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Renewable energy and negative externalities: The effect of wind turbines on house prices[☆]

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ABSTRACT

In many countries, wind turbines are constructed as part of a strategy to reduce dependence on fossil fuels. In this paper, we measure the external effect of wind turbines on the transaction prices of nearby houses. A unique Dutch house price dataset covering the period 1985–2011 is used, as well as the exact location of all wind turbines that were built in the Netherlands. Using a difference-in-differences methodology we find a 1.4% price decrease for houses within 2 km of a turbine. There is also evidence for anticipation effects a few years before placement of a turbine. The effect is larger for taller turbines and in urban areas. Especially the first turbine built close to a house has a negative effect on its price.

1. Introduction

The world's primary demand for renewable energy has increased from 1.1 billion tons of oil equivalent (Gtoe) in 1990 to 1.7 Gtoe in 2010 and is expected to grow to 3.1 Gtoe in 2035 (IEA, 2012). The production of clean electricity - either through renewable energy sources or nuclear power - is high on the political agenda of many countries. Besides hydro energy, wind energy is one of the most important sources of renewable energy accounting for 8% of renewable electricity production in 2010. Its share in production is expected to increase to 24% by 2035 (IEA, 2012).

Wind energy is produced by wind turbines. The number of wind turbines is currently about 225,000 worldwide (GWEC, 2012). At the end of 2012, the total wind power capacity was 283,000 MW (39% of capacity is located in Europe), an increase of 16% compared to a year earlier (GWEC, 2012). Some of the wind turbines are placed in large wind parks (wind farms), some of them offshore, but there is also an increasingly large number of turbines located close to urbanized areas, especially in countries with space constraints. Given that wind turbines make noise, reduce the quality of views on open space, and cast shadows on nearby properties, we would expect to see a clear negative economic impact as a result of wind turbine construction. There is indeed substantial anecdotal evidence that homeowners are strongly opposed to the construction of wind turbines nearby their own houses, because of the proclaimed negative effects on housing values (e.g. NRC, 2013; Trouw, 2013).

The aim of this paper is to examine the effect of wind turbines on house prices. We use a highly detailed housing transactions dataset from the Netherlands covering the period 1985 to 2011. Using data on all wind turbines placed in the Netherlands since 1980, we calculate the distance from every property that is sold to the nearest wind turbine. We employ a difference-in-differences approach to identify the effect of the placement of a wind turbine on the value of nearby properties. We aim to accurately measure the effect of distance, the impact of wind turbine characteristics (e.g. height, diameter of the blades, 'shadow' areas, direct view),

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and the effect of multiple treatments. Although we will discuss the effect of direct view, households may frequently visit other parts of the neighborhood (e.g. for shopping, to take a walk), so we would expect that this 'indirect' view effect is also an important determinant of the decrease in housing values as a result of wind turbine construction.

We address selection and endogeneity concerns. In particular, wind turbines are not randomly allocated across space, but are mainly constructed in rural areas with lower house prices. Our difference-in-differences strategy with detailed zip code fixed effects deals with all time-invariant unobserved locational differences. To the extent that there is additional unobserved variation, such as unobserved trends that are correlated with the location of wind turbines, we check the robustness of our results by including location-specific time trends and by using comparable locations relatively close to wind turbines as control group. We experiment with different control groups located closely and further away from wind turbines and, to measure the geographic extent of the treatment effect, show results based on different sets of distance bands around wind turbines. Moreover, the Dutch government has recently announced a list of locations where new wind turbines are to be constructed. We show results conditional upon this set of locations to further address endogeneity concerns.

Our key findings can be summarized as follows. After the construction of the first wind turbine house prices within a 2 km radius are on average 1.4% lower than prices in comparable neighborhoods that have no nearby wind turbines. The negative treatment effect seems to hold under a variety of different setups. However, it is important to emphasize that there is considerable spatial and temporal variation in the treatment effect. For example, the effect is highest close to a wind turbine (–2.6%) and there is not much evidence for an effect beyond 2 km, which leads us to conclude that the effect of wind turbines on house prices is a relatively local effect. In addition, the effect of wind turbines on house prices is not necessarily immediate or permanent. One may expect that there are anticipation/announcement effects or ex-post learning effects. Furthermore, because of search and transaction costs, housing markets may need time to adjust to changes in the physical environment (Case and Shiller, 1989; Wheaton, 1990; McMillen and McDonald, 2004). We find that about two years before the placement of a turbine, house prices are already statistically significantly lower than prices in comparable neighborhoods, suggesting that households anticipate price decreases before the actual placement of turbines. We do not find strong evidence for adjustments of the house price effect after placement of a wind turbine. The long-run effect after ten years is –2.2%. We also find that the effect is stronger for larger turbines, and in residential/urban areas.

The results in this paper do not imply that we should not construct wind turbines, but that we should carefully determine where to place those turbines. If wind turbines are placed close to (future) urban areas our findings suggest that the external economic costs of wind turbines are substantial. These costs should be taken into consideration when building wind turbines. We calculate that, given a range of assumptions, the external costs of a wind turbine are at least 16% of its construction cost. Moreover, we find that the total loss in housing values of owner-occupied housing in the Netherlands – based on the current stock of wind turbines and a –1.4% price effect – is 900 million Euros, which is considerable.

This is not the first study that examines the effect of wind turbines on property values. Sims et al. (2008) and Carter (2011) investigate the effect of a single wind farm on house prices in the UK and US, respectively. Hoen et al. (2010) examine the effect on house prices of 24 wind farms located in 9 states in the US. A recent study by Lang et al. (2014) looks at several individual wind turbines located in Rhode Island. Moreover, Vyn and McCullough (2014) examine the impact of a windfarm in Ontario on house prices. None of these studies find a statistically significant effect of wind farms on house prices. On the other hand, Ladenburg and Dubgaard (2007) do find evidence that household in Denmark are willing to pay 122 Euros per year to increase the distance of an off-shore wind park from 8 to 50 km. In addition, Gibbons (2015) finds that house prices are 5 to 6% lower within 2 km of a visible wind park in the UK. Our paper also belongs to a small but growing literature on the local effects of energy production (see Davis, 2011 for the negative effects of power plants; Des François, 2002 for the effects of power lines, Bohlen and Lewis, 2009 for the effects of hydropower, and Muehlenbachs et al., 2012 for the effects of shale gas developments).

In terms of research design, our study uses a similar setup as Lang et al. (2014); Vyn and McCullough (2014), and Gibbons (2015) by examining the effect of wind turbine proximity and visibility using a difference-in-differences approach. There are, however, also some important differences. Both the Lang et al. (2014) and Vyn and McCullough (2014) papers find that there is no statistically significant effect of wind turbines on nearby property values. It is easy to mistakenly conclude that there is no effect, while the results are actually inconclusive (see, amongst other, The Guardian, 2014). Lang et al. (2014), for example, find a negative 4% coefficient on house prices within 1–2 miles from a wind turbine (pre-construction) and a small negative post-construction effect. The repeat sales estimates show a higher post-construction effect of up to –2.4%. However, they focus on only 10 turbine sites in Rhode Island, most of which are single turbine sites. Similarly, Vyn and McCullough (2014) use data on a single wind farm in Canada and find no statistically significant effects, although the point estimates are negative and sizeable. By comparison, we use about 1800 onshore wind turbines in our analysis, which allows us to more accurately estimate the average treatment effect.[1] Moreover, by combining these data with a panel dataset containing 2.2 million transactions over a period of 25 years, we are also able to adequately control for preexisting trends and to answer the important question whether the effect on house prices is actually persistent over time.

In terms of research findings, our results are in line with Gibbons (2015). One particular concern is that Gibbons (2015) uses the distance to the center of several wind farms in the UK, rather than the distance to the nearest individual wind turbine. This setup cannot be used to measure the considerable heterogeneity in the treatment effect (e.g. as a result of differences in turbine height, blades, shadow, and uncertainty about the location of wind turbines). Moreover, Gibbons (2015) in some specifications finds an effect on house prices up to 14 km using the difference between houses with and without wind turbine visibility. This finding seems unrealistic.[2] It suggests that part of the treatment effect is most likely the result of unobserved heterogeneity. Instead, the estimated effect based on our analysis is about one third of the effect of Gibbons (2015) and the effect also turns out to be very local (within 2 km of a turbine).

