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Wind power volatility and its impact on production failures in the Nordic electricity market

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ABSTRACT

Wind power generation of electricity has gained popular support because of its low environmental impact and its low costs relative to other renewable energy sources. However, concerns have been raised in the power sector that wind power generation will come at the price of increased damage to other power generators. Wind power generation is naturally volatile which requires other power sources to start up and shut down in accordance with weather conditions, which for instance coal or gas generators are in general not built to do. The previous literature has used simulations to show that the damage done and the associated costs can be substantial. We use a dataset containing all reported failures in the Nordic electricity market Nord Pool and data for Danish wind power generation. The analysis shows that for both Denmark and the rest of Nord Pool the short-term costs associated with the volatility of wind power generation are non-significant.

1. Introduction

The demand for renewable energy sources has increased due to environmental concerns. One of the most important options for meeting renewable energy targets has been wind power since it is clean and reasonably cost effective. However, since wind generation is volatile, the imbalances in the net demand (demand less intermittent generation) have to be complemented with large amounts of other capacity, often provided through coal, gas, oil or hydro. When wind power ceases to provide electricity, the other capacity is required to start up and conversely it needs to shut down when the winds are sufficiently strong. The frequent start-ups and shut-downs put a strain on the other generators which could potentially mean more frequent failures or increased needs for maintenance compared to when wind power is not part of the energy mix [28,30,31]. This may be a significant problem since failures and maintenance threaten supply security and can increase prices for consumers. Moreover, cycling can negatively impact plant lifetime and costs [31]. There have been various studies assessing the impact of large amounts of wind power on the operations of the power systems. However, to the best of our knowledge, there is no systematic empirical assessment of the effects intermittent power has on the cycling costs in the system and associated failure rates.

In this paper we empirically investigate how volatility in wind power production affects the failure rates of conventional power sources. We estimate effects for Denmark, which is part of Nord Pool, one of the largest European electricity markets, and for all of Nord Pool. A well-integrated electricity market with less congestion can balance the volatility of wind power production better through export or import, compared to a market with restricted export and import possibilities [14]. That is, if imbalances in net demand can seamlessly be met through export and import, cycling of own units can be expected to be less of a problem. This is especially true for Denmark since neighboring countries in Nord Pool have substantial amounts of hydro power, which can be argued to be naturally more flexible than for instance coal and gas. For this reason we estimate separate effects for when Denmark experiences congestion, and hence is import or export constrained, and when Denmark can freely export and import. We expect more failures in Denmark as a consequence of cycling when Denmark is export or import constrained.

The main analysis reported in this paper can have a causal interpretation as wind is naturally exogenous and moreover, due to the minimal marginal cost of wind power production, wind power units are utilized whenever it is windy [4]. Additionally, we provide

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some descriptive relations between wind power production in MW and the number of failures reported per week over the seven-year period 2006–2012. The purpose of these descriptive regressions is to verify whether there are any correlations between the number of failures in the system and a more compound effect of wind power, i.e., a continuous increased use of wind power over time and more sudden changes in wind production levels between different weeks in our sample.

In our analysis we use a unique dataset containing wind power utilization in Denmark and failures reported in Urgent Market Messages (UMMs) released in the Nordic electricity market Nord Pool for the years 2006–2012. Denmark has the largest share of wind power use in the world and in 2013 33.2% of the Danish electricity consumption was covered by wind, which makes the results for Denmark especially interesting [12]. The results in this paper will also have policy implications for other areas investing heavily in wind power generation, such as Texas or Spain.

The results show that there is no short-term effect of wind power volatility on production failures in Denmark or Nord Pool. Production failures do not seem to be affected by whether there is congestion or not. Descriptive regressions aimed to capture a more compound effect of wind power use on the power generation units show some significant effects for Nord Pool but only a weakly significant effect on oil power plants for Denmark. The insignificant effects for Denmark could however be due to increased market integration with Sweden and Norway, as a larger market can enable better balancing, especially with the use of hydro generation [24].[1] It is also possible that increased damage to units due to cycling was expected and hence the investment in maintenance increased in our sample over time. Our results provide evidence that in Nord Pool and Denmark, the inclusion of wind power in the market mix has an insignificant effect on the number of failures and associated costs in the short run. As such, it contributes by revealing new evidence in support of wind power.

There have been various studies assessing the impact of large amounts of wind power on the operations of the power systems. A study of integration of high levels of intermittent power into the western US electrical system revealed that a reduction of the value of wind and solar power due to cycling costs of thermal units in systems (were 30% of demand was supplied by this type of power) was between 0.1 and 2.4% [19]. Another study of European electricity systems indicated that cycling costs are more pronounced in systems with a lot of wind power. With larger variations of net load, the level of cycling costs impacts the competitiveness of generating units, i.e., “low cycling costs represent an increasingly relevant competitive advantage” [11]. The same author states also that “for systems in which the differences in cycling costs between the generation units are large but the differences in running costs are small, the impact on the capacity factors of the generation units will be evident already at low levels of wind-power penetration”. The cost of integrating wind power has been also discussed by Refs. [29] and [6]; who point out that already at the 10% level of wind power penetration the economic cost of the operation of power system as a whole will increase. Moreover, [21] and [6] conclude that cycling associated with the operation of units generating electricity at varying load levels puts pressure on the operating equipment resulting in higher plant operations and maintenance expenditures. It is increasingly difficult to put one number on the costs related with frequent start-ups and shut-downs of the conventional power plants. Therefore, as [31] points out “uncertainty surrounding cycling cots can lead to these costs being under-estimated by generators, which in turn can lead to increased cycling”. Some estimates of operation and maintenance (O&M) costs for a start and shut down cycle of certain units have been presented in the literature, for e.g. a gas unit has been found to range from $300 to $80,000 in the O&M costs. These costs represent the increased damage to plant equipment, lower fuel efficiencies and potentially shortened plant life [23].

The effects that integration of large amounts of wind power into the electricity grid has on the workings of the power sector have been studied in the literature. It has been pointed out that increased cycling can lead to deterioration of various components [22,31] and hence increased rates of forced outages. However, to the best of our knowledge, there is no systematic empirical assessment of the effects intermittent power has on the failure rates of conventional generators, which is the contribution of this paper.

