effect on investors' behavior can be separated from the effect on actual investments by also analyzing applications that were rejected. Since a non-trivial share of the applications are rejected due to local opposition not only in Sweden but also throughout the continent, such frictions may be non-negligible.

By comparing investments in each zone before and after the reform using a difference-in-differences (DiD) estimator, I find that 18 percent of all projects constructed by large developers after the

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[1] Except for Sweden, the only European countries involving more than one price zone are Norway, Denmark, and Italy. The latter three were partitioned already at the outset of liberalization, and a pre/post analysis is therefore not possible. In Norway, zonal alterations occur on a relatively frequent basis, but there are no studies on the investment effects of these alterations. A recent example of a market splitting reform is the German-Austrian zone, that split into two zones in October 2018.

reform were allocated to the high price zone due to the reform. This effect is not driven by geographic differences in approval rates, indicating that the estimated effect also captures the causal effect on investors' locational choices. Since the price effect of the reform was comparatively modest during most of the sample period, I conjecture that the reform had a negligible effect on the total volume of projects, but that it affected investors' locational choices. In accordance with this assumption, I find that small, sometimes locally owned developers, did not react to the reform, likely since their locational choice set only includes one zone.

Although the DiD estimator constitutes my main model, a drawback in terms of identification is that investments in wind power were relatively few before the announcement of the reform. Therefore, I complement the DiD analysis with a matching estimator by compiling a data set on the geographic characteristics of every 10 x 10 km of Sweden. This allows me to match areas in different zones based on variables related to wind power suitability. A nearest neighbor matching estimator then compares investments within the matched pairs. This analysis largely confirm the DiD results. Robustness results obtained by altering the definition of a large developer, the choice of matching variables, and the number of matches identified by the matching algorithm, also largely confirm the main results.

By contrast to the European experience, all electricity markets in the US have now abandoned zonal pricing. Instead, these markets have adopted auction designs that respect all transmission constraints, so that all different locations may face different prices at times of congestion. The theoretical basis for the short- and long run economic efficiency of locational pricing was developed by Schweppe et al. (1988).[2] Despite the conceptual difference between zonal and locational pricing, differences in market outcomes are decreasing in the number of zones, and in the limit the two designs are equivalent. Eicke and Schittekatte (2022) discuss the potential benefits for the EU of transitioning to a nodal market, instead of merely increasing the number of bidding zones. Using economic reasoning, they demonstrate that the perceived flaws of a nodal market design put forth in the European policy debate are based on misconceptions about the functioning of nodal markets. Specifically, these perceived flaws relate to susceptibility to market power, barriers to unlock flexibility, market liquidity concerns, increased investment risks, unmanageable complexity, and political undesirability of locational price differentiation.

Although studies of the investment effects following the transition from a zonal to a nodal market are lacking, Brown et al. (2020) use data from Texas's nodal market to investigate the relationship between nodal prices and investment location decisions of utility-scale generation. They find some evidence that new investment arises in areas with recently elevated nodal prices. However, the estimated effects are generally economically and statistically weak. However, several studies have demonstrated the *short run* benefits of transitioning to a nodal market, see e.g. Wolak (2011); Triolo and Wolak (2021) for empirical studies from California and Texas.

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[2] In theory, a well designed zonal market with a redispatch mechanism could also lead to efficient short run outcomes under ideal circumstances. However, even with such a mechanism in place, payments to producers will be distorted, leading to inefficient investment incentives (Holmberg and Lazarczyk, 2015).

Previous studies on the determinants of wind power allocation in Sweden mainly examine political and geographical factors. Ek et al. (2013); Lauf et al. (2020) estimate cross-sectional statistical relationships between installed wind power capacity and a number of geographical and political determinants (such as average wind speed and political constitution of the municipal board) across Swedish municipalities, but do not consider prices or other financial incentives. In terms of the international literature, several studies examine the importance of financial incentives. An example from the US is Hitaj (2013), demonstrating that government renewable energy incentives have played an important role in promoting wind power. Another example is Gugler et al. (2020) who examine how financial incentives have shaped wind power development in the EU, with a special emphasis on uncertainty. For an international overview on financial incentives and wind power investments, see Qadir et al. (2021).

2 The Swedish electricity market

2.1 The Swedish electricity market splitting reform

The national electricity markets in the Nordic countries were restructured one after the other during the 1990s, and integrated to create a common wholesale electricity market. Norway was the first country to deregulate in 1993, followed by Sweden in 1996, and Denmark and Finland in 1999. This Nordic market was later expanded to include Estonia, Latvia, and Lithuania. Full market coupling with continental Europe was recently implemented.

The main trading platform for physical energy is the day-ahead market, *Elspot*, operated by the Nordic power exchange, *Nord Pool*. Elspot trades more than 80 percent of all electricity produced in the region. It works as follows: Every day at noon, market participants submit bids to Nord Pool for each of the 24 hours of the following day. Each participant can submit hourly bids consisting of quantity/price pairs. Each bid is tied to a price zone. When computing the market clearing price for the different price zones, Nord Pool takes into account the available trading transmission capacity across zones. If there is no congestion, all zones clear at the same price. But if transmission capacities are insufficient, Elspot can be divided into as much as 15 different price zones.

Even before the liberalization of the electricity market there was a regional mismatch between supply and demand, with demand mainly located in the more densely populated south and supply in the form of hydro power in the north. Therefore, the Swedish TSO introduced a geographic differentiation of the grid usage charges already in the 1990s, to encourage new production (consumption) in the south (north). Such locational price signals are not unique to Sweden; see Eicke et al. (2020) for an international overview. The strength of the signal, measured as the mean difference in grid charges between north and south, remained approximately constant at 3-4 SEK/MWh during the entire sample period. See Appendix B for a detailed account of how grid usage charges have been computed. This corresponds to about 40 percent of the regional price difference in the wholesale market during the first years following the reform (2012-2019). In 2020 the price difference in the wholesale market increased dramatically, and during January 2020 - April 2022 it reached 281 EUR/MWh, which by far exceeds the difference in the grid usage charges (see Figure 2 for price trends in each zone). Futures contracts for the upcoming years indicate that large price differences will remain.

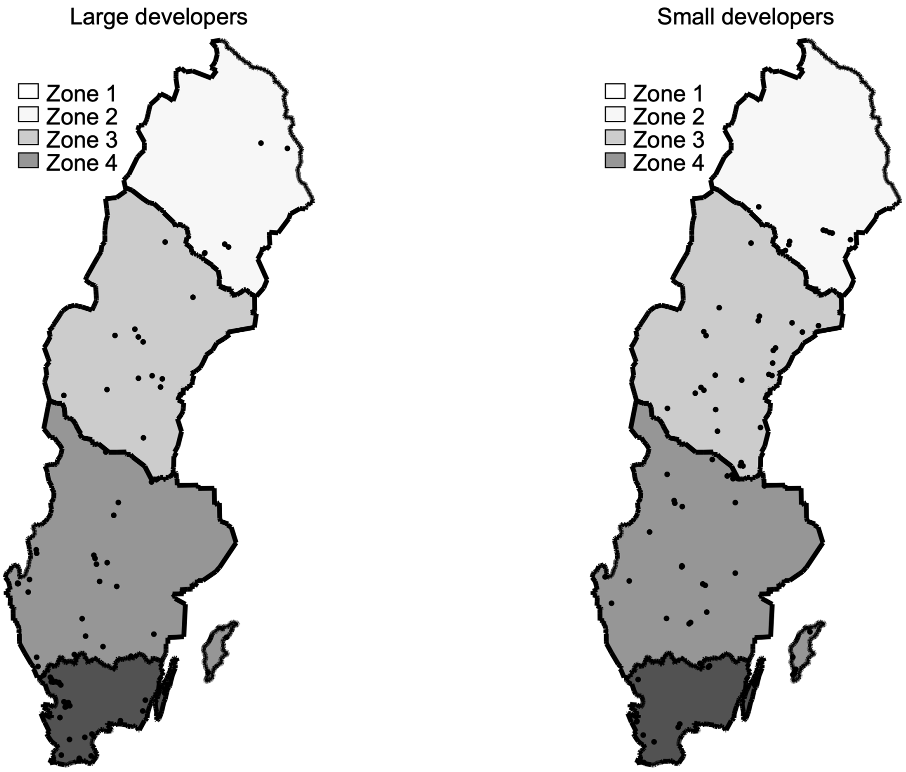
Since regional differences in the grid charges were approximately equal both before and after the market splitting reform, the estimated effect of the reform should not be influenced by the grid charge, since the DiD-estimator is identified through changes over time. Still, it cannot be completely ruled out that the grid charge at least to some extent has influenced the estimated treatment effect, and results should therefore be interpreted with care.

The national TSOs set cross-border transmission capacities based on the physical limitations of the lines as well as a set of security criteria individually decided by each TSO. These security criteria are not stable and invariable, because some flexibility is needed by the very nature of the power system. Glachant and Pignon (2005) note that the Nordic congestion management model gives financial incentives for the TSO to artificially reduce cross-border capacities. First, it increases TSO cross-border congestion rents, and in the case of exporting countries, keeps domestic prices low. Second, it relieves internal congestion, thereby lowering costs associated with domestic counter-trading that is financed by the TSO. With an increased number of domestic zones following market splitting, the effects of such arbitrary curtailments become limited. During the first decade after deregulation, when Sweden consisted of one price zone, the Swedish TSO used to implement cross-border curtailments by reducing exports to Denmark. However, in 2006, two Danish umbrella organizations representing Danish energy firms made a claim to the European Commission that the Swedish TSO was abusing its dominant position by limiting export capacity to Denmark. This was the first, and to this date, the only time that a TSO has been reported to the commission for limiting export capacity.

It was soon understood that the EU Commission would likely require Sweden to stop curtailing export capacities on its interconnectors as a solution to relieve internal congestion. In 2007, a report was produced jointly by the Swedish Energy Markets Inspectorate, the TSO, Swedenergy (an umbrella organization representing the producer side) and the Confederation of Swedish Enterprise (Energy Markets Inspectorate, 2007). The aim of the report was to investigate the possibility of a market split. The report was commonly known by its Swedish acronym POMPE. It proposed a split of Sweden into two price zones. An interview with an industry representative from the wind power industry also confirmed that the POMPE-report was commonly seen as the first step towards a market split (OX2, 2021). The interview also confirmed that there was an increase in project applications in the south zone during the period following the POMPE-report, since many investors believed that the high prices of continental Europe would primarily influence the southern part of Sweden as export transmission capacities increased.