[1] Previous studies have often used a relatively low number of transactions because houses are typically not closely located near wind turbines. Hoen et al. (2011), for instance, hypothesizes that there might be effects relatively close to wind turbines – the observations they use are unfortunately predominately located between 1.6 to 4.8 km from a wind turbine. The average distance to a wind turbine in Carter (2011) is 12 miles. Sims et al. (2008) do have a considerable share of their data within half a mile of a wind turbine, but they only have 120 observations in total. Vyn and McCullough (2014) only have 143 properties within 5 km of a wind turbine.

[2] To illustrate, a turbine of 100m 14 km away has a perceived height of about 0.7 cm (100/14,000). Features of the landscape, such as trees, hills, etc., are likely to hide the view of such a distant object.

The remainder of this paper is structured as follows. Section 2 provides a discussion on renewable energy policy and wind turbines. Section 3 contains the methodology, which is followed by a description of the data in Section 4. In Section 5 we report the results and Section 6 concludes.

2. Renewable energy policy and wind turbines

As a result of the Kyoto Protocol, many countries have set targets to reduce their greenhouse gas emissions. The Kyoto Protocol has been active for the period 2008–2012 and, after the United Nations Framework Convention on Climate Change (UNFCCC) Conference in 2012, it has been extended (in limited form) until 2020. As of 2015 a new protocol will be developed (for a discussion, see IEA, 2013).

The policy focus on sustainable development is reflected in renewable energy policies around the world. In the United States, there are production tax credits to stimulate the production of renewable energy and regulations regarding renewable portfolio standards for electricity suppliers. China aims to produce 15% of energy in 2020 using nuclear or renewable energy sources (IEA, 2012). The European Union issued the Renewable Energy Directive in 2009, which stipulates that the renewable energy part of energy consumption is to increase to 20% by 2020. The European Union leaves it up to its member states how to achieve this goal (European Commission, 2013).

Many countries have responded to the policy focus on renewable energy by increasing their wind power capacity. China, for instance, aims to increase its wind power capacity from 62 to 200 gigawatts by 2020 (IEA, 2012). Wind power production has been particularly popular in the European Union. Currently, about 39% of the wind power capacity is located in the European Union, 26% in China, and 20% in the United States (IEA, 2012). Although wind power capacity is increasing, at current rates the European member states will not meet their required targets (European Commission, 2013).

In the Netherlands, the country to which our data refer, the goal set by the Renewable Energy Directive is to increase the share of renewable energy to 14% (European Commission, 2013).[3] In 2013, a widely supported agreement was reached (Energy Agreement) to increase the wind power capacity on sea from 1000 to 4450 MW. Also, the amount of wind power capacity on land needs to increase from 2160 to 6000 MW (SER, 2013). Because the current generation wind turbines produce about 3 MW per turbine, the increase in wind power capacity on land is equivalent to about 1280 wind turbines (1150 on sea). Relative to the current stock of about 1800 onshore wind turbines (which produce on average much less than 3 MW per turbine), this implies a massive increase in the number of turbines. Not all turbines will be placed offshore because constructing turbines at sea is relatively costly. It also requires the construction of an offshore power grid implying additional investments. The question is where to exactly place these turbines, especially those turbines that are to be placed on land, since the Netherlands is a relatively small country in terms of land area and a country with one of the highest population densities in the world.

3. Empirical methodology

In this paper, we focus on estimating the average treatment effect after the *first* wind turbine is constructed within d km of a property. We adopt a difference-in-differences methodology to estimate this effect. Let p_{it} be the price of property i in year t and w_{it-1} is an indicator variable that equals one in the years *after* the first wind turbine is placed within d km of property i.[4] v_i is the treatment group dummy, which controls for possible selection effects: wind turbines are typically placed in areas where house prices are low. The treatment group includes properties that were treated at least once during the sample period. As such, v_i does not change over time. The treatment indicator w_{it-1} captures the interaction of v_i with a before/after treatment dummy. This dummy is absorbed by the year (and month) fixed effects θ_t. To summarize, the difference-in-differences model we estimate is:

$$\log p_{it} = \alpha w_{it-1} + \gamma v_i + \theta_t + \epsilon_{it}, \tag{1}$$

where α captures the average treatment effect and ε_{it} is an identically and independently distributed error term. As mentioned, we assume that $d = 2$. To validate this choice, we will also investigate whether wind turbines have any measurable effect beyond 2 km.

It is important to note that we rely on two sources of identifying variation to measure the treatment effect. First, we compare the price change before/after placement of a wind turbine for those houses within versus outside a 2 km radius of a wind turbine (standard difference-in-differences). Furthermore, because not all wind turbines are constructed at the same time, we also compare price changes of properties in areas that have received a wind turbine with areas that did not yet receive a wind turbine at that particular point in time, but will receive one at a future date.

To control for differences in the housing composition of the control and treatment group, we subsequently estimate the following hedonic price model:

$$\log p_{it} = \alpha w_{it-1} + \gamma v_i + \beta x_{it} + \theta_t + \epsilon_{it}, \tag{2}$$

where x_{it} is a set of housing characteristics including the size of the house, the number of rooms, house type dummies, construction year dummies, and indicators for garage, garden, maintenance quality, central heating, and whether the house is listed as cultural heritage.

Wind turbines are not randomly distributed across space. They may for instance be placed in less attractive areas, which may lead to a selection effect. Because there are many unobserved factors (e.g. zoning regulations) that characterize the treatment area and affect house prices it is preferable to include more detailed location fixed effects. We include location fixed effects at the six-digit (PC6) zip code level. In the Netherlands, PC6 areas encompass about half a street (on average 15 households), which is comparable to a census block in the United States. Note that the treatment group dummy is excluded in the specifications that follow since it is almost perfectly collinear with the PC6 fixed effects. We also show estimates based on repeat sales in the sensitivity analysis. The fixed effects essentially deal with all unobserved time-invariant spatial attributes that may cause the construction of wind turbines and may be correlated with ε_{it} (Van Ommeren and Wentink, 2011). This lead to

$$\log p_{it} = \alpha w_{it-1} + \beta x_{it} + \eta_j + \theta_t + \epsilon_{it}, \tag{3}$$

where η_j is a fixed effect for PC6 location j.

One may argue that the current identification strategy does not adequately deal with differences in unobserved local trends (e.g. changes in local building restrictions) that are correlated with the placement of wind turbines. To account for such trends, we also estimate Eq. (3) using a restricted sample: we compare houses within the treatment area with houses outside the treatment area but within a short distance (3 km) of a wind turbine based on

[3] The share of renewable energy in the Netherlands was 2.4 percent in 2005 and 3.8 percent in 2010. For France the target is 23 percent and it is 18 percent for Germany. The target ranges from 11 percent for Luxembourg to 49 percent for Sweden (European Commission, 2013).

[4] We use the year after construction as starting date to avoid measurement error (we only know the construction year, not the exact construction date).

the final stock of wind turbines (i.e., in 2012). This will lead to a much smaller sample, but addresses the problem of unobserved time trends.[5] Moreover, although the PC6 areas are relatively small in size, rural PC6 areas are likely larger than the typical PC6 area, such that we again not adequately control for location. We will discuss the treatment effect in urban and rural areas in more detail in Section 5.5.

The effect of wind turbines may become less pronounced when properties are located further away from a wind turbine. We therefore allow the treatment effect to differ over different distances from the nearest wind turbine:

$$\log p_{it} = \sum_{z} \alpha_z w_{itz} + \beta x_{it} + \eta_j + \theta_t + \epsilon_{it}, \tag{4}$$

where w_{itz} equals one after the first wind turbine is placed and the property is located within the corresponding 250 m band z. In essence, we divide the 3 km circle around a wind turbine into different zones, where we use the 2.5–3 km zone as the reference category. The cut-off value for d is determined by examining at which point the effect on house prices α_z become statistically insignificant relative to the reference category. This procedure is, therefore, based on the assumption that the price effect for the reference category is zero. We will (i) show that using a 3–5 km reference group does not change the distance profile, and (ii) using the full sample and a distance profile up to 8 km – at which point it is very unlikely that an onshore wind turbine will have any price effect – will lead to the same cut-off value of 2 km.