The paper is structured as follows. The next section describes Danish wind power. Section 3 discusses consequences of increased wind production volatility and its effect on the power system. Section 4 describes data and Section 5 the empirical strategy. The results are discussed in Section 6. The last section concludes the paper.

2. Danish wind power penetration and market conditions

Development of wind power generation has been popular in Denmark since the 1970’s when the oil crises led to economic difficulties. The impact of coal power on the climate and the local environment, together with a popular distrust in nuclear power, paved the way for efforts to expand wind power [8]. Until 1973, 90% of the country’s energy supply was based on imported oil. At the beginning of the 1980’s subsidies for the construction and operation of wind turbines, taxes imposed on oil and coal and additional tax incentives aimed at Danish families for generating power for their communities, increased the interest in renewable power [18].

The subsidies for the wind power were canceled in 1988 and in 1993 feed-in tariffs for wind power were introduced, to be replaced in 1999 by a system of tradable green certificates. Since 2003 an environmental premium has instead been added to the market-clearing price for wind power generated electricity. The feed-in tariffs for turbines of all sizes were re-introduced in 2009. The initial drop of the feed-in tariff decreased the willingness to invest in new turbines as can be seen in Fig. 1 [18]. This can explain why capacity and the number of turbines have diverging time trends at the beginning of the 21 st century. At the same time the Danish government ordered additional offshore wind power to be installed at five different locations. The turbines scrapping system that was first introduced in 2001 and later had several follow-ups [2] can be another reason for the diverging trends. It was introduced in April 2001 by the Danish government in order to expand wind power and decommission old turbines [25].

Between 2004 and 2006, less than 40 MW of new wind capacity was added in Denmark. Local opposition to proposed wind projects grew and became an increasingly important political force. Most of the increase in Danish wind power capacity in the years after 2005 was due to the construction of large offshore wind farms. Denmark is the world-leading producer of commercial turbines and the domestic use of wind power has increased rapidly up until present numbers [2].

Since 2000 Denmark has been part of the integrated Nordic energy market Nord Pool. In 2006 Denmark had a nominal exporting capacity of 5220 MW and was using around 60% of this capacity [27]. Congestion between Denmark and other Nord Pool price areas is still a frequent phenomenon. Theoretically there is a

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[1] Also [16] in their simulation study of western Denmark showed that after accounting for decreased fuel costs and higher cycling costs, a large part of the Danish wind generation and associated variations in net load were exported to the neighboring countries.

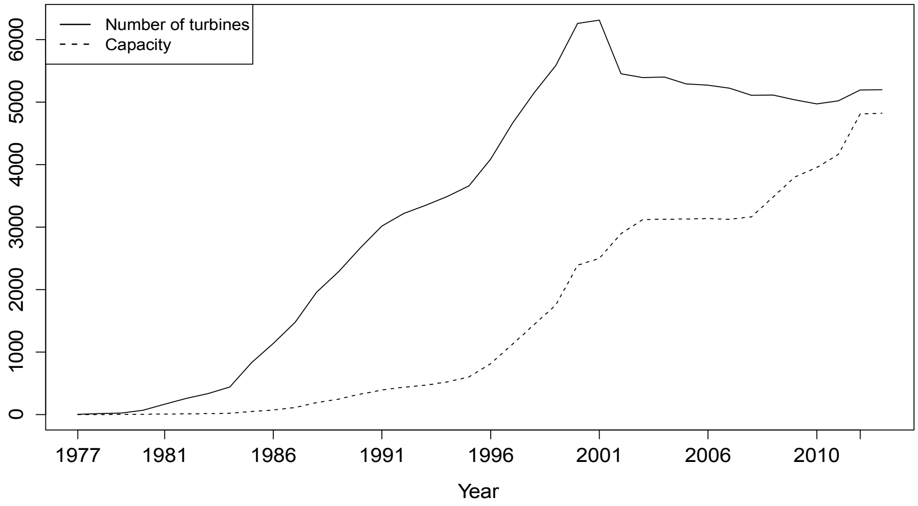

Fig. 1. Development of Danish wind power use. Note: This figure shows the number of turbines and the amount of installed wind capacity in Denmark over time. The data source is the Danish energy agency.[21] The capacity is measured in MW.

joint market clearing spot price on Nord Pool but different price zones emerge due to congestion. Denmark has two price zones, one for west Denmark and one for east Denmark. While Denmark's electricity production mix is dominated by wind and coal, hydro and nuclear dominate in the countries north of Denmark. Norway produces electricity predominantly using hydro and Sweden's share of hydro is approximately 45% [17]. Today about 30% of the electricity consumed in Denmark comes from wind power and the number is projected to increase to 50% by 2020 [12].

3. Consequences of wind production volatility

Rising amounts of wind power entering the electricity grids make the operation of the power system more complex as variations in the net load (load minus wind) increase. Wind is volatile by its nature, moreover, its almost zero marginal cost makes the intermittent generators produce power whenever they can therefore, additionally, increasing already high variability of this type of power. The difficulty of predicting accurately how much it will blow – so the uncertainty of the wind – additionally challenges the operation of the power system [13] requiring greater operational flexibility of the incumbent generators in order to meet the varying net load. According to a study by Ref. [15] maximum variations of wind output in Denmark amount to around 20% of total installed capacity within an hour, rise to 50% within 4 h and reach 80% of total installed capacity during a span of 12 h. A study of a UK power system revealed that compared with the current status the development of intermittent power will result in additional 210 start-ups per year for mid-merit Combined Cycle Gas Turbines (CCGTs) by 2030 [9]. Another study focusing on residual demand changes in UK and Germany by 2050 determined that with a 50% share of intermittent power production in electricity consumption, the maximum values of hourly load changes will double between 2011 and 2050 [1]. These variations in net load require that other types of generation have to start up and shut down more frequently.