In 2010, after several years of investigations, the commission released its decision (European Commission, 2010). Shortly after, the Swedish TSO formally announced that Sweden would be partitioned into price zones beginning Nov 1 2011. Formally, Sweden was split into four and not two zones as was originally proposed by the POMPE-report. The borders of these zones are depicted in Figure 1. The price zones run from north to south, with zone 1 in the north and zone 4 in the south. Geographically, the two zones originally proposed by the POMPE-report corresponds exactly to zones 1-2 and 3-4 respectively. The trends in mean yearly prices in each respective zone until April 2022 are depicted in Figure 2. The percentages in the legend express prices as a share of the price in SE4. Zones 1 and 2 had almost identical prices throughout the period, with a mean of 86 percent (the trends in zone 1 and 2 are visibly indistinguishable from each other). The corresponding figure for zone 3 is 95 percent. During the last years, prices in zones 1 and 2 dropped to below 50 percent of the price in zone 4 (the corresponding figure for zone 3 is 82 percent). This relative price change can be explained by an unexpectedly high inflow to the hydro reservoirs in zone 1 and 2, the phase-out of a nuclear reactor (Ringhals 2) in zone 3 in December 2019, as well as a higher price level in the Baltic countries and Denmark, leading to exports and higher prices in the southern zones. However, since the vast majority of

Figure 1: Map of realized projects by developer size and price zone



Note: Each dot represents the location of a wind project for large (left) and small (right) developers respectively, by 2020. Also shown are the zonal borders. Only projects with five or more turbines are included in the map.

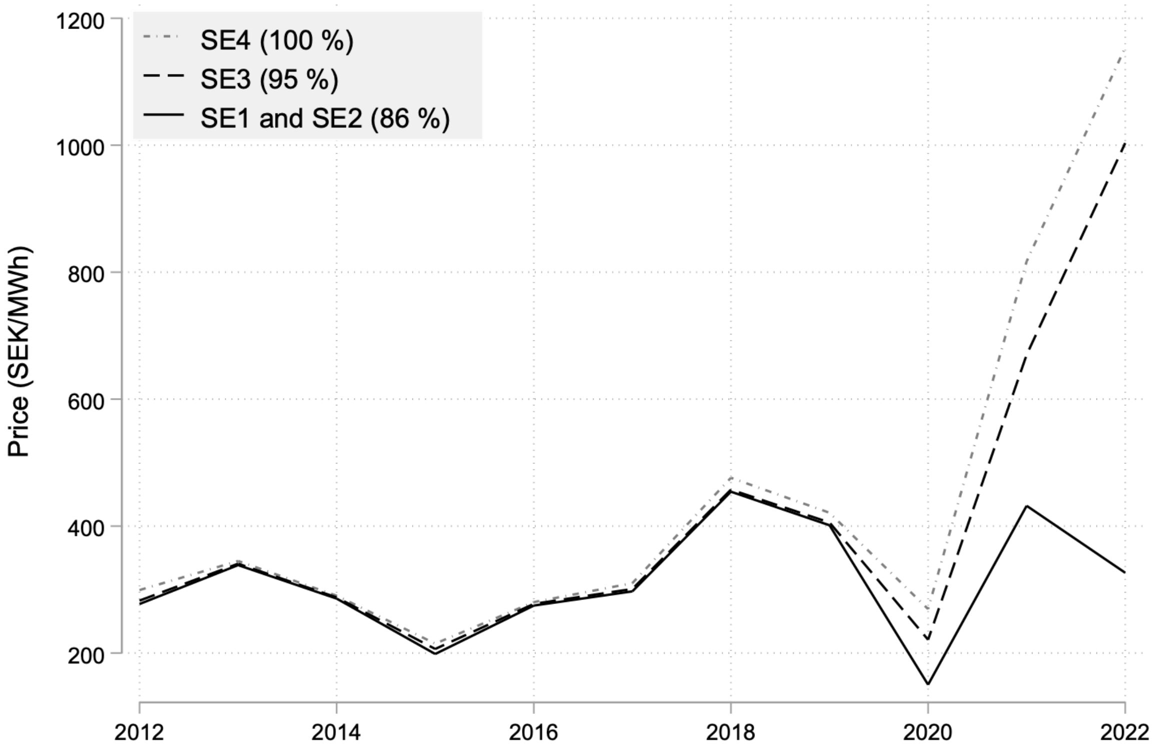
all wind power applications during the sample period were submitted before 2020, the current study does not capture the potential investment effects following this sudden price change. Since price levels up until the last sample year were similar in zones 1-2 and 3-4 respectively, in the analysis I henceforth treat zones 1-2 as the same low-price *northern* zone, and zones 3-4 as the same high-price *southern* zone.

Will there be additional European market splitting reforms?

A few countries, namely Norway, Denmark, and Italy, were partitioned into multiple zones already at the outset of deregulation. However, the European Commission has identified the lack of sufficient cross-border capacity as one of the main barriers to the integration of electricity markets, establishing that 70 percent of each country's cross-border transmission capacity should be available for trade at least within the end of 2025 (European Council, 2019). It is therefore expected that further market splitting reforms will be implemented throughout Europe during the upcoming years, in order to meet the 70 percent target.

There are several reasons why zonal partitioning has not been implemented spontaneously to any greater extent. A main reason is that consumers in different zones will then pay different electricity prices, leading to distributional consequences, which may be politically sensitive. An

Figure 2: Electricity spot prices by zone



Note: Trends in the mean yearly electricity spot prices in each price zone, expressed as a percentage of the price in zone 4 (the most southern zone). The *north* zone is zones 1-2, while the *south* zone is zones 3-4.

illustrative example is Germany. The European Council has proposed that Germany should be split into two zones (ENTSOE, 2018), and simulations show that the geographic distribution of future wind power investments in Germany would vary significantly with the degree of spatial price granularity (Schmidt and Zinke, 2020). But due to a strong German opposition, the split has not been implemented. In this respect, it is worth noting that Tangerås and Wolak (2020) demonstrate that, under fairly general conditions, productive efficiency could improve under a market design where all consumers face the same price, but where producers meet geographically heterogenous prices.

2.2 Wind power in Sweden

Before the turn of the century, large scale wind power plants were virtually non-existent in Sweden. A green electricity certificates system was introduced in 2003. It works as follows: For every MWh of wind power injected to the grid, a certificate is awarded to the owner of the plant. Also bio-fuelled thermal, solar, or small-scale hydro production are awarded certificates, although wind power accounts for the vast majority of the investments. A market for certificates is created by imposing consumers to buy certificates to cover a certain quota of their consumption. At the time of market splitting in 2011, the quota was 18 percent. In 2020 it was decided that the quota would be gradually phased out until 2035 (Swedish Government, 2020). The certificate price has varied substantially throughout the sample period, but since the certificate price does not vary with the geographic location of the plant, it is unlikely that the certificates system has had any first-order effects on the geographic distribution of wind power investments. After the introduction of the certificate system, wind power investments grew rapidly with a sharp increase from 2007 and onward. Wind power is still expanding steadily, with the rate of increase being approximately constant during the last decade. However, the number of applications peaked in 2011-2012, and has since then been declining. In other words, the majority of plants now being constructed have been granted permits several years ago.

There are two distinct rationales behind wind power investments. First, there are commercial projects that involve multiple turbines. These projects are often investor-owned, although they may also be owned by smaller firms or local consumer-owned economic associations. These projects usually comprise five turbines or more, with the purpose of generating profit. Of all project applications in the sample, only about one third fall into this category. Second, individuals and consumer-owned economic associations often also initiate small scale wind power projects ($<$ 5 turbines) with the combined purpose of generating electricity for its members, and also due to an intrinsic preference for carbon-neutral electricity generation. As discussed further below, the interest of the present study lies in large, commercially viable projects, that are more likely to be affected by the price reform than the smaller projects. Since there is no reason to believe that the smaller projects would respond to the price incentives created by the zonal reform, I disregard these smaller projects from the analysis.

Application process

Applications for wind power are submitted to the municipality where the project is intended to be located. All applications have to be approved by the local government, which means that the possibilities of approval may depend on the composition of the local government. Local elections are held every four years in each of the 290 municipalities. There are seven main parties, and usually, a ruling coalition consisting of several parties is formed. One party that distinguishes itself as the strongest proponent for wind power is the Environmental Party (EP). During the sample period, it was a member of the ruling coalition in about 30 percent of all municipalities. In addition to approval by the local government, larger projects also have to be approved by the environmental board of the county administration. For a more detailed account of the application process, see Appendix A.

3 Data

Data have been collected from several public sources, including the Energy Agency, the Land use Authority, the Election Authority, Statistics Sweden, and the IFN Serrano database. Data sources are described in detail in Appendix A.

3.1 Outcome variables

First, I estimate the effect on the number of realized projects, using the application year as the reference year for each project. Since investors should respond shortly after the publication of the POMPE-report in 2007, I use 2007 as the year of treatment. By visual inspection of the upper diagrams in Figure 3, it is evident that the comparatively sharp increase in applications in the south zone that took place after the announcement was only present for large developers. The lower diagrams depict the same projects as above, but where the reference year is instead the year of construction. From these diagrams, it is evident that lead times vary substantially across projects, and therefore I only estimate the model using the application year as the reference year.