Another important issue is that we would expect the effect to differ before and after the turbine is constructed. The placement of wind turbines is usually announced some years before construction. It is likely that house prices already incorporate this information, which implies that α may be an underestimate of the causal effect if we do not take into account anticipation effects. On the other hand, it might also be the case that because of search and transaction costs, housing markets may need time to adjust to changes in the physical environment (Case and Shiller, 1989; Wheaton, 1990; McMillen and McDonald, 2004; Redfearn, 2009), which may also lead to ex post adjustment effects. To account for anticipation and adjustment effects, we therefore estimate the following specification:

$$\log p_{it} = \sum_{s=t-T}^{t-1} \alpha_s w_{is} + \sum_{s=t}^{t+T} \alpha_s w_{is} + \beta x_{it} + \eta_j + \theta_t + \epsilon_{it}, \tag{5}$$

where w_{is} equals one when the property is treated, based on a wind turbine constructed in year s, and zero otherwise. Hence, the first term on the right hand side captures anticipation effects of wind turbines that will be constructed at a future date, whereas the second term captures adjustment effects after the wind turbine has been constructed. We use a window of ten years (so $T=10$), as we do not expect that anticipation effects or adjustment effects are important or measurable beyond this time window. Note that if anticipation effects would be absent $\alpha_s = 0\ \forall s < 0$, and if there are no adjustment effects then $\alpha_s = \alpha\ \forall s \geq 0$. Although we do not have exact announcement dates, specification (5) still allows us to test whether the pre-existing trends in house prices are equal between the control and treatment group.

One may still question some of the identifying assumptions we make, some of which are inherent to the difference-in-differences approach (see Bertrand et al., 2004; Abadie, 2005; Donald and Lang, 2007). We therefore will show results using a variety of different fixed effects, control/treatment groups, time-varying parameters, estimation methodologies (repeat sales, turbine density), and sets of control variables. For a more detailed discussion, we refer to Section 5.4.

[5] In the sensitivity analysis, we also show estimates where we control for municipality trends and neighborhood-specific trends. In addition, we experiment with different local control groups.

Table 1
Descriptive statistics: Wind turbines.

	Mean	Std. dev.	Min	Max
Axis height (*m*)	59.496	20.231	21.000	135.000
Diameter of rotor blades (*m*)	55.997	21.963	11.000	127.000
Capacity (*MW*)	1.260	0.953	0.015	7.500
Onshore	0.949	0.219		
Construction year	2002	5.507	1982	2012
Number of observations		1898		

Notes: This table contains descriptive statistics on all wind turbines constructed between 1982 and 2012. The axis height and diameter of the rotor blades is only available for, respectively, 1793 and 1893 observations.

4. Data

The analysis in this paper is based on two main datasets. The first dataset contains the exact location of all wind turbines in the Netherlands from 1982–2012 and is obtained from www.windstats.nl. For each wind turbine we know the exact location, the axis height, the diameter of the rotor blades, the installed capacity, the manufacturer, and importantly, the construction year.

Table 1 contains the descriptive statistics for the wind turbine dataset. There are 1898 wind turbines in the Netherlands in 2012. The average axis height is 59 m, with a minimum of 21 m and a maximum of 135 m. The average diameter of the rotor blades is 56 m. The average capacity is 1.3 MW. The construction costs per wind turbine are about 1.7 million Euros.[6] A typical wind turbine has a life span of 20 years or even longer (if it is properly maintained). About 95% of wind turbines are placed on land (96 turbines are placed offshore). The main manufacturer of wind turbines in the Netherlands is the Danish company Vestas. They constructed 1128 (59.4%) of the wind turbines in the Netherlands.[7] Wind turbines are often owned by Dutch energy companies NUON, Eneco, and Essent.

The construction of small wind turbine parks (<100 MW) is decided upon by the provinces and municipalities, typically on initiative of a Dutch energy company. The location of large wind turbine parks (>100 MW) is chosen by the national government in consultation with the provinces. There is no predefined exact timeline wind turbine construction plans have to conform to, although there are typically several stages (including getting the right permits and actually building the turbines). Although we do not have data on the exact announcement date of each and every wind turbine park, it is evident that the construction of a wind turbine park – from initiative to final construction – can take years. A typical example is given by the planned construction of a wind turbine park ('Wieringermeer') in one of the Northern provinces in the Netherlands. The potential scenarios for constructing a wind turbine park were announced in June 2010. After several information meetings for residents, the environmental report was released in October 2014. The construction is expected to start in December 2017. In this example, it would be reasonable to expect price adjustment prior to the construction of a wind turbine. The extent to which this actually occurs and how many year in advance the treatment effect adjusts, however, is mainly an empirical question.

Fig. 1 shows the spatial distribution of wind turbines across the Netherlands. Wind turbines are predominately clustered in

[6] Construction costs are proportional to the installed capacity of the turbine (as a rule of thumb, about 1325 Euros per kW installed capacity, see ECN, 2008).

[7] This includes the turbines placed by NEG Micon. In 2004, NEG Micon and Vestas merged, which resulted in the creation of one of the largest wind turbine manufacturing companies in the world.

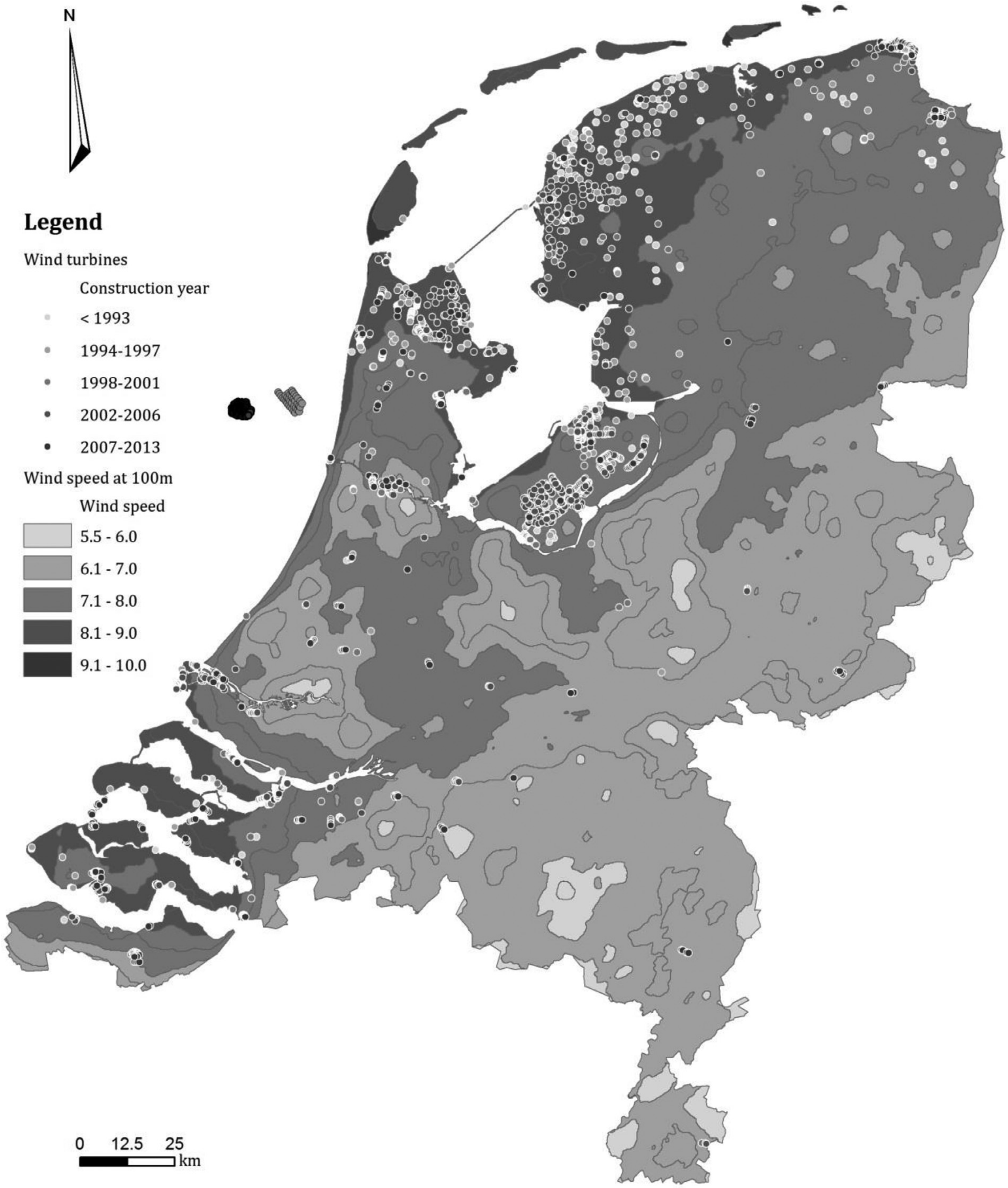


Fig. 1. Spatial distribution of wind turbines in the Netherlands. *Notes:* We also depict the wind speed at 100 m above ground level, as calculated by KEMA Netherlands B.V. and Geodan IT in 2005.