Baseload technologies such as coal, oil and nuclear are built to withstand constant stress from being consistently used at full production. In the technical literature the stress involved with a constant high production is referred to as creep conditions [3]. Fluctuating stresses caused by temperature and pressure changes are commonly called fatigue. Fatigue typically happens when units start up and shut off production. When units not built to withstand creep conditions are cycled, this results in creep fatigue, which in turn leads to damages such as cracking and mechanical failures [22]. “Thermal shock, metal fatigue, corrosion, erosion and heat decay are common damage mechanisms that result from cycling operation” [30].

All conventional units will be impacted by wind integration to some extent. Most units are designed with minimal operational flexibility and thus, cycling will result in an increased deterioration of various components leading to more frequent forced outages [5]. However, the severity of plant cycling will not only depend on the generation mix but also on the availability of interconnection, which can potentially compensate the imbalances from wind power via exports/imports [30]. Consequences of wind volatility will not only affect Denmark itself but the whole Nord Pool as the Nordic market is well integrated. It is possible that problems with creep fatigue in Denmark have actually decreased over time, as Norway and Sweden have substantial amounts of hydro power to balance the Danish wind power, if there is enough transmission capacity, and it is possible that also in the future, in the hydro based system “the varying and partly unpredictable nature of wind” will not be an issue [20]. It may also be a case that Danish wind production is “exporting” its cycling problems to the rest of Nord Pool.

4. Data

The wind production data used in this paper come from Energinet, the Danish Transmission System Operator (TSO). Data for failures are from a collection of Nord Pool's Urgent Market Messages (UMMs). The dataset is composed of messages providing information about all unplanned outages exceeding 100 MW and lasting for more than 60 min that were recorded in the Nord Pool area. Based on the information extracted from the UMMs we are able to identify the area that is potentially going to be most affected by the event that the message provides information about. The affected area is identified by the issuer of the message. Failure data is available for generators using different fuel types. We have access to hourly data for the years 2006–2012.

In Tables 1 and 2 we report weekly data describing Danish wind production and the number of failures registered by different types of units generating electricity in Denmark and in the whole of Nord Pool. The average weekly variation in Danish wind power amounts to over 500 MW.

Table 1
Summary statistics of the standard deviation (s.d) in Danish wind production and the number of failures registered as affecting Denmark, weekly data.

	Mean	Standard dev.	Min	Max
Wind production (s.d)	594.96	222.71	76.86	1168.11
Failure	3.4	2.34	0	13
Failure coal	2.76	2.15	0	10
Failure gas	0.43	0.77	0	5
Failure oil	0.46	0.89	0	7

Note: This table presents summary statistics for Danish weekly wind production and the weekly number of new production failures registered as affecting Denmark between the 1st of January 2006 and the 31st of December 2012. Wind production is measured as the standard deviation of wind production (in MW) over a week.

Table 2
Summary statistics of the number of failures registered in Nord Pool, weekly data.

	Mean	Standard dev.	Min	Max
Failure	13.54	6.04	0	35
Failure coal	4.24	2.69	0	17
Failure gas	1.04	1.37	0	8
Failure oil	1.07	1.66	0	9
Failure biofuel	0.06	0.3	0	2
Failure nuclear	0.83	0.98	0	6
Failure hydro	5.65	3.41	0	18

Note: This table presents summary weekly statistics of the number of new production failures registered in the Nord Pool between the 1st of January 2006 and the 31st of December 2012.

In Denmark on average 3.4 failures per week have been registered during the analysed period, with the most frequent failures observed in coal-fueled units. Gas and oil-fueled units were relatively less prone to damages with on average 0.43 and 0.46 registered failures per week. The mean number of failures registered in the entire Nord Pool over a week is 13.54; with hydro failures reaching the number of 5.65 over a week.

We have also summarized our data in Figs. 2–6. In Fig. 2 the wind volatility and the number of failures in Denmark over the analysed time-period can be seen. It is important to note that the scales for both variables (wind volatility and number of failures) differ. The left-hand-side axis measures the number of failures and the right-hand-side axis shows values for wind volatility. Fig. 3 shows the corresponding variables for Nord Pool.

There is a slight increasing trend in the wind volatility, visible also in Fig. 4, where it can be observed that yearly means of the wind production volatility rise from slightly below 500 MW in 2006 to around 750 MW in 2012.

The number of reported failures for Denmark and Nord Pool over different years in the dataset are reported below (Figs. 5 and 6). In the graphs the white stripe indicates the median in a given year, the bottom and the top of each box show first and third quartiles and the whiskers indicate the lowest and highest adjacent value[3] for a given year, dots indicate outliers.

As can be observed the number of failures in Denmark does not change much over the time with median varying from 3 failures per week in 2006, by 4.50 failures in 2007 and then remaining around 3 for the reminder of the analysed period (Fig. 5). For Nord Pool the median number of failures changes from 5 failures per week in 2006 to roughly 14 failures per week in the later period (Fig. 6).[4]

5. Econometric strategy

In this paper we aim to measure how the volatility of wind power generation affects the risk of failures being reported by other power generation sources, such as oil, coal, gas, hydro and nuclear. We estimate the effects both for failures affecting Denmark (hence to a higher degree domestic production sources) and all failures reported on Nord Pool. We also estimate the effects for all fuel types together. The null hypothesis that we are testing is hence the following – *H0: the level of wind volatility does not have a statistically significant effect on the number of failures in Denmark/Nord Pool.* H0 is tested against the alternative hypothesis – *H1: the level of wind volatility does have a statistically significant effect on the number of failures in Denmark/Nord Pool.* The same H0 and H1 are formulated for each of the generation types (coal, oil, gas, hydro and nuclear). In order to test the null hypothesis against the alternative hypothesis for Denmark/Nord Pool and for the different fuel types we formulate a regression model (equation (1)) which we, like all other models in this paper, estimate using Ordinary Least Squares method, otherwise known as OLS.[5] The regression model will have the following structure:

$$Y_{wt} = \alpha + \beta V_w + \delta_t + \varepsilon_{wt} \tag{1}$$

where the dependent variable Y_{wt} is the log of the sum of failures in a particular week w and V_w is the independent variable measured as the log of the standard deviation in wind production on a particular week w. δ_t are year fixed effects in order to account for changes in the market composition over time. β is the coefficient of interest (H0: $\beta = 0$, H1: $\beta \neq 0$), α is the intercept and ε_{wt} is the error term. The observations used for calculating wind production's weekly standard deviation are on an hourly basis. Failures are also reported on an hourly basis and they are aggregated to weekly numbers.[6] Since there are some zeros in the outcome variables we transform the failure variables by adding one before we take the log. We have chosen to take the log of both the dependent and independent variables in this paper so that our results can be interpreted as elasticities.