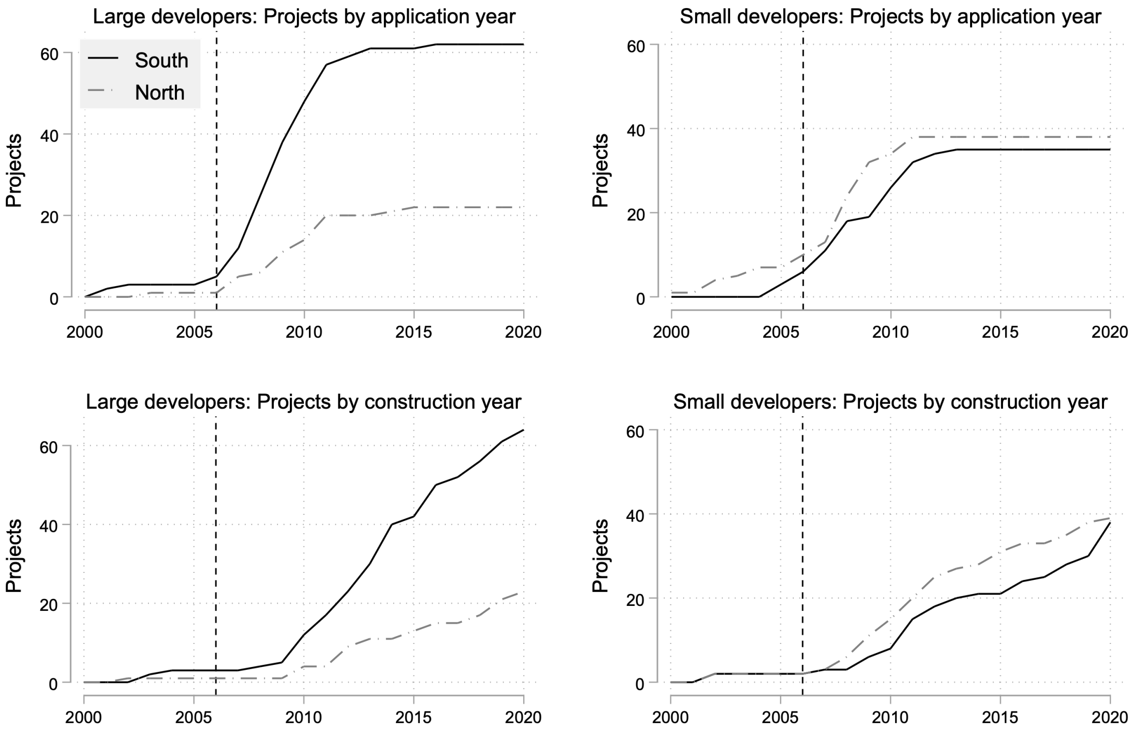
Second, I estimate the effect on the number of project applications submitted, irrespective of project realization. The upper diagrams in Figure 4 depict this variable for large and small developers respectively. It is evident that most project applications have not been realized. For both large and small developers, the share of project applications submitted before 2012 that have been realized during the sample period is around 30%. For reference, the lower diagrams depict similar figures, but exclude rejected applications. The acceptance rate (i.e. the number of accepted applications divided by the total number of applications) is rather similar across developer size, although somewhat higher in the north for both groups, at around 0.4 versus 0.3 in the south.

By estimating the effect on applications unconditional on acceptance, I obtain a more precise estimate of investors' locational choices, which is less affected by geographic differences in acceptance rates than the number of realized projects. Still, it is not expected that this variable *exactly* reflects investors' preferred locations. This is since rational investors should only submit applications in locations where the probability of approval is comparatively high, or equivalently, where the expected profit from a project application (net of application costs) is positive.

3.2 Ownership characteristics and control variables

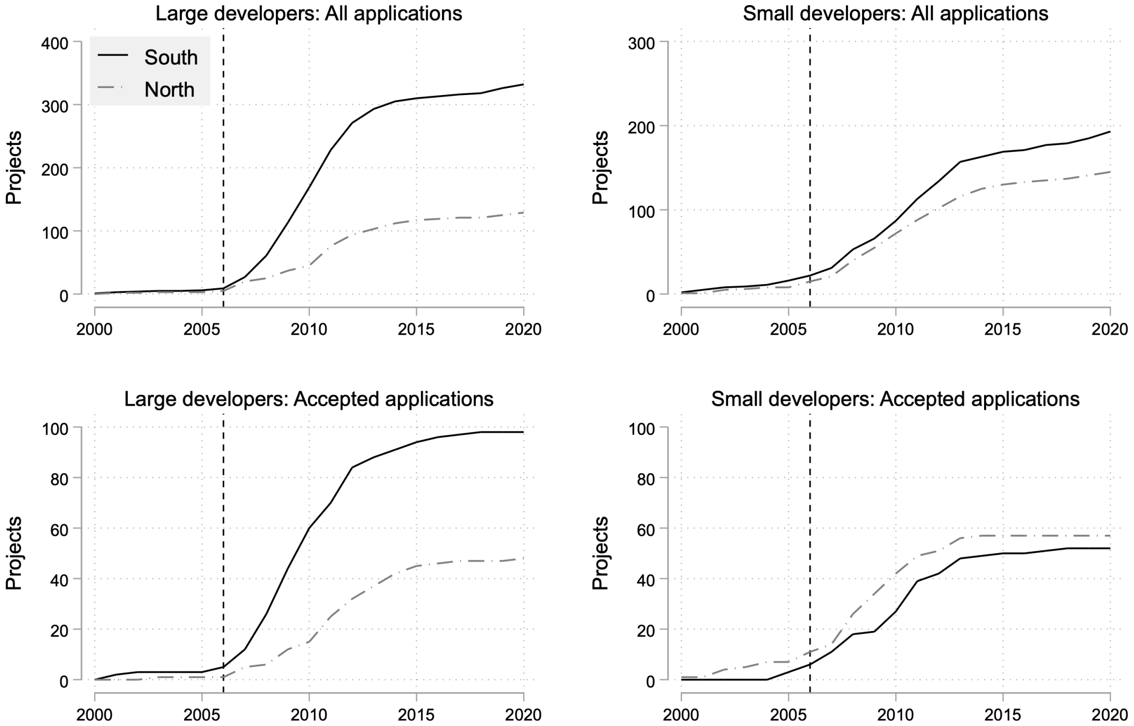
Table 1 displays summary statistics for ownership characteristics and control variables, by project and developer size. A developer is defined as large if it has submitted at least ten wind project applications during the sample period. Out of 530 developers in the sample, only 35 are defined as large. This partitioning creates two groups of projects, with 529 (425) projects owned by large (small) developers respectively. All small projects have been removed from the sample, defined as projects with less than five turbines. A map showing the geographic dispersion of the projects by the end of the sample period, by zone and developer size, is displayed in Figure 1. For reference, Figure A1 constitutes a similar map, but where also small projects are included. Below, each group of variables is described in detail.

Figure 3: Realized projects by zone and developer size



Note: Trends in realized projects by price zone and developer size, aggregated over time. Upper diagrams are constructed using year of application, and lower diagrams are constructed using year of construction. Vertical lines are in 2006.

Figure 4: Applied projects by price zone and developer size



Note: Trends in all project applications by price zone and developer size, unconditional on project realization, aggregated over time. Upper diagrams include also rejected applications. Lower diagrams exclude rejected applications, but include applications that were accepted but not yet realized during the sample period. Vertical lines are in 2006.

Ownership

All of the ownership variables vary with developer size, both in terms of statistical and economic significance. The first variable is the time aggregated number of applications submitted by the owner of the project. For projects owned by large developers, the mean of this figure is 83.96 applications, while the corresponding number for small developers is 3.54. This is a notable difference, indicating that the locational decision making process is likely to vary with developer size. The second variable indicates if a project has a local owner, defined as a project where the physical address of the developer (or the parent company, if such exists) is located in the same municipality as the project itself. Only 3 percent of the projects owned by large developers are located in the same municipality as the owner, which is usually a densely populated city like Stockholm that is not suitable for wind power development. For the small developers, the corresponding figure is 14.5 percent. Further, none of the large developers are present in one municipality only. The corresponding figure for projects owned by small developers is 26 percent.

Application characteristics

In terms of statistical significance, the only variable that vary with developer size is the first variable, *installed capacity*, which is somewhat higher for small developers, at 65 MW compared to 44 MW for large developers. The following variable, *nr of turbines*, is also somewhat higher for small developers, at 22 compared to 18 turbines. Further, *accepted and realized* indicates if the project has been accepted and realized. The next variables, *accepted*, *rejected* and *revoked* indicates if the project has been accepted but not yet realized, rejected, or revoked by the owner. When a project is revoked by the owner, the reason is in practice always that the owner has received an informal indication from the decision makers that the project will get rejected, and that the owner therefore chooses to revoke the project before the final decision has been made. Therefore, although the formal rejection rate is only about 13 percent, the *de facto* rejection rate is above 50 percent for both groups. The next variable, *application year*, indicates the year when the application was submitted. As seen, the large boom in applications took place around 2010-2011 for both groups. The next variable, *in process for decision*, indicates if the project has not yet received a decision. This figure is low for both groups, since the majority of applications had been submitted already a decade ago. The next variable, *time to decision* (from the day of submission) is above two years for both groups, and the time to construction (from the day of approval) is slightly less than five years for both groups, which means that the total lead time between submission and construction is around seven years.

Geography

In terms of statistical significance, only *wind speed* varies with developer size, with on average 0.3 m/s greater for large developers. This is not surprising, since it is expected that large developers are somewhat more active in finding optimal locations than small developers. The next variable, *on designated area*, indicates if the project is located on an area proposed by the Energy Agency

Table 1: Summary statistics by project and developer size

	Large developers		***Small developers***		***Large-Small***
	Mean	Sd	Mean	Sd	
Ownership					
Owner total no. projects	83.96	109.37	3.54	2.83	80.42***
Local owner (%)	3.02	17.14	14.50	35.26	-11.48***
Owner present in one muni only (%)	0.00	0.00	26.35	44.11	-26.35***
Application characteristics					
Installed capacity	44.43	49.09	65.08	153.73	-20.64*
Nr of turbines	18.67	36.46	21.40	36.80	-2.73
Accepted and realized	0.20	0.40	0.24	0.42	-0.03
Accepted	0.13	0.34	0.09	0.29	0.03
Rejected	0.14	0.34	0.13	0.34	0.00
Revoked	0.46	0.50	0.44	0.50	0.02
In process for decision	0.04	0.20	0.07	0.25	-0.02
Application year	2010.79	3.33	2010.71	4.37	0.08
Time to decision	2.68	1.72	2.37	1.67	0.31
Time to construction	4.88	2.49	4.89	2.93	-0.01
Geography					
Wind speed	6.57	1.22	6.27	1.25	0.30***
On designated area	0.47	0.50	0.46	0.50	0.01
On arable land	0.35	0.48	0.34	0.47	0.01
On open ground	0.32	0.47	0.29	0.45	0.03
Dist to road >7m wide	11.80	13.72	13.66	17.82	-1.86
Dist to regional transmission	11.33	12.14	10.64	11.36	0.69
Some nature reserve exists	0.09	0.29	0.11	0.32	-0.02
Military interest exists	0.36	0.48	0.33	0.47	0.02
Time-varying variables					
Employment rate	0.56	0.07	0.55	0.07	0.00
Wage	0.05	0.94	-0.06	1.07	0.11
Education level	-0.01	1.00	0.02	1.00	-0.03
EP in rule	0.30	0.46	0.28	0.45	0.02
Observations	529		425		954

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$

Note: Descriptive statistics by project and developer size. Only projects involving five or more turbines are included in the sample. Time to decision and time to construction in years. Wind speed in m/s. Installed capacity in GW. Distances in km. Time-varying variables are computed with respect to the municipality where the project is located. Employment rate is continuous and may take any value between zero and unity. Wage and education level are standardized to unit variance and mean. EP in rule indicates if the Environmental Party is a member of the ruling coalition. A *t-test* is used to test for differences in means across large and small developers.

as a suitable place for wind power. These areas constitute only about 1.5 percent of Sweden's total area, so the fact that more than 40 percent of all applications are located here is notable. The next variables, *distance to regional transmission* and *distance to road $>$ 7 meter* measure km from the centroid of the project to the closest point of connection to the regional transmission network, and any road greater than 7 metres wide, respectively. Naturally, both of these variables are cost drivers, due to connection fees and transportation costs. The last variables, *some nature reserve exists* and *military interest exists* indicate if the project is located on areas that are less suited for wind power. It is notable that more than 30 percent of all projects are located on areas where some type of military interest exists, and it is not uncommon that projects get rejected due to a conflict of interest with military activities.