Flevoland (27.6%), a mostly rural area in the center of the Netherlands. The early wind turbines were mainly constructed in the northern part of the Netherlands. The northern part is not so urbanized as, for instance, the western part of the Netherlands. In addition, the wind speed – also depicted in Fig. 1 – is relatively high in the northern part of the Netherlands. Other concentrations of wind turbines can be found in the coastal province of Zeeland, where also high average wind speeds are recorded. More recently, two offshore wind parks have become operational (in 2006 and 2008). These offshore wind parks are located more than ten km from the shore. In this paper, we will focus on the external effects of wind turbines placed on land.

The second dataset we use in this paper covers about 70% of all housing transactions in the Netherlands from 1985–2011 and is obtained from the Dutch Association of Realtors (NVM). For more than two million observations we know the transaction price of each property, as well as a host of housing characteristics, such as the size in square meters, the construction year, number of rooms and variables that indicate the presence of a garage, garden and central heating. Because the exact location of each property is

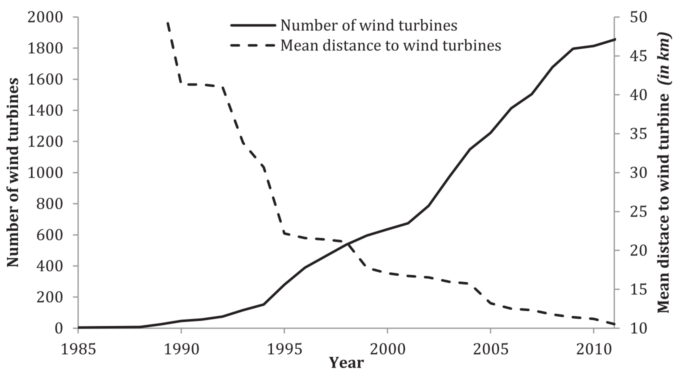


Fig. 2. Number of wind turbines in the Netherlands.

Table 2
Descriptive statistics: housing transactions.

	Mean	Std. dev.	Min	Max
Price (€)	193,960	114,713	25,000	1,000,0000
Price per m² (€)	1654	750	500	5000
Distance to nearest wind turbine *(km)*	20.523	27.706	0.081	315.606
Wind turbine in 2012 ≤ 2km	0.068			
Wind turbine ≤2 km	0.041			
Density wind turbines per km² ≤2 km	0.006	0.040	0	1.989
Size in m²	118.089	37.765	26.000	250.000
Rooms	4.333	1.317	0	25.000
Apartment	0.271			
Terraced	0.319			
Semi-detached	0.281			
Detached	0.130			
Garage	0.338			
Garden	0.652			
Maintenance quality – good	0.863			
Central heating	0.900			
Listed (as cultural heritage)	0.006			
Construction year < 1945	0.248			
Construction year 1945–1959	0.074			
Construction year 1960–1970	0.161			
Construction year 1971–1980	0.186			
Construction year 1981–1990	0.152			
Construction year 1991–2000	0.130			
Construction year ≥2000	0.049			
Year of observation	2002	5.896	1985	2011
Number of observations		2,219,088		

known, we can calculate the straight-line distance of each property to the nearest wind turbine.

Fig. 2 shows that the number of wind turbines has been steadily increasing since the construction of the first wind turbine in 1982. Before 1990 only 25 wind turbines were constructed. Not surprisingly, the average distance of a property to the nearest wind turbine has been decreasing over the years. The average distance only decreased marginally after 2005, while the number of wind turbines has increased with 34% during the same period.

Table 2 presents descriptive statistics for the housing transactions dataset.[8] The average distance to the nearest wind turbine is about 20.5 km. We consider observations within 2 km of a (future) wind turbine as part of the treatment group. In the Appendix, we also plot the transactions over space (see Figs. A1 and A2). Table 2 shows that 6.8% of observations are in the treatment group and 4.1% of the housing transactions are located within a 2 km radius of a wind turbine after it has been constructed. Note that the share of treated observations is lower than the number of observations in the treatment group because about 40% of the transactions in the treatment group took place before the construction of a wind turbine.

Table 3 reports the descriptive statistics for observations within and outside a 2 km radius of a wind turbine in 2012, which essentially shows the differences between the treatment and the control group. Note that the distance to the nearest wind turbine is much higher than 2 km in the treatment group, because observations that are not yet treated are more than 2 km away from the nearest wind turbine at that moment. As expected, wind turbines are placed in areas with a relatively low house price (i.e. rural areas). In the regression analysis, any differences in average house prices across locations are captured by the PC6 fixed effects. There are 161,065 unique PC6 areas in our dataset with, on average, 14 transactions per PC6. There are 15,456 PC6 areas for which we only have one transaction (0.7% of the total number of observations). Given the other differences in housing characteristics between the treatment and control group, it may be important to also control for housing characteristics in the empirical analysis. There are, for example, relatively a lot of detached houses and a low share of apartments close to wind turbines.

To increase our understanding on the different sources explaining the external effect of wind turbines, it is important to examine the spatial distribution of the observations (see Fig. 3) within a 2 km radius of a wind turbine after it has been constructed (90,000 transactions, about 80,000 houses). There are few observations that are within 500 m of a wind turbine (only about 1.6% of the 90,000 transactions). In part, this reflects zoning restrictions. It also implies that the main effect we will be measuring is not the effect of noise. As a rule of thumb, wind turbine noise is typically deemed to be a problem within four to five times the axis height (Dooper et al., 2010). Since the typical (current generation) of wind turbines have an axis height of about 100 m (note that the average is much lower), the effect of noise on house prices should predominately occur within a 500 m radius. It turns out that at about 400 to 500 m distance a turbine makes about 40 to 50 dB noise, which is about the amount of noise a refrigerator makes.

A further issue is the effect of shadow and flickering of the blades on house prices. As a rule of thumb, this effect is only regarded as a problem within twelve times the rotor diameter (Dooper et al., 2010).[9] The typical rotor diameter of current wind turbines is 90 m (again, the average is much lower), which suggests that this effect is mainly relevant within about 1 km of a turbine. If a turbine creates more than about six hours of shadow, it is required to have a 'stand-still' feature installed to reduce the amount of flickering (Dooper et al., 2010). We will report some results about the price effect of shadow in Section 5.5.

We argue that we predominantly measure the effect of direct and indirect views of wind turbines. The effect of shadow and noise mainly occurs within a 1.0 km radius from a wind turbine. Fig. 3 suggest that the majority of observations are, however, outside a 1 km radius. Outside this 1 km radius the effect on house prices is probably a view effect. Because the Netherlands is a flat country, a wind turbine is often highly visible from many different locations close to a wind turbine, although the direct view from a house might be obstructed by other buildings. Because households may frequently visit other parts of the neighborhood (e.g. for shopping, to take a walk), we would expect that the 'indirect' view effect is an important determinant of the decrease in housing values as a result of wind turbine construction. We will show some results about the effect of a direct and indirect view in the empirical analysis.

[8] We exclude transactions with prices that are above €1.0 million or below €25,000 or a square meter price below €500 or above €5,000. Furthermore, we exclude transactions that refer to properties smaller than 25m^2 or larger than 250m^2. These selections comprise less than one percent of the observations.

[9] A typical turbine creates flickering at a rate of 1.5 Hz. Flickering between 2.5 and 14 Hz is considered to be a health risk (Dooper et al., 2010).

Table 3
Descriptive statistics: treatment and control group.