To capture whether market integration and congestion matter for the probability of failures we estimate an expanded model in which failures (dependent variable) is explained by a set of independent variables: wind volatility, import congestion, export congestion and additional interaction variables that help to capture the joint effect of wind volatility and congestion constraints. The regression model has the following form:

$$Y_{wt} = \alpha + \beta_1 V_w + \beta_2 IC_w + \beta_3 EC_w + \beta_4 (V_w{*}IC_w) + \beta_5 (V_w{*}EC_w) + \delta_t + \varepsilon_{wt} \tag{2}$$

where Y_{wt} is the log of the sum of failures on a particular week w. V_w is the log of the standard deviation in wind production on a particular week w. IC_w is a variable for import congestion, defined as the sum of hours over a week where prices in Denmark were higher than prices in neighboring zones. EC_w is a variable for export congestion defined as the sum of hours over a week where the

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[2] http://www.ens.dk/info/tal-kort/statistik-noegletal/oversigt-energisektoren/stamdataregister-vindmoller).

[3] Adjacent values are the most extreme values within 1.5 iqr of the nearer quartile, where iqr = upper quartile - lower quartile.

[4] An initial analysis of data indicates that part of the jump is due to an increased number of hydro failures which values rise from 1.27 per week in 2006 to 5.19 in 2007 and fluctuate at that level throughout the rest of the analysed period.

[5] See for instance [26]; chapter 11 for an introduction to OLS. OLS (Ordinary Least Squares) is often also referred to as Least Squares.

[6] Doing the analysis with daily or monthly standard deviation for wind power production, and daily or monthly aggregated number of failures, gives very similar results as the results presented in this paper that are on a weekly level.

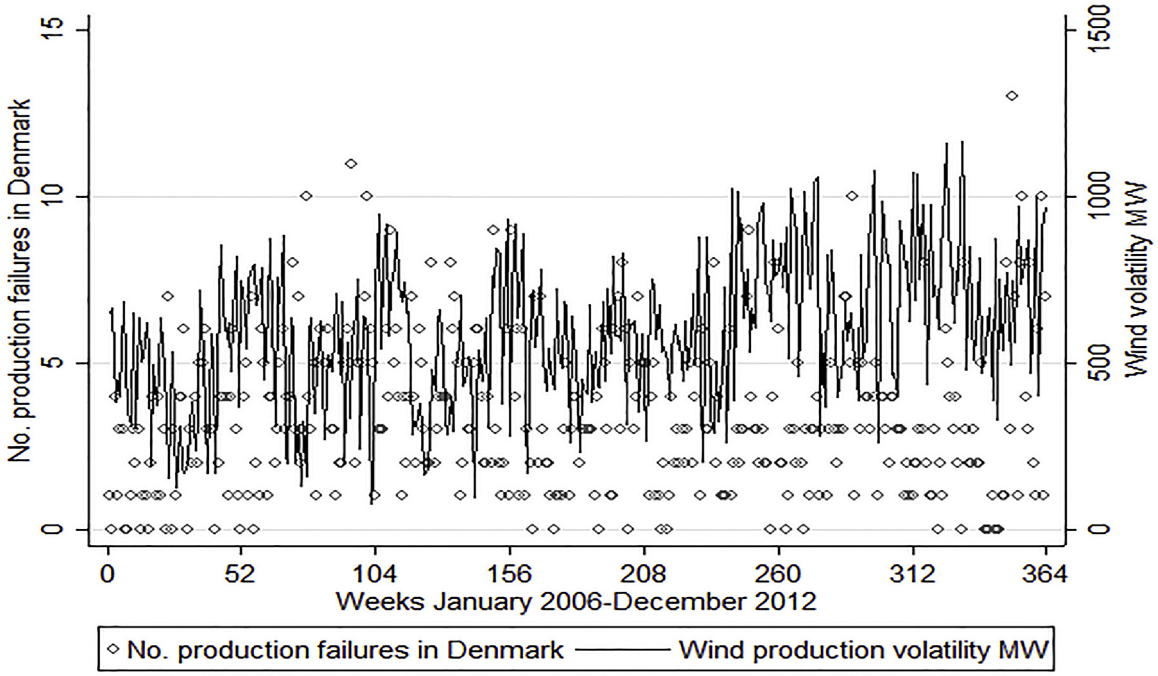

Fig. 2. Wind volatility and production failures in Denmark. Note: Fig. 2 shows wind volatility measured as a weekly standard deviation of wind production in MW and the number of production failures in Denmark.

prices in neighboring zones were higher than in Denmark. $V_w \times IC_w$ and $V_w \times EC_w$ are interaction variables for wind volatility and import/export congestion respectively. β_1, β_4, and β_5 are the coefficients of interest, as they capture the effect of wind volatility on the number of failures in Denmark/Nord Pool, as well as the integrated effect of wind volatility and import or export congestion.

Because of the negligible marginal cost of production, wind power is generated whenever it is windy, even when prices are very low [10,24]. Wind in itself is strictly exogenous, which enables us to interpret the estimates as causal effects of wind power volatility. As pointed out by Ref. [24]; there may be two cases in which wind generation is not only dependent on wind. The first case is that the system operator may order some wind generation off the market to balance supply and demand. On rare occasions in Denmark the price goes down to zero or becomes negative, which would imply that, there is a potential balancing problem in the market. The