Time-varying variables

The time-varying variables are measured with respect to the mean in the municipality where the project is located. *Employment rate* is continuous and may take any value between zero and unity. *Wage* and *education level* are standardized to unit variance and mean. *EP in rule* indicates if the Environmental Party is a member of the ruling coalition of the municipality. In terms of statistical significance, only wage level varies with developer size, but the difference is only significant at the ten percent level.

Table 2 displays summary statistics for the same variables, by price zone instead of developer size. In contrast to Table 1, the difference between north and south is statistically significant for almost all variables. The fact that the prerequisites for wind power vary between north and south imposes challenges on the identification strategy, and is discussed in greater depth in Section 4.

Trends in time-varying variables

Most of the variables in Table 2 only exhibit trivial variation over time. However, the last four variables exhibit at least some variation over time, which potentially could influence also trends in wind power investments. Figure 5 illustrates these trends, by zone and sample year. At least from visual inspection, it does not appear that trends are notably different in the north compared to the south, although absolute levels differ. On average, all socioeconomic indicators are somewhat higher in the southern zone. This is expected, since most major cities are located here. A similar relationship is expected for the support for the Environmental Party, since it covaries positively with education, and has a strong support among urban populations.

4 Econometric model

4.1 A basic DiD approach

A natural starting point for examining the effect of the price reform is the DiD-estimator. In a conventional DiD-setup, one group is assigned to a treatment, while the other group serves

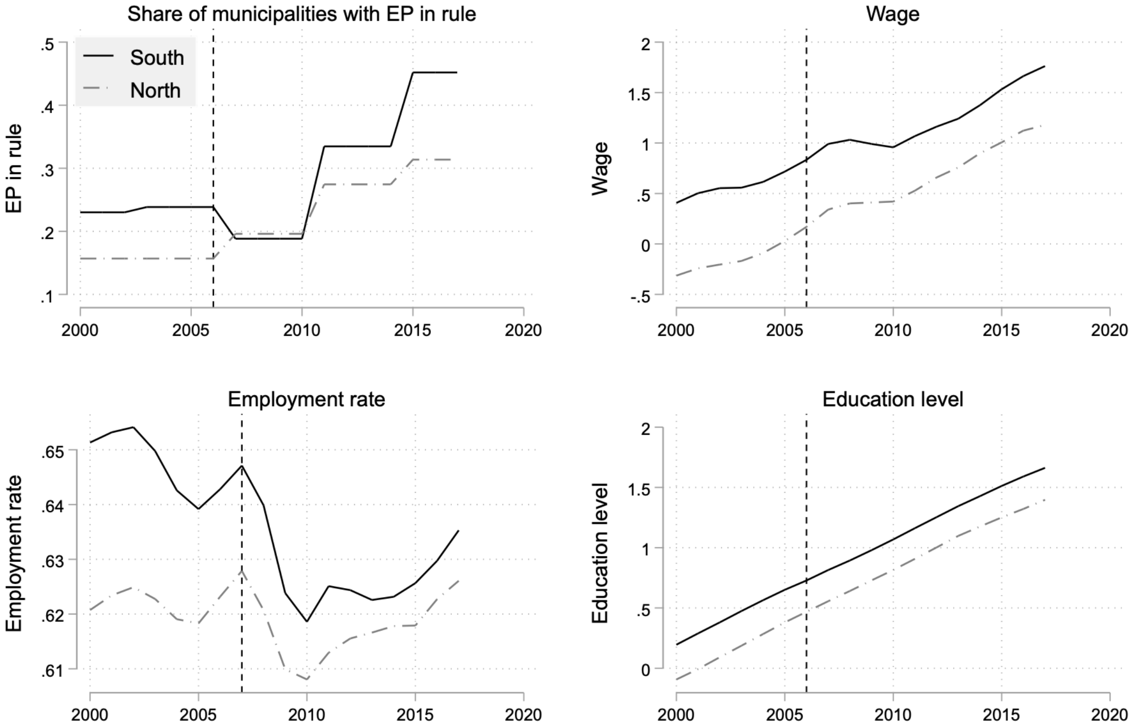
Table 2: Summary statistics by project and price zone

	South		***North***		***South-North***
	Mean	Sd	Mean	Sd	
Ownership					
Owner total no. projects	54.91	95.33	34.12	78.66	20.79***
Local owner (%)	9.51	29.36	3.42	18.22	6.08***
Owner present in one muni only (%)	11.35	31.75	12.54	33.17	-1.19
Application characteristics					
Installed capacity	32.67	33.41	96.20	177.00	-63.54***
Nr of turbines	14.21	30.73	31.60	44.28	-17.39***
Accepted and realized	0.21	0.41	0.23	0.42	-0.02
Accepted	0.08	0.27	0.19	0.39	-0.11***
Rejected	0.15	0.36	0.10	0.30	0.05*
Revoked	0.50	0.50	0.36	0.48	0.13***
In process for decision	0.03	0.17	0.10	0.30	-0.07***
Application year	2010.34	3.79	2011.60	3.70	-1.26***
Time to decision	2.49	1.65	2.64	1.80	-0.15
Time to construction	4.23	2.58	6.02	2.53	-1.79***
Geography					
Wind speed	6.72	1.19	5.77	1.10	0.95***
On designated area	0.44	0.50	0.51	0.50	-0.07
On arable land	0.38	0.49	0.25	0.44	0.13***
On open ground	0.37	0.48	0.14	0.35	0.23***
Dist to road >7m wide	10.26	11.21	18.31	22.09	-8.05***
Dist to regional transmission	10.38	11.49	12.63	12.43	-2.24*
Some nature reserve exists	0.09	0.28	0.14	0.34	-0.05*
Military interest exists	0.37	0.48	0.29	0.45	0.08*
Time-varying variables					
Employment rate	0.56	0.07	0.54	0.06	0.02***
Wage	0.12	1.02	-0.25	0.91	0.37***
Education level	0.08	1.06	-0.17	0.84	0.25***
EP in rule	0.33	0.47	0.21	0.41	0.12***
Observations	643		311		954

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$

Note: Descriptive statistics by project and developer size. Only projects involving five or more turbines are included in the sample. Time to decision and time to construction in years. Wind speed in m/s. Installed capacity in MW. Distances in km. Time-varying variables are computed with respect to the municipality where the project is located. Employment rate is continuous and may take any value between zero and unity. Wage and education level are standardized to unit variance and mean. EP in rule indicates if the Environmental Party is a member of the ruling coalition. A *t-test* is used to test for differences in means across zones.

Figure 5: Trends in time-varying variables



Note: Trends in control variables. Each variable is computed as a yearly mean for the municipalities in each respective zone. Wage and education level are standardized to unit variance and mean.

as a control. The current setup is somewhat different, since the price reform merely imposes a change in the relative prices between the price zones. In its basic form, the DiD-estimator may be formalized as:

$$Y_{it} = \alpha + \beta_1 South_i + \beta_2 post_t + \delta[South_i \times post_t] + \boldsymbol{\gamma}\mathbf{X}_{it} + \varepsilon_{it} \tag{1}$$

Where Y_{it} is the outcome of interest, for example the number of constructed projects in zone i in year t. Further, α is a constant, $South_i$ is a south zone indicator variable, and $post_t$ is a post-reform indicator variable taking the value one for all observations in the year 2007 and after. Further, δ is the coefficient of interest, estimating the effect of the interaction variable $South_i \times post_t$. Further, $\mathbf{X}_{it}$ is a set of time-varying zone-specific political and sociodemographic characteristics with its associated coefficient vector $\boldsymbol{\gamma}$, and ε_{it} is the error term following a Newey-West autocorrelation structure.

Decision making for small vs. large developers

For a meaningful interpretation of δ, it is useful with a more detailed understanding of investors' decision making. For large developers, the financing of a project is usually determined before the location is decided. The locational choice set usually includes both price zones, since these developers are active all across Sweden and sometimes also abroad.[3] For smaller investors, on the other hand, the locational choice set usually includes one or a few municipalities located close to the investor's head office. Since the price effect of the reform was comparatively modest during the first eight years, it is likely that it only had a modest effect on the *total* volume of wind power investments for both large and small developers. The decision whether to invest or not is likely more sensitive to expectations about the absolute price level (including the price for green certificates, which is harmonized across Sweden). However, it is still plausible that the reform had an effect on the locational decisions of the large developers. Therefore, it is crucial to estimate the effect on large and small developers separately. Given that the decision making process of large developers follows these steps, the number of projects that switched location due to the reform is $\frac{\delta}{2}$. To exemplify, assume that ten projects are constructed in each period. Before the reform, five projects are constructed in each zone, but after the reform, two projects that would otherwise have been constructed in the north instead moved to the south. In this case, the DiD-estimator is: $\hat{\delta} = (y_{south1} - y_{south2}) - (y_{north1} - y_{north2}) = (5-3) - (5-7) = 4$.

The fact that the tradable green certificates system was designed to increase renewable electricity generation by a fixed amount further supports the presumption that any changes to market

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[3] While a conventional DiD approach may give important insights about the aggregate effect of the reform on wind power investments, it says little about how the reform affects the *probability* that an investor will choose a certain zone. In principle, it would be possible to combine a DiD-approach with a model of discrete choice, such as the logit model. However, interpreting the corresponding interaction effects such as the treatment coefficient *South x post* in a DiD-setting is generally not informative about the change in probabilities that an investor will choose to locate in the high price zone (See Karaca-Mandic et al. (2012) for a formal review of the general case). Therefore, the current identification strategy does not lend itself to a model of discrete choice. From a policy perspective, it is also more useful to estimate the aggregate investment effect.

design mainly had an impact on the spatial distribution of wind power, but not the total level of generation.