	<2 km of a wind turbine *in 2012*				>2 km of a wind turbine *in 2012*			
	Mean	Std. dev.	Min	Max	Mean	Std. dev.	Min	Max
Price (€)	180,183	102,471	25,865	1,000,000	194,959	115,486	25,000	1,000,000
Price per m² (€)	1552	659	500	5000	1661	756	500	5000
Distance to nearest wind turbine *(km)*	9.903	24.690	0.081	297.776	21.293	27.754	1.785	315.606
Wind turbine in 2012 ≤2km	1.000				0.000			
Wind turbine ≤2km	0.604				0.000			
Density wind turbines per km² ≤2km	0.093	0.125	0.000	1.989	0.000	0.000	0.000	0.000
Size in m²	116.075	35.597	27.000	250.000	118.235	37.913	26.000	250.000
Rooms	4.361	1.240	0.000	24.000	4.331	1.323	0.000	25.000
Apartment	0.197				0.276			
Terraced	0.367				0.315			
Semi-detached	0.284				0.280			
Detached	0.152				0.128			
Garage	0.322				0.339			
Garden	0.708				0.647			
Maintenance quality – good	0.856				0.863			
Central heating	0.885				0.901			
Listed (as cultural heritage)	0.005				0.006			
Construction year < 1945	0.276				0.246			
Construction year 1945–1959	0.068				0.074			
Construction year 1960–1970	0.143				0.163			
Construction year 1971–1980	0.167				0.187			
Construction year 1981–1990	0.153				0.152			
Construction year 1991–2000	0.139				0.130			
Construction year ≥ 2000	0.055				0.049			
Year of observation	2002	5.839	1985	2011	2002	5.900	1985	2011
Number of observations	149,939				2,069,149			

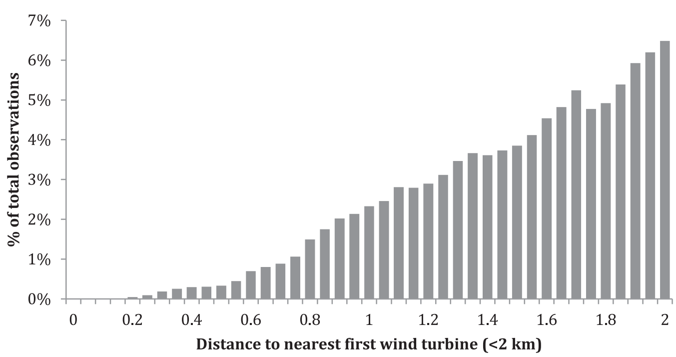


Fig. 3. Distance to wind turbines within 2 km, after construction.

5. Results

The results section is organized as follows. We first present our baseline estimates for the average treatment effect. We then elaborate on the exact radius of the treatment effect and examine whether anticipation and adjustment effects are important (Sections 5.2 and 5.3, respectively). Section 5.4 checks robustness of the results regarding different identifying assumptions. Then, we look more closely at further heterogeneity in the treatment effect in Section 5.5. Finally, we discuss the total loss in housing values as a result of the construction of wind turbines in the Netherlands relative to construction cost and CO_2 gains in Section 5.6.

5.1. Average treatment effect

Table 4 contains the regression estimates based on Eqs. (1)–(5).[10] Column (1) reports the regression estimates of Eq. (1), the standard difference-in-differences (DID) model. The results in column (1) suggest that areas within a 2 km distance from a wind turbine (after construction) have on average 6.6% lower house prices in comparison with areas that do not have a wind turbine located nearby.[11] In column (2) we add housing characteristics as additional control variables. The treatment effect is very similar in magnitude (–6.1%) as the previous estimate. The results also suggest that wind turbines are placed at locations where house prices are about 2.8% lower. This selection effect together with the treatment effect contributes to the idea that wind turbines have a strong effect on house prices. This price effect, however, is not necessarily causal. In column (3), we add PC6 location fixed effects (see Eq. (3)). Note that the treatment versus control group dummy is essentially perfectly collinear with the fixed effects and is therefore omitted from the regression model. By controlling for unobserved time-invariant locational attributes, the effect of wind turbines is much smaller. According to this model, the treatment effect is –1.2%.

There might still be other unobserved traits, like changes in zoning regulations, which might affect the estimates. Consequently, we compare house price changes between the treatment group and the control group, implying that we only select observations that are within 3 km of a wind turbine in 2012. The results are reported in column (4). House prices decrease by 1.4% after a wind turbine is constructed. This is most likely a conservative estimate for at least two reasons. First, when there are some effects of wind turbines beyond 2 km, the estimated coefficient will be an underestimate. We will discuss the geographical extent of the negative external effects of wind turbines in Section 5.2. Second, when anticipation effects are important and the effect is not immediate, the average treatment effect will also be an underestimate. Anticipation (and adjustment) effects will be discussed in Section 5.3.

[10] Bertrand et al. (2004) argue that standard errors in difference-in-difference estimation are too small when outcomes are serially correlated. We therefore use clustered standard errors at the 4-digit zip code level (about the size of a neighborhood). We experimented with standard errors clustered at either the 6-digit zip code, municipality, or wind turbine ID level. Our main conclusions remain unchanged.

[11] The marginal effects throughout this paper are calculated as $\exp(\alpha) - 1$.

Table 4
Baseline regression results: the effect of wind turbines on house prices

	(1)	(2)	(3)	(4)	(5)	(6)
	Classical DID	Housing characteristics	PC6 fixed effects	Control group 2–3km	Geographical extent	Dynamic response
Wind turbine ≤2km	−0.0682***	−0.0626***	−0.0123**	−0.0144**		
	(0.0252)	(0.0190)	(0.005)	(0.006)	See Fig. 4	See Fig. 5
Wind turbine in 2012 ≤2km	−0.0365	−0.0284**				
	(0.0225)	(0.0142)				
House size *(log)*		0.8566***	0.5961***	0.5762***	0.5762***	0.5764***
		(0.0104)	(0.0042)	(0.0088)	(0.0088)	(0.0088)
Rooms		0.0076***	0.0161***	0.0195***	0.0195***	0.0195***
		(0.0014)	(0.0003)	(0.0009)	(0.0009)	(0.0009)
Terraced		−0.1142***	0.0396***	0.0511***	0.0512***	0.0510***
		(0.0114)	(0.0036)	(0.0084)	(0.0084)	(0.0084)
Semi-detached		−0.0743***	0.1004***	0.1044***	0.1045***	0.1043***
		(0.0121)	(0.0036)	(0.0080)	(0.0080)	(0.0080)
Detached		0.0950***	0.3258***	0.3223***	0.3223***	0.3222***
		(0.0142)	(0.0043)	(0.0103)	(0.0103)	(0.0103)
Garage		0.0956***	0.0987***	0.1046***	0.1046***	0.1046***
		(0.0032)	(0.0010)	(0.0022)	(0.0022)	(0.0022)
Garden		−0.0016	0.0069***	0.0061	0.0061	0.0061
		(0.0024)	(0.0020)	(0.0049)	(0.0049)	(0.0049)
Maintenance quality		0.1070***	0.1000***	0.1036***	0.1035***	0.1035***
		(0.0027)	(0.0009)	(0.0022)	(0.0022)	(0.0022)
Central heating		0.0959***	0.0746***	0.0829***	0.0829***	0.0826***
		(0.0033)	(0.0013)	(0.0025)	(0.0025)	(0.0025)
Listed		0.2398***	0.0604***	0.0773***	0.0774***	0.0769***
		(0.0288)	(0.0055)	(0.0112)	(0.0112)	(0.0111)
Construction year 1945–1959		−0.0810***	−0.0218***	−0.0078	−0.0077	−0.0078*
		(0.0118)	(0.0022)	(0.0047)	(0.0047)	(0.0047)
Construction year 1960–1970		−0.1504***	−0.0328***	−0.0083	−0.0082	−0.0083
		(0.0126)	(0.0024)	(0.0056)	(0.0056)	(0.0056)
Construction year 1971–1980		−0.1565***	−0.0010	0.0242***	0.0242***	0.0242***
		(0.0118)	(0.0024)	(0.0056)	(0.0056)	(0.0056)
Construction year 1981–1990		−0.0829***	0.0371***	0.0647***	0.0648***	0.0647***
		(0.0118)	(0.0027)	(0.0060)	(0.0060)	(0.0060)
Construction year 1991–2000		0.0028	0.1058***	0.1341***	0.1342***	0.1340***
		(0.0122)	(0.0037)	(0.0068)	(0.0068)	(0.0068)
Construction year ≥ 2000		0.0398***	0.1513***	0.1881***	0.1881***	0.1879***
		(0.0126)	(0.0042)	(0.0095)	(0.0095)	(0.0095)
Housing characteristics (16)	No	Yes	Yes	Yes	Yes	Yes
Year and month fixed effects (37)	Yes	Yes	Yes	Yes	Yes	Yes
PC6 fixed effects	No	No	Yes	Yes	Yes	Yes
Only obs. ≤ 3 km of wind turb. in 2012	No	No	No	Yes	Yes	Yes
Number of observations	2,219,088	2,219,088	2,219,088	357,745	357,745	357,745
Adjusted R^2	0.3632	0.7381	0.9243	0.9231	0.9232	0.9232