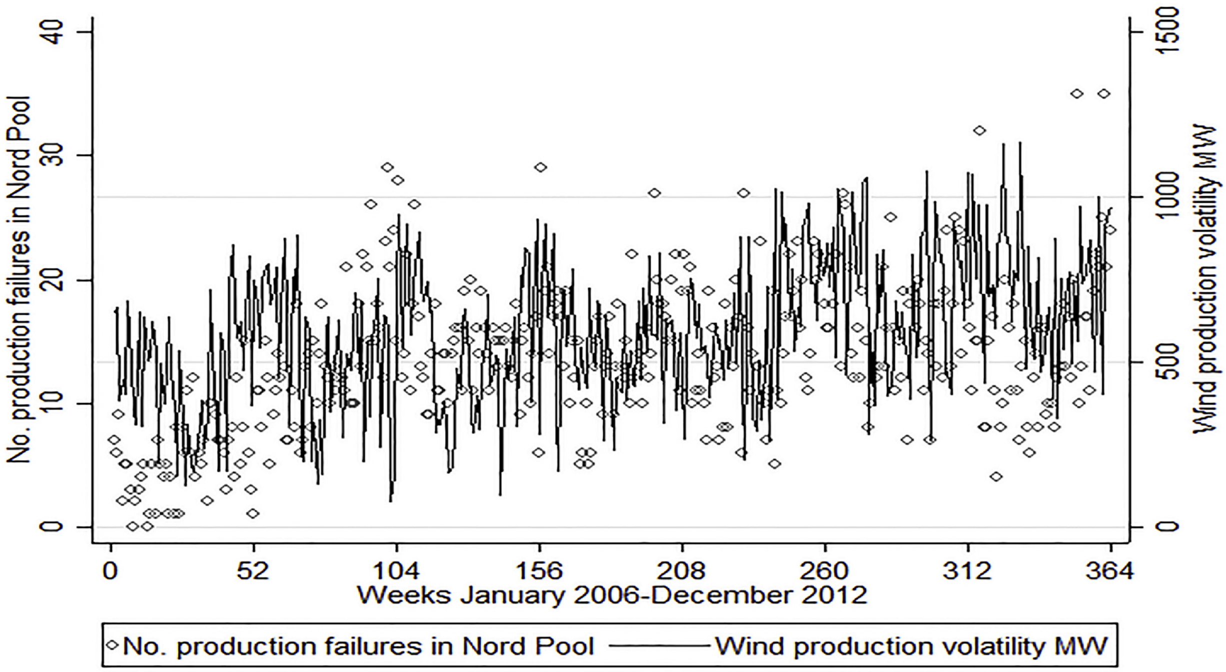

Fig. 3. Wind volatility and production failures in Nord Pool. Note: Fig. 3 shows wind volatility measured as a weekly standard deviation of wind production in MW and the number of production failures in Nord Pool.

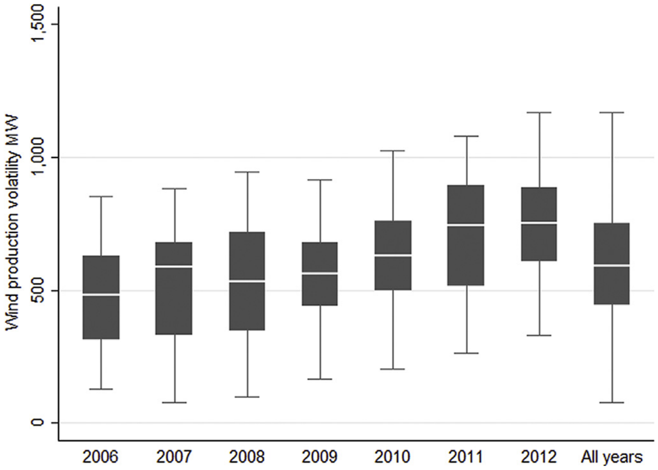

Fig. 4. Wind volatility over time. Note: This figure shows Box-and-whiskers plots of the yearly means of wind production volatility in MW (where wind volatility is measured as a weekly standard deviation of wind production). The white stripe indicates the median in a given year, the bottom and the top of each box show first and third quartiles and the whiskers indicate the minimum and maximum value obtained in the given dataset.

impact of this on the results should be marginal however. We checked how often prices drop to zero or below zero in the intraday market for the years 2010–2012. Out of 404,744 trades in that market only 0.05% were negative or zero.

A second plausible problem is that a producer that owns several generation technologies might try to influence prices by withholding wind power generation. However, wind power would, given its low marginal production cost, be the least likely type of

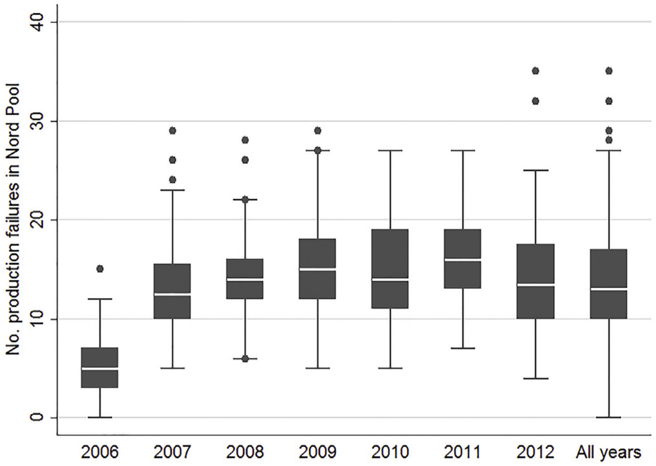

Fig. 6. Failures in Nord Pool over time.

Table 3
OLS-estimates showing the effect of wind power volatility on power generation failures in Denmark. Log-log models with time trends corresponding to equation (1).

	All failures	Gas	Oil	Coal
Wind volatility	−0.0335 (0.0692)	−0.0189 (0.0468)	0.0167 (0.0537)	−0.0546 (0.0737)
Observations	364	364	364	364
R^2	0.0725	0.0276	0.0633	0.0897

Note: Robust standard errors in parentheses. *p < 0.1, **p < 0.05, ***p < 0.01, no asterix p ≥ 0.1.