Identification issues related to the parallel trends assumption

A crucial assumption of the DiD estimator is the parallel trends assumption, stating that pretreatment trends in outcomes across treatment and control groups should be identical, although absolute levels may differ. Parallel trends strengthen the plausibility that the observed difference in outcomes would have remained constant in absence of the reform. By visual inspection of the diagrams in Figure 3, it appears that this assumption is fulfilled (except for in the upper right diagram displaying the trend in projects by application year for small developers). However, the number of applications were relatively few in both zones during the pretreatment period, since the industry was still in its infancy. This casts doubts on the relevance of the observed parallel trends. To exemplify, assume that the conditions for wind power investments were inherently better in the south than in the north, but that these differences were only materialized as the industry began to grow. Since this happened around the time of the announcement of the reform, the estimated treatment coefficient in equation (1) may therefore also capture elements that are not related to the reform itself. At worst, it *only* reflects the fact that the southern zone may be relatively better suited for wind power. In the following section, I therefore propose a DiD matching algorithm that compares investments in smaller regions in the south to similar regions in the north, after matching on geographic characteristics that determine wind power suitability.

4.2 A nearest neighbor matching estimator

To decide the determinants of wind power suitability, I begin by partitioning Sweden into approximately 4000 squares of 10 *x* 10 *km* each, with the north and south zones approximately equal in terms of area.[4] I then perform a LASSO selection regression according to:

$$appl_s^{2020} = \alpha + \eta South_i + \boldsymbol{\beta}\mathbf{X_s} + \varepsilon_s \tag{2}$$

Where $appl_s^{2020}$ is the accumulated number of project applications submitted to square s by 2020, $South_i$ is a south zone dummy with its corresponding coefficient η (to account for the fact that more applications are expected in the south due to the reform), and $\mathbf{X_s}$ is the set of geographic variables described in Table 2, with its associated coefficient vector $\boldsymbol{\beta}$. Contrary to the control variables in the DiD approach, which by design have to vary over time, the geographic matching variables are static. Since the level of the original data collection is by km^2, most of these variables can now be expressed as a percentage, reflecting the mean share of each square that is covered by each respective ground type. For the variables *distance to regional transmission* and *wind speed*, I instead compute the average distance within each large square s. The following

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[4] The official GIS-grid used by Statistics Sweden has one observation per km^2. I use this grid as a template, and let every tenth square serve as the north-west coordinate for the new grid.

variables are selected by the LASSO: *Share of arable land, share of open ground* (as opposed to e.g. forest and mountains), *share of Energy Agency designated wind power area, mean distance to regional transmission*, and *mean wind speed.* I then proceed to find the closest match to each square in the other price zone, based on the mahalanobis distance[5] computed using the variables chosen by the LASSO. For each of the matched pairs, the average of the difference is then computed for the outcome variable of interest.[6]

Since the main outcome of interest is the total number of projects by the end of the sample period, I use the time aggregated values for each outcome during 2007-2020. Following the logic of the DiD estimator, I also subtract the corresponding value from the years predating 2007 for each observation. When including all matched pairs, the estimator corresponds to the Average Treatment Effect (ATE). This is the expected effect of the reform if a random square would have been assigned to the high price zone, and its match to the low price zone. If instead computing the effect using only southern squares and their northern counterparts, the estimator corresponds to the Treatment On the Treated (TOT), i.e. the expected effect if a random *southern* municipality had been assigned to the high price.

5 Results

Below, I describe the results separately for each model. Robustness results are discussed separately at the end of each section, and Table A9 provides a compilation of all robustness results.

5.1 Results from the conventional DiD estimator

Table 3 displays results from the main specification in equation (1), with results for large firms in columns (1)-(4). In columns (1)-(2), the dependent variable is the number of applications submitted, conditional on project realization (see the top left diagram in Figure 3 for the corresponding DiD-graph). The main specification, which includes covariates, is column (2), in which the treatment coefficient $\hat{\delta}$ is estimated precisely at about 26 projects. The interpretation is that, in absence of the reform, 26 more projects would have been realized in the north compared to the south. Under the assumption that the total volume of projects was not affected by the reform, this implies that $\frac{\hat{\delta}}{2} = 13$ projects switched location due to the reform. Expressed as a percentage of the total number of realized projects applications submitted by large firms in 2007 or after, the corresponding figure is $\frac{13}{72} = 18$ percent. Expressed as a percentage of the total installed capacity in the south by the end of the sample period, this figure amounts to 12 percent.[7]

In the next two specifications (3)-(4), the dependent variable is instead the total number of

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[5] The malalanobis distance is based on the inverse of the covariates' variance–covariance matrix, and is the most widely used metric in nearest neighborhood matching. It corresponds to the euclidean distance given that variables are transformed to a unit variance. Matching is done using resampling, so that one square may serve as the match for several other squares.

[6] I estimate the model using Stata's built-in *teffects* command, obtaining standard errors by implementing the bias-corrected estimator proposed by Abadie and Imbens (2011) to correct for inconsistency when matching on

Table 3: Basic DiD results

	Large developers				Small developers			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
South x post ($\hat{\delta}$)	32.4***	26.2***	150.6***	137.6***	−0.79	−5.18*	27.1	19.5
	(7.83)	(4.53)	(54.3)	(27.4)	(5.73)	(2.67)	(34.6)	(12.0)
Wage		−8.16		35.1		−9.35		−29.3
		(23.4)		(151.3)		(14.2)		(59.8)
EP in rule		46.1*		312.6		17.4		212.9***
		(24.8)		(188.7)		(10.7)		(43.3)
Edu level (1-7)		29.5		113.6		26.9*		117.3*
		(23.9)		(154.3)		(13.8)		(68.8)
Emp rate		−413.0		−1720.0		−251.0		−681.4
		(262.8)		(1401.8)		(176.9)		(626.4)
Application type	Realized	Realized	All	All	Realized	Realized	All	All
N	42	42	42	42	42	42	42	42

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$

Note: Estimation results from equation (1). The dependent variable is the number of project applications submitted. In specifications (1)-(2) and (5)-(6), only applications that were realized during the sample period are included. Standard errors are Newey-West with lag 4.

applications, irrespective of project realization. When including covariates in column (4), $\hat{\delta}$ is precisely estimated at 138. Expressed as a percentage of the total number of projects applications submitted by large developers in 2007 or after, the corresponding figure is $\frac{138/2}{402} = 17$ percent, which is only marginally different from the previous figure, indicating that geographic differences in approval rates do not drive the results.

The following columns (5)-(8) display results for small developers (see the top right diagrams in Figure 3 and 4 for the corresponding DiD-graphs). As expected, $\hat{\delta}$ is estimated imprecisely in all specifications. All of the coefficients are also economically insignificant. Therefore I do not comment further on these results.

Robustness

In Table 3, a developer is defined as large if it submitted at least ten applications during the sample period. Since this cutoff is arbitrary, I also estimate specifications (2), (4), (6) and (8) while letting the cutoff vary between five and fifteen applications. The corresponding treatment coefficients are depicted graphically in Figure A2, together with 95 percent confidence intervals.

All treatment coefficients corresponding to specifications (2) and (4) are estimated precisely, which is reassuring. The coefficients attain their highest value when the cutoff is defined at ten projects, as in the main specification. The respective minimum values for the treatment

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continuous variables.

[7] This figure is obtained by first computing the mean capacity for all realized project applications submitted by large developers in the south in 2007 or after, multiplied by 13. Then, this number is divided by the total observed installed wind power capacity in the south by the end of the sample period. Note that the total installed capacity also includes plants with less than 5 turbines, as well as plants owned by small developers.

Table 4: Variable balance before and after matching

	Standardized difference		***Variance ratio***	
	Observed	Matched	Observed	Matched
Nr. projects applied pre 2007	0.061	0.065	4.159	7.111
Arable land	1.311	0.128	27.771	1.342
Open ground area	0.748	0.123	3.834	1.248
Dist to regional transmission (mean)	−0.782	0.382	0.139	2.326
Designated wind power area	−0.001	−0.016	0.993	0.910
Mean wind speed *(m/sec)*	1.040	0.106	1.345	1.029

Note: Differences in observed and matched values for the matching variables. The standardized difference for the observed sample is $(X_{south} - X_{north})/X^{sd}$, and the variance ratio is $X^{var}_{south}/X^{var}_{north}$. Corresponding figures for the matched sample are defined equivalently, but every square is now compared to its matched counterpart.

coefficients are 19 and 125 respectively, which is not notably different from the original estimates of 26 and 138.

The coefficients corresponding to specification (6) are imprecisely estimated throughout, as in the main specification. Quantitatively, coefficients vary between -5 and 2, which is economically insignificant. Some of the coefficients corresponding to specification (8) are estimated somewhat more precisely than the original estimate, although this only holds for less than half of the robustness specifications. However, coefficients are still notably smaller than the corresponding figures for large developers.

5.2 Results from the matching DiD estimator

For a meaningful interpretation of the results, it is crucial that the matched variables are balanced across matched pairs. Table 4 displays the standardized differences, $(X_{south} - X_{north})/X^{sd}$, as well as the variance ratio, $X^{var}_{south}/X^{var}_{north}$, for the observed as well as the matched sample. Looking at the first column, it is evident that the observed sample is highly unbalanced with respect to all variables except *designated wind power area.* Notably, all of the variables indicate that the southern zone is better suited for wind power, except for the population variable, since increased population density constitutes a hindrance for wind power development. On the contrary, the matched sample is much better balanced, although the variable *open ground area* still has a standardized difference of around 0.206, reflecting a nontrivial difference within the matched pairs. Further, for most of the variables, the variance ratio is much smaller in the matched compared to the observed sample.

Results are displayed in Table 5, with coefficients for large developers in columns (1)-(4). In columns (1)-(2), the dependent variable is the number of applications submitted, conditional on project realization. The ATE in column (1) is precisely estimated at 0.012 projects per square. In a common DiD setup, results are directly comparable to the corresponding matching results. In the present main DiD setup, however, the dependent variable is aggregated within each zone. A back-of-the-envelope computation demonstrates that the implied ATE when aggregating across

Table 5: Nearest neighbor matching results

	Large dev. (Realized)		Large dev. (All)		Small dev. (Realized)		Small dev. (All)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Treatment effect	0.012***	0.020***	0.042***	0.070***	0.0031	0.0056	0.079	0.033
	(0.0039)	(0.0037)	(0.014)	(0.013)	(0.022)	(0.026)	(0.067)	(0.050)
Effect estimated	ATE	TOT	ATE	TOT	ATE	TOT	ATE	TOT
N	4174	2106	4174	2106	4174	2106	4174	2106

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$

Note: Results from the nearest neighbor matching estimator described in section 4.2. Standard errors are obtained by implementing the bias-corrected estimator proposed by Abadie and Imbens (2011) to correct for inconsistency when matching on continuous variables. ATE is the average treatment effects, TOT is the treatment on the treated.

southern squares is $0.012 \ x \ 2106 = 25$. This figure is comparable to the corresponding effect from the main DiD estimator at 26, which is reassuring. It should also be noted that the TOT in column (2) is almost twice as large as the ATE, at 0.020. This demonstrates that the effect presumably would have been even greater if both zones would have characteristics similar to those of the southern zone.