Notes: The dependent variable is the logarithm of house price. The indicator 'wind turbine ≤2km' is one the first time a wind turbine is constructed (year after construction and all subsequent years) within 2 km of a property. Standard errors are clustered at the PC4 level and in parentheses.. *, **, ***, 10%, 5%, 1% significance, respectively.

Finally, the effects of the control variables on house prices are plausible and have the expected signs once we include PC6 fixed effects and, hence, control for time-invariant spatial unobservables that are potentially correlated with housing characteristics. Larger houses are more expensive. Detached houses are much more expensive than apartments, semi-detached and terraced houses. Well-maintained properties and properties with central heating also have higher house prices.

5.2. Geographical extent

Up to now, we used a cut-off value of 2 km to examine the treatment effect. To verify whether this is a valid choice, we let the treatment effect depend on distance (see Eq. (4)). In particular, we include a set of dummy variables for each 250 m (up to 2.5 km) and compare the results relative to those observations outside a 2.5 km radius but still within a 3 km radius. Fig. 4 reports the results (see Table 4, column (5) for the coefficient estimates of the control variables).

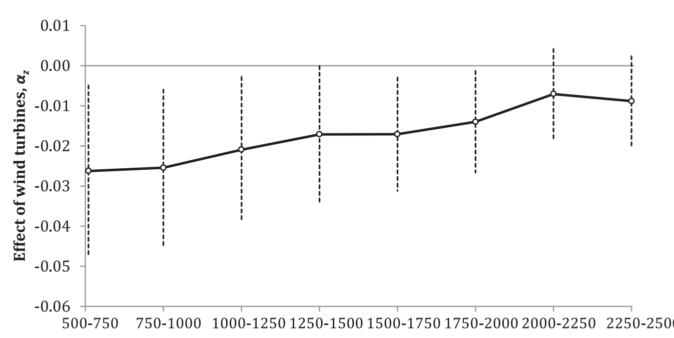


Fig. 4. Distance profile treatment effect. *Notes:* The dots represent conditional averages for a given distance band (e.g. 500–750 m, 750–1000 m, etc.). The vertical dashed lines represent 95% confidence intervals. The reference category consists of houses that are located further away than 2.5 km (but within 3 km) of a wind turbine. The effect for the category < 500 is not depicted, the effect is positive, small, and statistically insignificant.

Fig. 4 shows that the treatment effect is −2.6% at a 500–750 m distance from a turbine and it gradually decreases to about −1.4% at 1750–2000 m, after which the effect becomes smaller than one percent and statistically insignificant at the five percent signif-

Fig. 5. Anticipation and adjustment effects. *Notes:* This figure depicts the difference in house price changes between the control (2–3 km of a turbine) and treatment group (within 2 km of a turbine) in years to/after placement of a wind turbine. The vertical dashed lines represent 95% confidence intervals.

icance level. The effect below 500 m (not reported) is positive, small, and statistically insignificant (it has a very large confidence interval), due to the low number of observations in this category. The effect might also be positive because land owners typically receive financial compensation for turbines placed on their lands. The results in Fig. 4 suggest that most of the previously estimated average treatment effect is the result of a relatively high number of observations further away from wind turbines (see Fig. 3). This translates into smaller confidence intervals when distance to the nearest wind turbine increases. The results do not necessarily imply that there is no effect beyond 2 km distance from a turbine, but that the effect is most likely so small that we cannot reject the null hypothesis that there is no effect. Consequently, it seems plausible to use a 2 km radius as the relevant treatment area throughout this study.

In Section 5.4, we will also show some results using different sizes of the treatment and control area. In addition, Figs. A4 and A5 in the Appendix provide supplementary evidence for the distance profile based on a 3–5 km control group (the price effect for this control group is more likely to be zero) and an 8 km distance profile. These figures support our finding that the effect of wind turbines becomes statistically insignificant after 2 km. Moreover, it may be argued that the distance profile is caused by correlation with unobserved time-varying characteristics of the location, or because the implicit prices of housing characteristics are time-varying. To investigate this issue further, we produced two additional distance profiles, one with municipality×year fixed effects and another by including time-varying marginal prices (also interacting the year fixed effects with the treatment group dummy). The results are presented in Fig. A6 in the Appendix. It is shown that the spatial decay patterns are similar. Nevertheless, the specification with municipality×year fixed effects suggests that the treatment effect is statistically insignificant after 1250 m, while the specification with time-varying marginal prices suggests that the effect is important until 2500 m. Hence, although there is some variation in the distance profile (depending on different assumptions), our baseline estimate where we use a threshold of 2 km still seems to make sense.

5.3. Anticipation and adjustment effects

House prices may already decrease before a wind turbine becomes operational. It might also be the case that housing markets slowly incorporate new information, leading to adjustment effects in prices after the construction of a wind turbine. We therefore estimate a model that decomposes the treatment effect before and after the construction of a wind turbine (see Eq. (5)). Fig. 5 reports the results. The coefficients of the control variables are reported in Table 4, column (6).

The results in Fig. 5 seem to indicate that anticipation effects are indeed important. House prices are already statistically significantly lower (1.7%) two years before the placement of a wind turbine. Importantly, the effect earlier than two years before placement of a turbine is not statistically significantly different from zero. About 9 to 10 years before the placement we find an unexpected statistically significant positive effect. Hence, if anything, turbines might have been placed in areas with positive price trends 9 to 10 years in advance. Because wind turbines are heterogeneous (e.g. in terms of size, whether they are placed in a wind turbine park, etc.), the procedures to come from proposal to construction are very heterogeneous as well. Hence, we cannot exactly identify (the timing of the) anticipation effect because we do not have information on exact announcement dates. At least, our results seem to be in line with the idea that there are some anticipation effects present. The coefficients two years before construction, one year before, and the construction year itself are statistically significantly different from each other, but only at the 10% significance level (*F*-value of 2.4). When we exclude observations up to three years before construction from our baseline regression, to make sure that we address potential anticipation effects, this increases the average treatment effect to −1.7%.

Until four to five years after construction the effect decreases to about −3.5%. This seems to imply that there is a gradual adjustment in house prices. In the long term, the effect converges to −2.2%. The long-term effect is higher than the baseline estimate of −1.4% (see Table 4, column (4)). It is observed that the coefficients of the latter years are only statistically significant at the 10% level. This is mainly due to the fact that we have relatively few observations more than 8 years after the construction of a wind turbine, so that the effect of interest is less precisely estimated. The effect in the long-term (≥10 years) may be a bit lower than in the medium-term, because in the long-term we identify the effect based on older wind turbines, which are usually smaller and therefore have less pronounced effects on house prices (as we will show in Section 5.5). In addition, it may be that there is some learning or sorting effect going on. Note, however, that the coefficients after construction are not statistically significantly different from each other (*F*-value of 1.2). Hence, we have to conclude that we do not find conclusive evidence of adjustments effects after construction of a wind turbine.