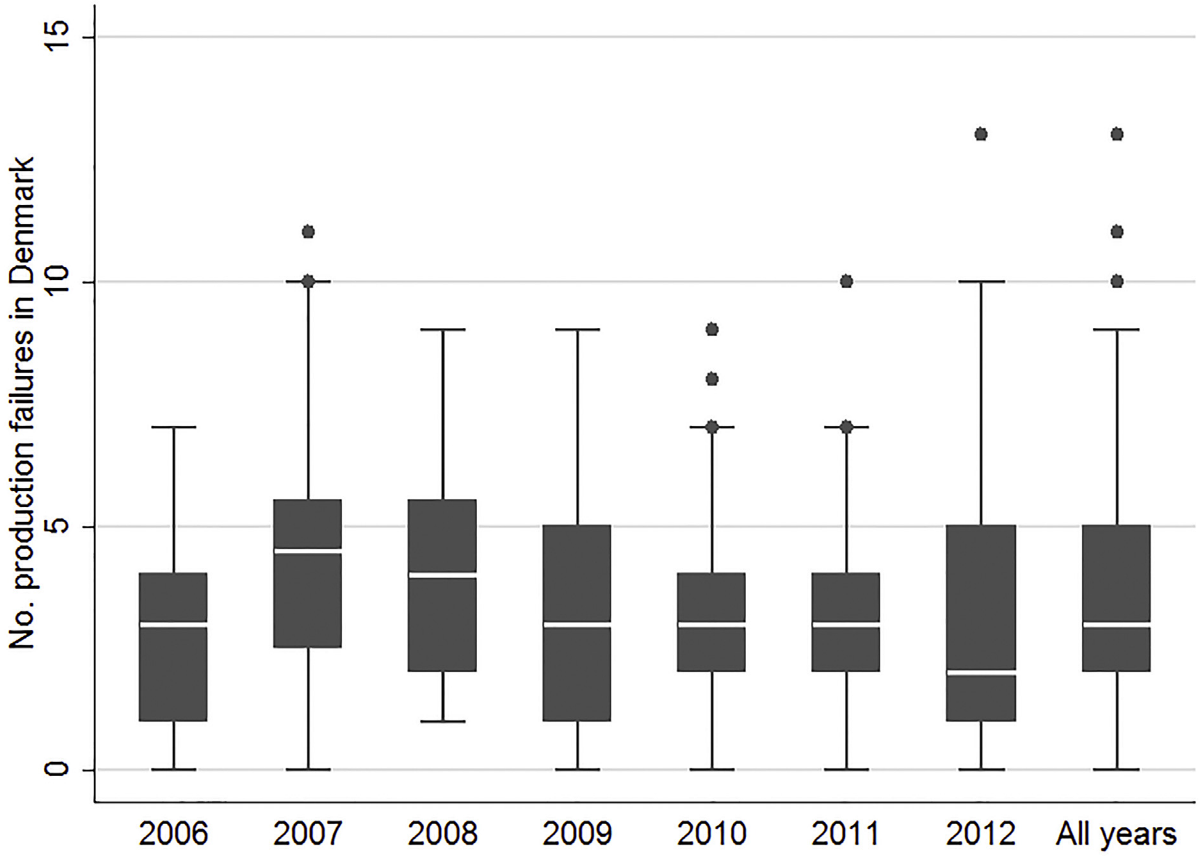

Fig. 5. Failures in Denmark over time.

Table 4
OLS-estimates showing the effect of wind power volatility on power generation failures in Nord Pool. Log-log models with time trends corresponding to equation (1).

	All failures	Gas	Oil	Coal	Hydro	Nuclear
Wind volatility	−0.00762	0.0160	0.0840	0.0163	−0.0734	−0.00162
	(0.0507)	(0.0679)	(0.0721)	(0.0659)	(0.0598)	(0.0591)
Observations	364	364	364	364	364	364
R^2	0.457	0.0881	0.381	0.121	0.487	0.0634

Note: Robust standard errors in parentheses. $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$, no asterix $p \geq 0.1$.

Table 5
OLS-estimates showing the effect of wind power volatility on power generation failures in Denmark. Log-log models with time trends corresponding to equation (2).

	All failures	Gas	Oil	Coal
Wind volatility	−0.0631	−0.0169	−0.00121	−0.0783
	(0.0860)	(0.0587)	(0.0656)	(0.0885)
Import congestion	−0.000550	0.000283	−0.000301	−0.000457
	(0.000673)	(0.000528)	(0.000524)	(0.000651)
Export congestion	−0.000616	−0.00114*	−0.000760	−0.000172
	(0.000985)	(0.000624)	(0.000721)	(0.000993)
Wind × import congestion	0.00000562	−0.00000148	0.00000315	0.00000600
	(0.00000655)	(0.00000502)	(0.00000502)	(0.00000618)
Wind × export congestion	0.00000194	0.00000772	0.00000335	−0.000000569
	(0.00000924)	(0.00000567)	(0.00000702)	(0.00000841)
Observations	364	364	364	364
R^2	0.0781	0.0393	0.0720	0.0931

Note: Robust standard errors in parentheses. $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$, no asterix $p \geq 0.1$.

Table 6
OLS-estimates showing the effect of wind power volatility on power generation failures in Nord Pool. Log-log models with time trends corresponding to equation (2).

	All failures	Gas	Oil	Coal	Hydro	Nuclear
Wind volatility	−0.0462	0.0715	0.115	−0.0364	−0.110	−0.0465
	(0.0584)	(0.0835)	(0.0866)	(0.0783)	(0.0732)	(0.0758)
Import congestion	−0.000892*	0.00044	0.000519	−0.00111*	−0.000684	−0.00101
	(0.000475)	(0.0007)	(0.000788)	(0.000580)	(0.000637)	(0.000650)
Export congestion	0.00127*	0.00043	0.000983	0.000664	0.00138*	0.000217
	(0.000664)	(0.0008)	(0.000918)	(0.000885)	(0.000747)	(0.00079)
Wind × import congestion	0.000008*	−0.0000	−0.000001	0.000008	0.000008	0.000009
	(0.000004)	(0.0000)	(0.000007)	(0.000006)	(0.000006)	(0.000006)
Wind × export congestion	−0.000009	−0.0000	−0.000005	−0.000005	−0.000008	−0.000004
	(0.00000)	(0.0000)	(0.000009)	(0.000007)	(0.000006)	(0.000008)
Observations	364	364	364	364	364	364
R^2	0.468	0.0926	0.385	0.128	0.495	0.0718

Note: Robust standard errors in parentheses; $^{***}p < 0.01$, $^{**}p < 0.05$, $^*p < 0.1$, no asterix for $p \geq 0.1$.

generation to withhold. Given good public information about installed capacity and strength of winds it would also constitute a rather transparent type of market power abuse.