The following columns (3)-(4) display results for all applications. Also here, the TOT is approximately twice the size of ATE. When expressed as percentages of the total number of applications, the ATE is somewhat smaller than the corresponding basic DiD estimate, at 11 instead of 17 percent.

The following columns (5)-(8) display the corresponding results for small developers. The effect is comparatively small and imprecisely estimated in all of the specifications, in accordance with the results from the previous models, and therefore I do not comment further on these results.

Robustness

I conduct robustness tests in two dimensions. First, I allow the matching estimator to identify up to five neighbors for each square, following the ranking of the mahalanobis distance to the squares in the other zone. Coefficients are depicted graphically in Figure A3, corresponding to specifications (1)-(4), and A4, corresponding to specifications (5)-(8). The variations in the coefficients are neither statistically nor economically different from the baseline estimate, except specification (7), which yields a precisely estimated treatment coefficient at 0.082 when including five neighbors (see the lower right diagram in Figure A4). In terms of economic significance, this figure is comparable to the corresponding baseline figure for large developers in specification (4).

Second, I examine the sensitivity to the choice of matching variables by iteratively removing one of the matching variables. Results are depicted in Table A1-A4 for large developers, and Table A5-A8 for small developers. For large developers, all coefficients are estimated precisely and generally do not vary notably across robustness specifications. An exception is specification

(1), where the estimated effect ranges between 0.01 and 0.028, although most iterations are close to the main result at 0.012. The corresponding results for small developers reveal that every coefficient is estimated imprecisely.

6 Concluding discussion

I present empirical evidence of the effect of the 2011 Swedish electricity market splitting reform on the allocation of wind power investments. I exploit a unique data set of all Swedish applications for wind power since 2003, including information on the submission date of each project application, the owner of the project, and whether it was rejected or approved and subsequently realized. I find that 18 percent of all projects submitted by large developers after the reform were allocated to the high price zone due to the reform. This corresponds to 12 percent of the total installed wind power capacity in this zone by the end of the sample period. This effect is not driven by geographic differences in approval rates, suggesting that the estimated effect also captures the causal effect on investors' locational choices. Qualitatively, results are verified using a nearest neighbor approach.

Further, I find that small, sometimes locally owned developers, did not react to the reform. A likely reason is that the locational choice set of small developers usually only includes one zone. Since the price effect of the reform was relatively modest during the majority of the sample period, it is unlikely that the reform would have an effect on the absolute volume of wind power investments, explaining the absence of an effect on small developers. Hence, it would be useful for policy makers to account for investor characteristics when evaluating, and potentially also forecasting, effects of further market splitting reforms throughout Europe.

Since there were relatively few applications submitted before the announcement of the reform, the parallel trends assumption of the DiD estimator cannot be entirely verified, suggesting that results should be interpreted with care. On top of the market splitting reform, other locational price signals are also present in the form of geographically differentiated grid usage charges. Although regional differences in these charges remained approximately constant during the sample period, it cannot be ruled out that they at least to some extent have had an impact on the estimated treatment effect, emphasizing that results should be interpreted with care.

A central rationale for market splitting reforms is that increased investments in production in high-price zones lead to an equalization of prices, eliminating the need to increase transmission capacity. Although the present study does not attempt to estimate the effect on prices, the results could be used as a basis for estimating such an effect.

Although it is beyond the scope of this study to examine the demand side effects of the reform, such a study would be a valuable complement to the present study. During the last decade, several data centers have chosen to locate in the northern zone. There is also an ongoing discussion about locating a large scale steel plant here in the near future, which would increase demand in the northern zone by around 30 percent. Future studies could examine the extent to which the locational decisions of such electricity intensive industries have been influenced by the reform. Given that the price divergence was most pronounced at the end of the sample period, it is expected that even greater supply- and demand effects could arise in the near future, underlining the value of continuous evaluations.

Another recent market splitting reform that has not yet been studied in terms of investment effects is the German-Austrian split. A similar analysis of this market split would be a welcome contribution to the understanding of such reforms.

References

Abadie, Alberto and Guido W. Imbens, "Bias-Corrected Matching Estimators for Average Treatment Effects," *Journal of Business & Economic Statistics*, January 2011, *29* (1), 1–11.

Brown, David P., Jay Zarnikau, and Chi-Keung Woo, "Does locational marginal pricing impact generation investment location decisions? An analysis of Texas's wholesale electricity market," *Journal of Regulatory Economics*, December 2020, *58* (2), 99–140.

Eicke, Anselm and Tim Schittekatte, "Fighting the wrong battle? A critical assessment of arguments against nodal electricity prices in the European debate," 2022.

_ **, Tarun Khanna, and Lion Hirth**, "Locational Investment Signals: How to Steer the Siting of New Generation Capacity in Power Systems?," *The Energy Journal*, 2020, *0* (Number 6), 281–304.

Ek, Kristina, Lars Persson, Maria Johansson, and Åsa Waldo, "Location of Swedish wind power—Random or not? A quantitative analysis of differences in installed wind power capacity across Swedish municipalities," *Energy Policy*, 2013, *58* (C), 135–141.

Energy Agency, "Kommunal tillstyrkan i praktiken. En enkätundersökning om kommunal tillstyrkan vid tillståndsprövning av vindkraftverk," Report ER 2014:21, The Swedish Energy Agency 2014.

Energy Markets Inspectorate, "Prisområden på elmarknaden (POMPE)," Report EMIR 2007:2, Energy Market Inspectorate 2007.

ENTSOE, "First edition of the bidding zone review," Report, ENTSOE 2018.

European Commission, "Summary of Commission Decision COMP/39.351 - Swedish Interconnectors," Official Journal of the European Union April 2010. `https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2010:142:0028:0029:EN:PDF`.

European Council, "Council regulation (EU) no 943/2019," 2019. `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R0943`.

Glachant, Jean-Michel and Virginie Pignon, "Nordic congestion's arrangement as a model for Europe? Physical constraints vs. economic incentives," *Utilities Policy*, 2005, *13* (2), 153–162. Electricity Transmission.

Gugler, Klaus, Adhurim Haxhimusa, Mario Liebensteiner, and Nora Schindler, "Investment opportunities, uncertainty, and renewables in European electricity markets," *Energy Economics*, 2020, *85*, 104575.

Hitaj, Claudia, "Wind power development in the United States," *Journal of Environmental Economics and Management*, 2013, *65* (3), 394–410.

Holmberg, Pär and Ewa Lazarczyk, "Comparison of congestion management techniques: Nodal, zonal and discriminatory pricing," *The Energy Journal*, 2015, *0* (Number 2).

Karaca-Mandic, Pinar, Edward C. Norton, and Bryan Dowd, "Interaction Terms in Nonlinear Models," *Health Services Research*, 2012, *47* (1pt1), 255–274.

Lauf, Thomas, Kristina Ek, Erik Gawel, Paul Lehmann, and Patrik Söderholm, "The regional heterogeneity of wind power deployment: an empirical investigation of land-use policies in Germany and Sweden," *Journal of Environmental Planning and Management*, 2020, *63* (4), 751–778.

Nutek, "Nätkostnader i överföring och distribution av el," Report Nutek R1994:68, Nutek 1994.

OX2, "Informal interview with Hillevi Priscar, Country Manager Sweden at OX2," 2021.

Qadir, Sikandar Abdul, Hessah Al-Motairi, Furqan Tahir, and Luluwah Al-Fagih, "Incentives and strategies for financing the renewable energy transition: A review," *Energy Reports*, 2021, *7*, 3590–3606.

Schmidt, Lukas and Jonas Zinke, "One price fits all? Wind power expansion under uniform and nodal pricing in Germany," Working Paper 20/06, EWI 2020.

Schweppe, Fred C., Michael C. Caramanis, Richard D. Tabors, and Roger E. Bohn, *Spot pricing of electricity*, Springer US, 1988.

Swedish Government, "Elcertifikat - stoppregel och kontrollstation 2019," Government announcement 2020/21:44 2020. https://www.riksdagen.se/sv/dokument-lagar/arende/betankande/elcertifikat---stoppregel-och-kontrollstation-2019_H801NU6.

Tangerås, Thomas and Frank A. Wolak, "The Competitive Effects of Linking Electricity Markets Across Space and Time," Working Paper 1184, Research Institute of Industrial Economics 2020.

Triolo, Ryan C. and Frank A. Wolak, "Quantifying the Benefits of Nodal Market Design in the Texas Electricity Market," Working Paper, Stanford University 2021.

Wolak, Frank A., "Measuring the Benefits of Greater Spatial Granularity in Short-Term Pricing in Wholesale Electricity Markets," *American Economic Review*, May 2011, *101* (3), 247–52.

Appendix A: Details of the application process

Information regarding the application process has been collected from www.vindlov.se.
Application process: Every wind turbine application is submitted to the municipality where the proposed site is located. If a project spans two municipalities, applications have to be submitted to both municipalities. Projects are divided into three main categories depending on their size:

1. Small projecs: **1 turbine $\leq$ 50 m**
   Decision is taken by the municipal land use committee. Members are often local politicians. The municipal council may also influence the decision directly. Application includes technical characteristics of the turbine, estimates of noise, shadows etc.

2. Medium projects: **1 turbine $>$ 50 m or 2 or more turbines**
   Decision by municipal land use committee *and* the municipal environmental committee. Application also includes environmental consequences documentation.

3. Large projects: **2 turbines that both are $>$ 150 m or 7 or more turbines each $>$ 120 m**
   Decision by municipality, but the project also needs to comply with extensive environmental legislation. Compliance is tried at the county level by non-political officials. These projects account for about half of all project applications in the data. Municipalities are free to choose how to make the decision. According to the Energy Agency (2014), the ruling coalition decides in 46 percent of the municipalities, the municipal council decides in 22 percent, and in the remaining cases the decision making body is a non-political bureaucratic entity. These projects demand more thorough environmental consequences documentation.