One may argue that treatment areas (having a turbine within 2 km in 2012) are declining in popularity and price, regardless of the installation of turbines. We have checked for this in the sensitivity analysis (Section 5.4) by including time-varying marginal prices and by interacting the year fixed effects with the treatment group dummy. In addition, Fig. A7 shows the anticipation and adjustment effects in this case. It becomes clear that the pattern we find is almost identical to Fig. 5, the long-term effect becomes even stronger in magnitude and statistical terms. Moreover, we also estimated a response profile with interaction effects between the response profile and a dummy variable based on the distance from a wind turbine (<1 km versus 1 and 2 km). These interaction effects are statistically insignificant (*F*-value of 0.53). Hence, there does not seem to be much spatial heterogeneity in the anticipation and adjustment effects.

5.4. Identification revisited

To identify the causal effect of wind turbines on house prices, we include PC6 fixed effects and only use observations that are within 3 km of a wind turbine in 2012. The identifying assumption is that any remaining unobservable time-varying factors are not correlated with the treatment effect. Furthermore, we assume that preferences for housing characteristics are fixed over time. To investigate the validity of these and other assumptions in more detail, we have done several robustness checks. In Table 5 we report the sensitivity of the results with respect to the inclusion of more detailed fixed effects and time-varying preferences. The second set of robustness checks in Table 6 focuses on the composition of the control and treatment groups. In general, our initial findings seem to be fairly robust in terms of both sign and magnitude. The lowest estimate of the average treatment effect is −0.7% and the highest −3.1%.

First, there may be unobserved PC6 time trends or municipality time trends that are not captured by the year fixed effects but are correlated with the treatment effect. Because our data spans a long time period (more than 25 years), we might expect that most unobservable factors are changing over time. To address this issue, we control for PC6-decade trends by including fixed effects for each PC6×decade combination (1985–1990, 1991–2000, 2001–2011). We have also estimated a specification with municipality-specific linear time trends, and a specification with municipality×year fixed effects. Moreover, we show the results of a specification including additional neighborhood characteristics. The coefficient estimates are reported in Table 5, columns (1)–(4).

The results in column (1) indicate that the effect of wind turbines on house prices is −0.8%, but it is still statistically significant at the five percent significance level. The fact that the effect is somewhat lower than our baseline estimate (see Table 4, column (4)) is not too surprising, given that part of the treatment effect is absorbed by the PC6×decade fixed effects. We also estimated a specification with municipality-specific time trends. Column (2) suggests that after including those trends the treatment effect is still −1.2%. The results in column (3) are based on a model with municipality×year fixed effects. The results indicate that turbines have a −0.7% effect on house prices, although the treatment effect is only statistically significant at the 10% significance level. Again, the average effect is likely an underestimate as we do not take into account anticipation effects.

In Table 5, column (4), we use additional data on neighborhood (PC6) characteristics to further address the issue of omitted time-varying neighborhood traits. The demographics of the population living near turbines sites may change over time. When the willingness to pay for turbines is heterogeneous among the population, the estimated coefficients may change over time (see Bayer et al., 2007). We have gathered data from Statistics Netherlands on population density, the share of young population (<25 years), elderly population (65 years or older), and foreign population, household size, percentage land use that is residential (reference category), industrial, infrastructure, open space, or water, (log) distance to the nearest highway ramp, and the (log) distance to the nearest train station. These variables are time-varying, but are only available from 1996 onwards. The descriptive statistics of these variables are stated in Table A1 in the Appendix. When including these variables, the effect of wind turbines on house prices hardly changes. It is still −1.5% and highly statistically significant.[12]

A restrictive assumption in hedonic regressions based on long time-series is that the implicit prices of housing characteristics are assumed to be constant over time, which is unlikely to be true in practice. To relax this assumption, we add interaction effects between housing characteristics (and also the month fixed effects) and year fixed effects. The results are reported in column (5). The treatment effect is −1.7%, which is very much in line with our main results.

[12] Before 1996, the extra control variables are fixed to their 1996 values. Excluding the values before 1996 results in a statistically significant treatment effect of −0.9 percent.

Table 5
Sensitivity analysis: identification revisited

	(1) PC6×decade fixed effects	(2) Municipality× year trends	(3) Municipality× year FE	(4) Extended control set	(5) Time-varying marginal prices	(6) (5)+Treatment group×year	(7) Repeat sales	(8) PC4 fixed effects	(9) Apartments excluded
Wind turbine ≤2km	−0.0080**	−0.0119***	−0.0069*	−0.0149***	−0.0168***	−0.0159***	−0.0195***	−0.0101**	−0.0101*
	(0.0040)	(0.0041)	(0.0040)	(0.0051)	(0.0050)	(0.0050)	(0.0067)	(0.0049)	(0.0053)
Housing characteristics (16)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year and month fixed effects (37)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PC6 fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
PC6×decade fixed effects	Yes	No	No	No	No	No	No	No	No
Municipality×year trends	No	Yes	No	No	No	No	No	No	No
Municipality×year FE	No	No	Yes	No	No	No	No	No	No
Control variables×year FE	No	No	No	No	Yes	Yes	No	No	No
Additional neighborhood controls	No	No	No	Yes	No	No	No	No	No
Obs. ≤3 km of wind turbine in 2012	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	357,745	357,745	357,745	357,745	357,745	357,745	60,890	357,745	270,440
Adjusted R^2	0.9296	0.9320	0.9300	0.9249	0.9274	0.9336	0.8385	0.8845	0.9283

Notes: The dependent variable is the logarithm of house price. The indicator 'wind turbine ≤2km' is one the first time a wind turbine is constructed (year directly after construction and all subsequent years) within 2 km of a property. Standard errors are clustered at the PC4 level and in parentheses. *, **, ***, 10%, 5%, 1% significance, respectively.

Table 6
Sensitivity analysis: control groups

	(1)	(2)	(3)	(4)	(5)	(6)
	Only obs. ≤2 km and 3–5km	3 km circle, 3–5 km control group	Distance control vs. treatment ≤1km	Only obs. ≤2km	Only obs. in wind plan areas	Only obs. ≤3 km & in wind plan areas
Wind turbine ≤2km	−0.0233***	−0.0184***	−0.0139**	−0.0096	−0.0151	−0.0320
	(0.0075)	(0.0056)	(0.0059)	(0.0059)	(0.0163)	(0.0196)
Housing characteristics (16)	Yes	Yes	Yes	Yes	Yes	Yes
Year and month fixed effects (37)	Yes	Yes	Yes	Yes	Yes	Yes
PC6 fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Obs. ≤3 km of wind turbine in 2012	No	Yes	Yes	No	No	Yes
Obs. ≤2 km of wind turbine in 2012	Yes	Yes	Yes	Yes	No	Yes
Obs. 3–5 km of wind turbine in 2012	Yes	Yes	No	No	No	No
Obs. with dist. control-treat. ≤2km	No	No	Yes	No	No	No
Obs. in wind plan area	No	No	No	No	Yes	Yes
Number of observations	544,897	752,703	293,038	149,936	5606	2685
Adjusted R^2	0.9234	0.9229	0.9256	0.9229	0.8903	0.9062

Notes: The dependent variable is the logarithm of house price. The indicator 'wind turbine ≤2km' is one the first time a wind turbine is constructed (year directly after construction and all subsequent years) within 2 km of a property. Standard errors are clustered at the PC4 level and in parentheses. *, **, ***, 10%, 5%, 1% significance, respectively.

In column (6) we further relax the assumption of identical general economic trends between the treatment and control group by including interactions effects of the treatment group indicator with the year fixed effects, on top of the time-varying marginal prices of housing characteristics. Recall that there are differences in the timing of the placement of turbines, enabling us to identify the differential trend between the treatment and control group. Again, this hardly seems to influence the results: the coefficient estimate suggests that a wind turbine near a house leads to a price decrease of 1.6%. In Fig. A7 we extend this specification and also allow for anticipation and adjustment effects. The pattern of anticipation and adjustment effects is still remarkably similar to the one presented in Fig. 5. It, therefore, seems unlikely that the treatment effect (average or anticipation/adjustment) is the result of unobserved trends.