In the main specifications of this paper, equations (1) and (2), we cannot capture that wind power volatility may have a more long-term effect on failure rates of other generating units due to accumulated damage over time. Furthermore, equations (1) and (2) do not capture the fact that the aggregate amount of wind volatility to which the power system is exposed depends on the sum of produced wind power, which, in turn, depends on installed wind power capacity and actual production. With the higher penetration of wind power production in the power grid, the electricity system can experience more imbalances [7], hence the aggregate production volatility the system will experience might increase.[7] Therefore, we also report regressions describing the relationship between failures for conventional power plants and the use of wind power generation in MW. We estimate the following model:

$$Y_w = \alpha + \beta MW_w + \varepsilon_w \tag{3}$$

where Y_w is the log of the number of failures per week, MW_w is the log of wind production in MW per week, ε_w is the error term and β

Table 7
OLS-estimates showing the relationship between wind power production in MW and power generation failures in Denmark. Log-log models corresponding to equation (3).

	All failures	Gas	Oil	Coal
Wind production	−0.017	0.006	0.067*	−0.042
	(0.053)	(0.034)	(0.041)	(0.055)
Observations	364	364	364	364
R^2	0.000	0.000	0.008	0.002

Note: Robust standard errors in parentheses; $^{***}p < 0.01$, $^{**}p < 0.05$, $^*p < 0.1$, no asterix for $p \geq 0.1$.

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[7] In some cases geographical spread of wind production is supposed to smooth the intermittency problems inherent to Renewable Energy Sources (RES). For that to be true the area covered by RES would need to be large. This smoothing effect is however unlikely in a comparatively small country like Denmark. Our data shows a very high correlation between wind generation in the eastern part of Denmark and wind generation in the western part of Denmark (the correlation coefficient is 0.83), as well as between offshore generation and generation on land (correlation coefficients 0.82 and 0.68 respectively for East and West Denmark.)

Table 8

OLS-estimates showing the relationship between wind power production in MW and power generation failures in Nord Pool. Log-log models corresponding to equation (3).

	All failures	Gas	Oil	Coal	Hydro	Nuclear
Wind production	0.159***	0.081	0.296***	0.017	0.118**	0.062
	(0.049)	(0.050)	(0.060)	(0.050)	(0.058)	(0.045)
Observations	364	364	364	364	364	364
R^2	0.029	0.007	0.068	0.000	0.011	0.005

Note: Robust standard errors in parentheses; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, no asterix $p \geq 0.1$.

is the coefficient of interest. Unlike the results for equations (1) and (2), the results for equation (3) do not have a causal interpretation. Since we are interested in slightly longer-term results, we do not include year fixed effects that would otherwise account for changes in the market structure and other potential sources of bias. Results from equation (3) should hence be interpretated in a purely descriptive way.

To handle potential problems with heteroscedasticity, which could bias the test statistics, we report heteroscedasticity consistent (also known as "robust") Huber-White standard errors for all results. We report our estimates in Tables 3–8 together with robust standard errors (in brackets) and asterix indicating the p-values of the estimates. According to convention we consider a result statistically significant when a p-value is 0.05 or less, i.e. when the risk of falsely rejecting the true null hypothesis is less than 5%. If there is no asterix reported next to the result, the estimate has a p-value higher than 0.1, the estimate is not statistically significant, and we cannot reject the null. In the tables we also report R^2 values. The R^2 (coefficient of determination) values indicate the proportion of variance of the dependent variable that can be explained by the dependent variables in a model. For a robustness check we repeat the analysis (equations (1)–(3)) using Poisson regression and those results are reported in the Appendix.

6. Results

In Table 3 we report the effects of wind power volatility on failure rates in Denmark for all generation types together and separately for gas generators, oil generators and coal generators. In the regressions we control for time trends by including year dummies. The results should be interpreted as the short term impact of wind volatility on failure rates expressed as elasticities. As can be seen in Table 3, we cannot reject the null hypothesis of no effects of wind power volatility on the failure rates in Denmark (the result reported in the top row of the first column is not statistically significant), similarly we cannot reject the null of no effect of wind volatility on particular types of failures: gas, oil and coal (columns 2, 3, 4 of the top row).

In Table 4 we report effects of wind power volatility on failure rates in Nord Pool. Similarly, as for Denmark we find no significant effects of wind volatility on failures for all generation types together and separately for gas generation, oil generation or coal generation. There is also no significant effect on hydro generation failures or nuclear generation failures.

In Table 5 we investigate the effect of wind power volatility on failure rates in Denmark while incorporating the effects of import and export congestion. In the regressions we control for import and export congestion and we also include variables that interact wind volatility and import/export congestion. As in Table 3 the results are consistently insignificant, except for the effect of export congestion on gas generation. This effect is however very small in magnitude and only significant at a 10% level.

The effects of wind volatility on failure rates in Nord Pool, while incorporating effects of export and import congestion, are shown in Table 6. As for Denmark the effects are consistently insignificant and small in magnitude.

In Tables 7 and 8 we present results for model specifications corresponding to equation (3) in the econometric strategy section of this paper. That is, in Table 7, we report the descriptive relationship between Danish wind power production in MW and failure rates in Denmark for all power generators together and separately for different kinds of power plants. In Table 8 regressions showing the relationship between wind power production and failure rates for different generators in Nord Pool are reported.

The descriptive regressions for Denmark show that there is no significant relationship between wind production in MW and failures except for oil-fueled power plants. An increase of 1% in wind production is associated with a 0.07% increase in number of oil generation failures. If wind power production would increase with 100% the number of oil generation failures would increase with 7%, which would still be substantially less than one additional failure per week compared to the mean.[8]

The descriptive results for the entire Nord Pool are reported in Table 8 and show that for certain types of units there are some significant effects of the wind production in MW on the number of failures. A 1% increase in wind production is associated with a 0.16% increase in the overall number of production failures in Nord Pool, which is again less than one additional failure per week. Oil production seems to be affected the most with a 0.3% increase in the number of failures associated with a 1% increase in the wind power production. Significant results are also observed for hydro-fueled plants with a 0.12% increase in the number of failures.