Original decisions can be appealed. The appeal process for small and medium projects is handled by the county administration, but the county administrations only have the power to reject applications that have already been approved (so that the municipal veto to reject persists). Large projects can be appealed to the National Environmental Court. Also here, the municipal veto to reject persists.

Besides the approval process described above, the military also has the right to refuse a project if it is located in an area where there is a conflict of interest with military activities. A common reason is that military aircrafts should be able to fly through a landscape close to the ground without risking a collision with wind turbines.

Appendix B: Data

- **Geographic characteristics:** Data are publicly available and may be downloaded from the Swedish Land Use Authority ("Lantmäteriet").
  www.lantmateriet.se/sv/Kartor-och-geografisk-information/oppna-data

- **Election data:** Data are publicly available and may be downloaded from the Election Authority ("Valmyndigheten").
  www.val.se/valresultat

- **Wind turbine application data:** Data are publicly available and may be downloaded from the Energy Agency ("Energimyndigheten").
  www.vbk.lansstyrelsen.se

- **Wind turbine ownership data:** Data on turbine ownership from the Energy Agency data set are organization numbers. These numbers have then been merged with detailed ownership information, including parent companies (if applicable) and municipality of registration. This merge has been done using the private Serrano data-set of the Research Institute of Industrial Economics. Please contact the author directly for access to aggregate variables constructed using these data.

- **Sociodemographic data:** Data have been accessed using the LISA-database of Statistics Sweden. These data are not publicly available, but close to identical variables are publicly available from the Kolada data base of SKR.
  www.kolada.se

- **Grid usage charges:** Data on grid usage charges for the transmission network for the years 2012 and later have been downloaded from the TSO, comprising complete price lists for about 100 injection points across the country. Each injection point is geographically tied to price zone. I compute the mean grid charge in each region by averaging over all injection points within that region (i.e., zone 1 and 2 (3 and 4) for north (south). I then compute the difference in the total grid charge between north and south, to assess the strength of this locational price signal. The grid charge is a two-part tariff, and to enable a comparison with the wholesale price I approximate the grid charge in terms of SEK/MWh according to the following:

The fixed part depends on the installed capacity and is linearly decreasing with the latitude, resulting in variation also within price zones. To translate this figure into SEK/MWh, I assume a yearly wind power capacity factor of 34 percent, which is representative for land based wind turbines in Sweden.

The variable part is designed to cover grid losses and depends on the amount of electricity injected to the grid. The variable charge is computed using the formula SEK/MWh= $(P_{it}+10)F_k$, where P_{it} is the wholesale price in zone i during period t, and F_k is the location specific loss factor, which is also approximately linearly decreasing with the latitude. Naturally, before market splitting, P_{it} did not vary with location. Market splitting provides additional geographic differentiation of the grid usage charge through its effect on P_{it}. However, to isolate the geographic differentiation due to the loss factor, I here assume that every location meets the average wholesale price also after market splitting.

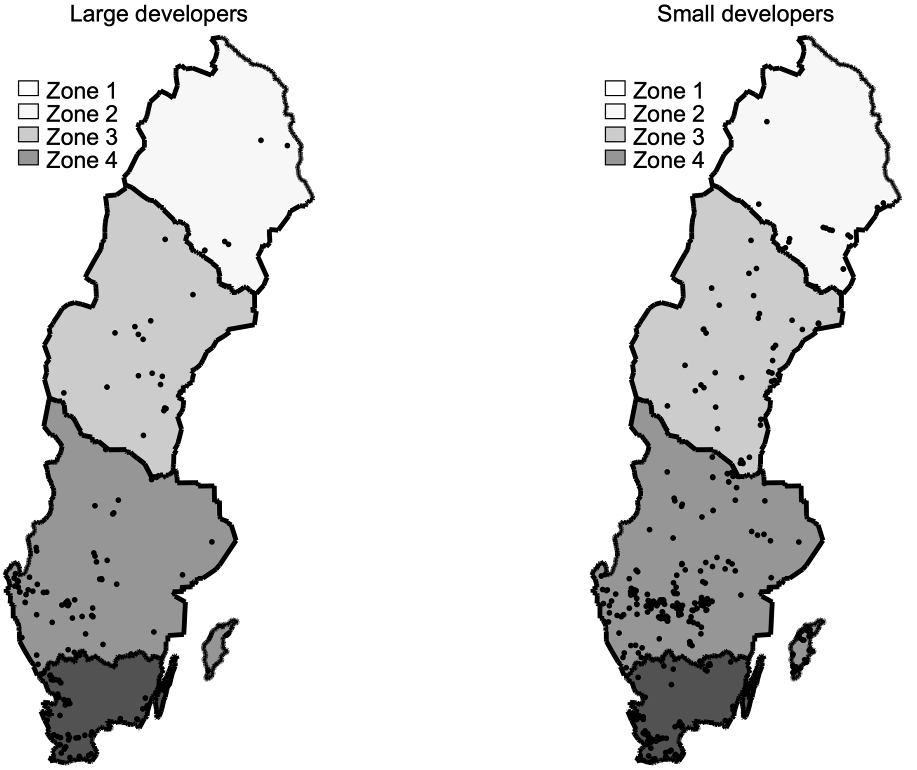
In total, the mean grid charge increased from about 25 to 45 SEK/MWh between 2012 until the end of the sample period. However, the strength of the signal (i.e. the price difference between north and south) remained approximately constant at around 3-4 SEK/MWh.

Data on grid usage charges for the years before 2012 are less detailed, but the annual reports of the TSO specify the mean fixed grid charges by region (north/south) for all years in the sample. Variable charges are, however, not always specified by region. The earliest complete data on grid usage charges by region are provided by Nutek (1994), where average fixed and variable charges for representative injection points in each region are specified for the year 1995. Given the same assumptions as when computing the total charges for themore recent years, the mean grid charge then amounts to 20 SEK/MWh, and the total price difference is 3.6 SEK/MWh, which is comparable to the corresponding figure for later years.

Last, it should be noted that the TSO, as well as lower voltage network owners, charge one-time grid connection charges when a plant is connected to the grid. These charges are geographically differentiated and should cover the initial necessary network investment cost. Each connection charge is assessed individually. The connection charge also includes the cost of necessary capacity increases on integrated networks (this is usually referred to as “deep” connection charges). It is not self-evident how the connection charge varies with latitude, and structured data on connection charges are not been available. Since plants in the north are usually located relatively far away from populated areas, it is likely that the connection charge is on average somewhat higher in the north.

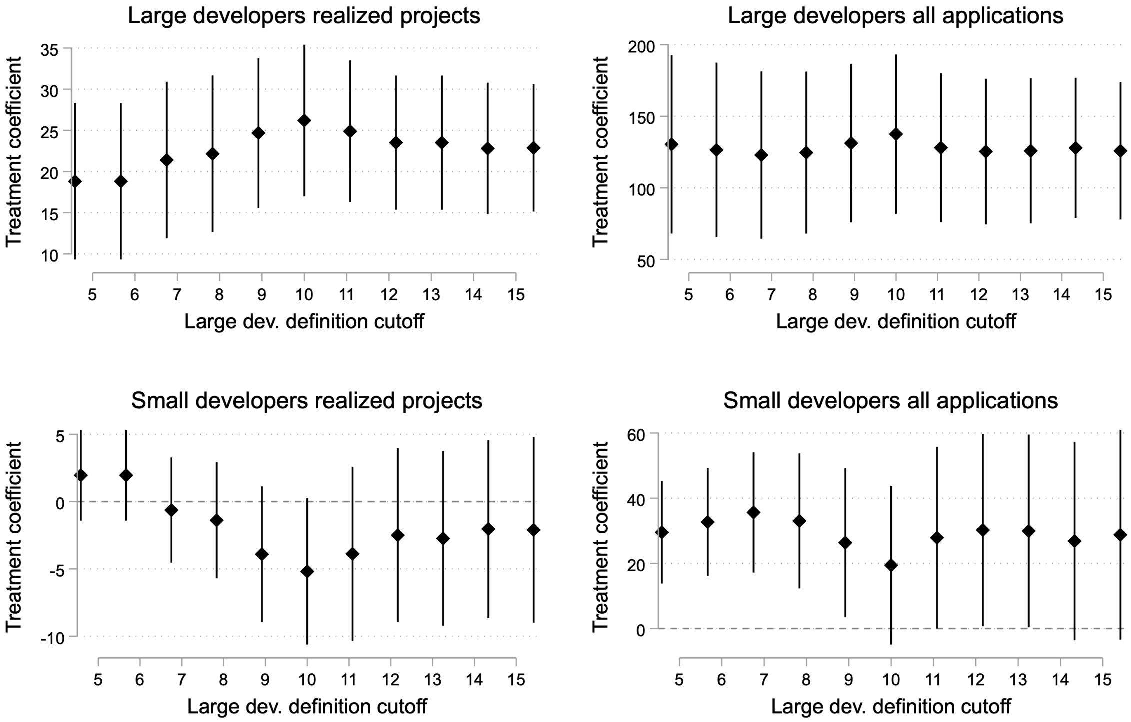
Appendix C

Figure A1: Map of realized projects by developer size and price zone, including small projects.



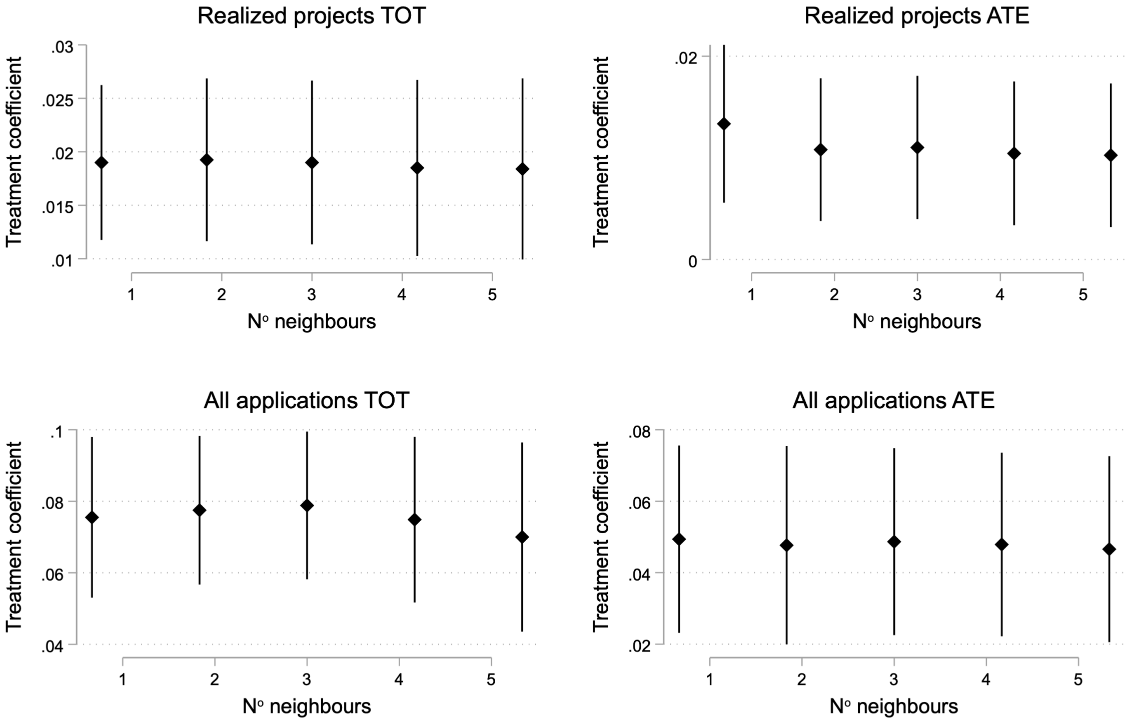
Note: Each dot represents the location of a wind project for large (left) and small (right) developers respectively, by 2020. Also shown are the zonal borders. All projects are included, also those with less than five turbines.

Figure A2: DiD sensitivity to the definition of a large developer



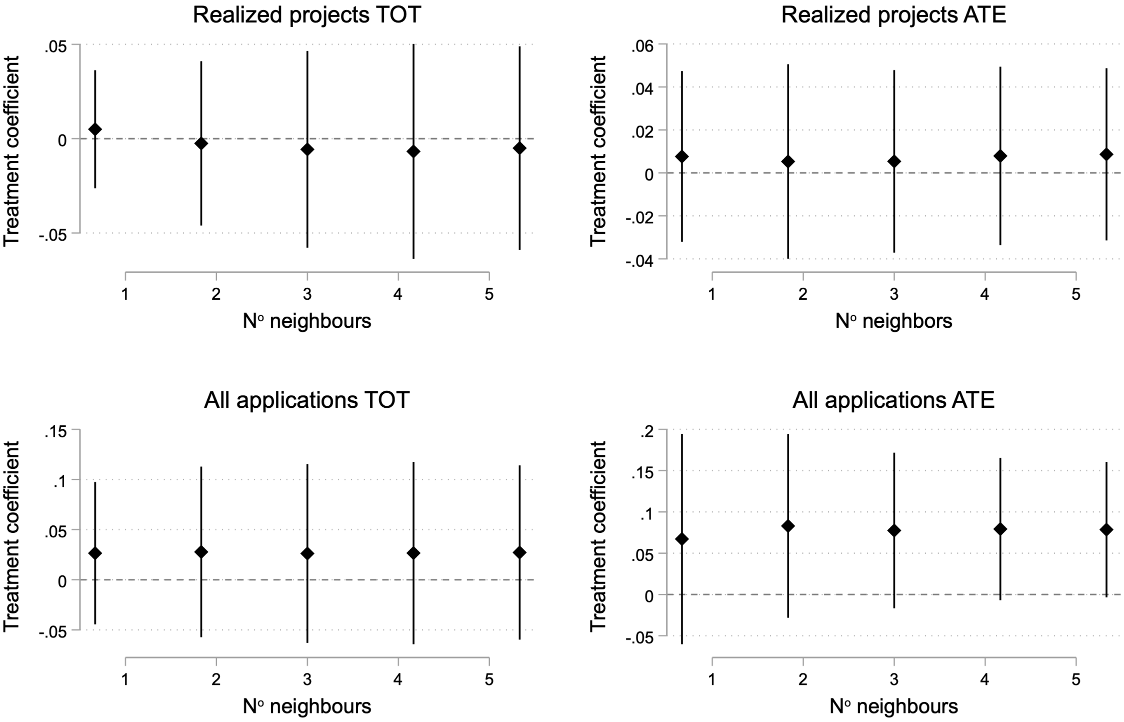
Note: Results when estimating specifications (2), (4), (6), and (8) in Table 3 and varying the number of applications required for a developer to be defined as large between 5-15. Treatment coefficients are displayed as dots. Vertical lines are 95 percent confidence intervals.

Figure A3: Nearest neighbor sensitivity to the number of neighbors, large developers



Note: Results when estimating specifications (1)-(4) in Table 5 and letting the matching estimator identify up to five neighbors. Treatment coefficients are displayed as dots. Vertical lines are 95 percent confidence intervals.

Figure A4: Nearest neighbor robustness results, small developers



Note: Results when estimating specifications (5)-(8) in Table 5 and allowing the matching estimator to identify up to five neighbors. Treatment coefficients are displayed as dots. Vertical lines are 95 percent confidence intervals.

Table A1: Leave-one-out: Large developers, ATE, realized projects

	(1)	(2)	(3)	(4)	(5)	(6)
Treatment effect	0.013***	0.0095***	0.021***	0.013***	0.010***	0.013***
	(0.0039)	(0.0034)	(0.0050)	(0.0040)	(0.0038)	(0.0040)
Left out variable	Pre 2007	Arable	Open	Transmission	Designated	Wind
N	4719	4719	4719	4719	4719	4719

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$

Note: Nearest neighbor results corresponding to specification (1) in Table 5 when iteratively leaving out one of the matching variables.

Table A2: Leave-one-out: Large developers, TOT, realized projects

	(1)	(2)	(3)	(4)	(5)	(6)
Treatment effect	0.020***	0.020***	0.020***	0.020***	0.020***	0.020***
	(0.0037)	(0.0039)	(0.0037)	(0.0038)	(0.0036)	(0.0037)
Left out variable	Pre 2007	Arable	Open	Transmission	Designated	Wind
N	4719	4719	4719	4719	4719	4719

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$
Note: Nearest neighbor results corresponding to specification (2) in Table 5 when iteratively leaving out one of the matching variables.

Table A3: Leave-one-out: Large developers, ATE, all applications

	(1)	(2)	(3)	(4)	(5)	(6)
ATE						
Treatment effect	0.019***	0.017**	0.021***	0.025***	0.015**	0.020***
	(0.0052)	(0.0066)	(0.0053)	(0.0058)	(0.0061)	(0.0052)
Left out variable	Pre 2007	Arable	Open	Transmission	Designated	Wind
N	4719	4719	4719	4719	4719	4719

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$
Note: Nearest neighbor results corresponding to specification (3) in Table 5 when iteratively leaving out one of the matching variables.

Table A4: Leave-one-out: Large developers, TOT, all applications

	(1)	(2)	(3)	(4)	(5)	(6)
Treatment effect	0.029	0.0092	0.025	0.027	0.027	0.022
	(0.049)	(0.028)	(0.031)	(0.10)	(0.051)	(0.027)
Left out variable	Pre 2007	Arable	Open	Transmission	Designated	Wind
N	4719	4719	4719	4719	4719	4719

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$
Note: Nearest neighbor results corresponding to specification (4) in Table 5 when iteratively leaving out one of the matching variables.

Table A5: Leave-one-out: Small developers, ATE, realized projects

	(1)	(2)	(3)	(4)	(5)	(6)
Treatment effect	0.0058	−0.0019	0.0024	0.015	0.0057	0.0031
	(0.022)	(0.0047)	(0.0088)	(0.044)	(0.023)	(0.020)
Left out variable	Pre 2007	Arable	Open	Transmission	Designated	Wind
N	4719	4719	4719	4719	4719	4719

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$
Note: Nearest neighbor results corresponding to specification (5) in Table 5 when iteratively leaving out one of the matching variables.

Table A6: Leave-one-out: Small developers, TOT, realized projects

	(1)	(2)	(3)	(4)	(5)	(6)
Treatment effect	0.012	0.0020	0.0086	0.0075	0.010	0.0062
	(0.026)	(0.0066)	(0.017)	(0.053)	(0.028)	(0.016)
Left out variable	Pre 2007	Arable	Open	Transmission	Designated	Wind
N	4719	4719	4719	4719	4719	4719

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$
Note: Nearest neighbor results corresponding to specification (6) in Table 5 when iteratively leaving out one of the matching variables.

Table A7: Leave-one-out: Small developers, ATE, all applications

	(1)	(2)	(3)	(4)	(5)	(6)
ATE						
Treatment effect	0.030	0.0055	0.0064	0.028	0.031	0.027
	(0.038)	(0.024)	(0.015)	(0.068)	(0.038)	(0.033)
Left out variable	Pre 2007	Arable	Open	Transmission	Designated	Wind
N	4719	4719	4719	4719	4719	4719

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$
Note: Nearest neighbor results corresponding to specification (7) in Table 5 when iteratively leaving out one of the matching variables.

Table A8: Leave-one-out: Small developers, TOT, all applications

	(1)	(2)	(3)	(4)	(5)	(6)
Treatment effect	0.029	0.0092	0.025	0.027	0.027	0.022
	(0.049)	(0.028)	(0.031)	(0.10)	(0.051)	(0.027)
Left out variable	Pre 2007	Arable	Open	Transmission	Designated	Wind
N	4719	4719	4719	4719	4719	4719

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$
Note: Nearest neighbor results corresponding to specification (8) in Table 5 when iteratively leaving out one of the matching variables.

Table A9: Compilation of robustness results

Type of test	**Large developers**	**Small developers**
Large developer def.	**DiD**	
Realized projects	19-26 [26]	ns [ns]
All applications	125-134 [134]	24-37 [ns]
№neighbors	**Matching**	
ATE, realized proj	0.01-0.012 [0.012]	ns [ns]
TOT, realized proj	0.018-0.020 [0.020]	ns [ns]
ATE, all applications	0.041-0.042 [0.042]	0.082-0.082 [ns]
TOT, all apps	0.070-0.075 [0.070]	ns [ns]
Leave-one-out		
ATE, realized proj	0.01-0.028 [0.012]	ns [ns]
TOT, realized proj	0.019-0.020 [0.020]	ns [ns]
ATE, all applications	0.015-0.021 [0.042]	ns [ns]
TOT, all applications	0.037-0.046 [0.070]	ns [ns]

Note: Compilation of treatment coefficients for various robustness tests. The first figure in each row is the lowest coefficient obtained in the test, and the second figure is the highest. The figure in brackets is the corresponding baseline coefficient. Coefficients are only printed out if $p < 0.05$, otherwise they are recorded as not significant (ns).