The results from the Poisson regressions lead to similar conclusions and are presented in Tables A1–A6 in the Appendix.

7. Conclusion

The results show that in the short run there is no systematic evidence that wind production volatility has an adverse effect on other power generators' risk of failure. The estimates presented in Tables 3–6 capture how wind production volatility within a particular week affects failure rates, and these results can have a causal interpretation due to the fact that wind volatility is exogenous. All the reported results in these tables are both small in magnitude and statistically insignificant, both for Denmark and for the rest of Nord Pool. It is also clear from the estimates that export and import congestion does not have a significant impact on how wind volatility affects failure rates in the short run.

Further we estimate descriptive relationships between wind production in MW over time and number of failures for different power sources. For Denmark there are no statistically significant results except for oil-fueled power plants, where an increase in wind power production with 1% is associated with 0.067% increase in failures, which is a small effect. For Nord Pool there are slightly more pronounced statistically significant effects for all failures, oil

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[8] If on average in Denmark we have 3.4 failures per week, then an increase of 0.07% in the number of failures would effectively increase the number of failures by 0.002 per week – substantially less then one additional failure.

and hydro.

To conclude, this paper provides evidence that wind power volatility does not increase the risk of failures in other power generators within a short time frame such as a week. This is true for both Denmark and the Nord Pool area. Descriptive regressions also show that for Denmark there is no correlation between utilized wind power in MWs and risk of failures, whereas for Nord Pool there are some significant effects for oil and hydro. The lack of significant effects for Denmark but existing effects for Nord Pool might indicate that Denmark has invested more in maintenance to meet the increased damage done by cycling, or that comparatively more pressure is put on generators in other parts of Nord Pool as a consequence of cycling. However, more research is needed to establish a causal link between wind power production in MW (or wind power production as a share of total production) and the risk of failures over time.

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Appendix A

Table A1
Poisson estimates showing the effect of wind volatility on failure rates in Denmark.

	All failures	Gas	Oil	Coal
Wind volatility	−0.0000544	−0.0000347	0.0000852	−0.000140
	(0.000164)	(0.000444)	(0.000434)	(0.000189)
Observations	364	364	364	364

Note: Robust standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.0$, no asterix $p \geq 0.1$.

Table A2
Poisson estimates showing the effect of wind volatility on failure rates in Nord Pool.

	All failures	Gas	Oil	Coal	Hydro	Nuclear
Wind volatility	0.0000501	0.000139	0.000323	0.000106	−0.000202	0.0000674
	(0.000102)	(0.000323)	(0.000287)	(0.000149)	(0.000145)	(0.000293)
Observations	364	364	364	364	364	364

Note: Robust standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$, no asterix $p \geq 0.1$.

Table A3
Poisson estimates showing the effect of wind volatility on failure rates in Denmark.

	All failures	Gas	Oil	Coal
Wind volatility	−0.000116	0.0000120	0.0000607	−0.000215
	(0.000200)	(0.000518)	(0.000479)	(0.000231)
Import congestion	−0.000566	0.000587	−0.000971	−0.000857
	(0.000742)	(0.00189)	(0.00205)	(0.000796)
Export congestion	−0.000657	−0.00508	−0.00462	0.0000907
	(0.00117)	(0.00342)	(0.00364)	(0.00117)
Wind × import congestion	0.00000645	−0.00000312	0.00000587	0.00000909
	(0.00000715)	(0.0000172)	(0.0000184)	(0.00000767)
Wind × export congestion	0.00000204	0.0000304	0.0000193	−0.00000414
	(0.0000114)	(0.0000263)	(0.0000320)	(0.0000104)
Observations	364	364	364	364

Note: Robust standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$, no asterix $p \geq 0.1$.

Table A4
Poisson estimates showing the effect of wind volatility on failure rates in Nord Pool.

	All failures	Gas	Oil	Coal	Hydro	Nuclear
Wind volatility	−0.00000367	0.000370	0.000419	−0.0000131	−0.000268	−0.000115
	(0.000122)	(0.000375)	(0.000331)	(0.000180)	(0.000168)	(0.000385)
Import congestion	−0.000617	0.000597	0.00103	−0.00120*	−0.000599	−0.00213
	(0.000477)	(0.00166)	(0.00150)	(0.000621)	(0.000661)	(0.00154)
Export congestion	0.00137**	0.00115	0.00101	0.000983	0.00183**	0.000339
	(0.000623)	(0.00205)	(0.00186)	(0.000906)	(0.000847)	(0.00197)
Wind × import congestion	0.00000502	−0.0000163	−0.00000584	0.00000822	0.00000736	0.0000197
	(0.00000425)	(0.0000164)	(0.0000125)	(0.00000640)	(0.00000594)	(0.0000137)
Wind × export congestion	−0.00000975	−0.0000182	−0.00000532	−0.00000797	−0.0000119	−0.00000963
	(0.00000628)	(0.0000183)	(0.0000192)	(0.00000770)	(0.00000774)	(0.0000198)
Observations	364	364	364	364	364	364

Note: Robust standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$, no asterix $p \geq 0.1$.

Table A5
Poisson estimates showing the relationship between of wind power production in MW and power generation failures in Denmark.

	All failures	Gas	Oil	Coal
Wind_production	−5.95e-08 (0.000000476)	0.000000147 (0.00000112)	0.00000143 (0.00000105)	−0.000000245 (0.000000519)
Observations	364	364	364	364

Note: Robust standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$, no asterix $p \geq 0.1$.

Table A6
Poisson estimates showing the relationship between of wind power production in MW and power generation failures in Nord Pool.

	All failures	Gas	Oil	Coal	Hydro	Nuclear
Wind_production	0.00000114^{***} (0.000000283)	0.00000105 (0.000000797)	0.00000408^{***} (0.000000775)	0.000000263 (0.000000407)	0.000000729^{*} (0.000000400)	0.00000163^{**} (0.000000703)
Observations	364	364	364	364	364	364

Note: Robust standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$, no asterix $p \geq 0.1$.

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