In the main analysis we included PC6 fixed effects to control for all unobserved time-invariant characteristics of a location. These PC6 areas are very small, although they may be a bit larger in rural areas because of low population densities. Alternatively, we may estimate a repeat sales model where we include property-specific fixed effects. If the base model with PC6 fixed effects adequately controls for unobserved locational quality, we should not expect to see a large difference between the base estimate and the repeat sales estimate (assuming there is no sample selection bias as a result of using repeat sales). Column (7) in Table 5 shows that the repeat sales estimate is fairly close to the baseline estimate of −1.4%: the estimated treatment effect is −1.9% and statistically significant. By contrast, one may argue that including PC6 fixed effects is overly restrictive, because they may capture part of the treatment effect (see Abbott and Klaiber, 2011). Consequently, in column (8) we add PC4 fixed effects (about the size of a neighborhood). The treatment effect is a bit smaller (−1.0%) than the baseline estimate but still statistically significant.

Finally, in column (9), Table 5, we re-estimate the baseline specification but include only single-family housing. Apartments can be quite heterogeneous in terms of both quality and location. Although the identification strategy adequately addresses these issues, we cannot control for other confounding factors such as the fact that apartments located at higher floor levels are more likely to have unobstructed views on a wind turbine. Indeed, the average effect for single-family housing is a bit lower (−1.0%) and only statistically significant at the 10% significance level. We will discuss the effect of a direct view in more detail in the next section.

In a second set of specifications, we check robustness of our results with respect to the definition and composition of the control and treatment group. Table 6 reports the results. As mentioned in Section 5.1, we might underestimate the treatment effect if there is still an effect in the control group area (also see Fig. 4, Section 5.2). Instead of using a 2–3 km radius as the control group area, we use those observations that are located between 3–5 km distance from a wind turbine in 2012. Further away from a wind turbine it seems plausible to assume that the treatment effect is zero. The coefficient in column (1) suggests that the treatment effect is −2.3%, which is indeed higher than the baseline estimate of −1.4%.[13] Alternatively, we also used a larger treatment area based on a 3 km radius. The treatment effect then becomes a bit larger (−1.8%). These findings suggest that the baseline estimate of −1.4% (based on a 2 km treatment area and a 2–3 km control group) is a somewhat conservative estimate.

There may still be a considerable distance between those houses that belong to the control group and the treatment group if we are just comparing transactions within a 2 km radius of a wind turbine and transactions 2–3 km away. To deal with this issue we have also estimated a model with an additional restriction imposed on the control/treatment group. In particular, the distance between the control and nearest treatment group observation must be smaller than 1 km. Although the sample size in Table 6, column (3), decreases by about 18% (relative to our baseline model). We still find an effect of −1.4%, which is statistically significant at the 5% significance level.

Furthermore, the estimates of the treatment effect have been based on the difference in price trends between the control and treatment groups *and* the difference in timing of wind turbine construction. In column (4), Table 6 we show estimates of the model that only uses observations within a 2 km radius of a wind turbine. That is, the treatment effect is identified using the difference in timing of wind turbine construction only. In this case, we find a treatment effect of about −1.0% (p-value of 0.101). Hence, although we cannot make strong statements, the results seem to support our initial findings as the point estimate is close to the baseline estimate.

Finally, one might argue that the locations in which the first generation wind turbines were placed (e.g. the northern part of the Netherlands) are considerably different from areas that have experienced a surge in the number of wind turbines more recently (e.g. Flevoland). If unobserved traits are substantially different and these unobservable trends are correlated with the placement of

[13] We also examined whether house prices have been higher (in comparison to the rest of the Netherlands) within a 3-5 km radius of a turbine after it has been constructed to measure a potential redistribution effect of housing demand on house prices. We did not find statistically significant evidence for such an effect.

wind turbines, our results may be biased. To address this issue, we use a recently announced plan to construct wind turbines in the Netherlands. In March 2014, the areas where future wind turbines are going to be placed were announced by the Dutch government. These areas are, among others, in Groningen, Flevoland, and near the port area of Rotterdam (see Fig. A3 in the Appendix) and likely have similar unobservable location characteristics. Column (5), Table 6, shows the estimate of the treatment effect where we only select observations located in future wind turbine areas. The estimated treatment effect is −1.5%, which is in line with the baseline estimate, but not statistically significant. Column (6) again adds the additional restriction that only observations within a 3 km radius of a wind turbine in 2012 are included in the regression analysis. In this case, the number of observations decreases even more (to 2570) and we find a treatment effect of −3.1%. This effect is, although very close, not statistically significant at conventional levels (p-value of 0.113).

5.5. Heterogeneity in the effect of wind turbines on house prices

There might be considerable heterogeneity in the implicit prices of housing characteristics (see Redfearn, 2009). Also the effect of wind turbines may be heterogeneous and may, for example, be dependent on wind turbine characteristics (e.g. height, diameter of the blades), the number of wind turbines that are placed, or may be dependent on the location where they are placed (e.g. urban versus rural areas). In Table 7 we investigate the heterogeneity in the effect of wind turbines over space and time. We also investigate whether the impact of having multiple turbines within a 2 km radius implies additional house price decreases. Table 8 reports regression results where we explore the effect of different wind turbine characteristics and the various external effects a turbine might impose on surrounding properties.

First, there may be considerable regional variation in the treatment effect. In column (1), Table 7, we report the results of the treatment effect interacted with province dummies. The results are shown in Fig. 6. In many cases the treatment effect is higher than our baseline estimate of −1.4%. This is mainly the result of a few provinces in which the treatment effect is positive (albeit highly statistically insignificant). Interestingly, in one of the southern provinces (Limburg) the point estimate seems to suggest that the construction of a turbine leads to a price decrease of −16.8%. Note, however, that in this case we are measuring the effect of only 3 turbines, implying that we identify the effect based on a very low number of transactions (1451 observations of which 382 are treated observations). A further interesting result is that in some of the northern provinces with a high density of wind turbines (Noord–Holland, Flevoland, and Friesland) the average treatment effect is not, or barely, statistically significant. In part, this may reflect the fact that these provinces are rural provinces. There are a variety of other reasons that can also result in spatial differences. For example, the type of wind turbines may differ between areas, or households with heterogeneous preferences may sort into certain areas. We explore some of the main sources of heterogeneity in more detail in the remainder of this subsection.

As mentioned, most of the turbines may be located in rural areas, to potentially avoid large negative external effects. It might be argued that the marginal price effect of a wind turbine in an urban area is more negative, because open space is valued higher. Hence, the opportunity costs of constructing a wind turbine may be higher. On the other hand, households in rural areas may have a stronger distaste for visual disamenities and noise, which would imply a more negative price effect in rural areas (i.e. preference-based sorting might play a role, see Chay and Greenstone, 2005). To examine whether the effect is different between rural and urban areas, we include an interaction effect between the treatment effect and an indicator whether an area is classified as urban. We consider houses that are located in areas with more than five thousand persons per square kilometer as urban areas (45% of observations). Note that also the housing characteristics, month and year fixed effect are interacted with this indicator. Column (2) shows that the effect of wind turbines on house prices is higher for urban areas. The interaction effect is −3.1%. For rural areas the treatment effect is close to zero and statistically insignificant. Note that the *total* negative external effect in urban areas is likely also higher because there are more properties affected by the placement of a wind turbine. Hence, these results imply that, from an policy point of view it is not a good strategy to place wind turbines close to urban areas.

A third issue is that the average treatment effect might differ over time. One particular reason is that the height of turbines has increased substantially over time. The average turbine (axis) height was only 30 m in 1990, while it is 86 m in 2012. Alternatively, households may have become more used to turbines or have learned more about the risks. Column (3) in Table 7 reports to what extent the treatment effects differ over different periods (1990–1999, 2000–2008, 2009–2011). We make the latter distinction because the crisis on the housing market started in 2008/2009, which may have had an influence on housing preferences. We excluded the period before 1990 since there were virtually no wind turbines built in this period. Again, the effect of the control variables (housing characteristics, month dummies) is also allowed to differ. The result suggests that, at least on average, we cannot find statistically significant differences in the treatment effect across time periods. Also note that the average effect is still in line with our baseline estimate of −1.4%.

Fourth, the price discount to locate near wind turbines may be dependent on household income. There is, for example, evidence that the preference for historic amenities and schools is positively correlated with income (Bayer et al., 2007; Koster et al., 2016). Moreover, the marginal willingness to pay for housing characteristics might differ by income. We do not have access to household-specific data on incomes or time-varying data on neighborhood incomes. However, we gathered data on average yearly disposable income in the neighborhood in 2000 from Statistics Netherlands. We interact the treatment effect with the share of high income households (which is defined as a yearly household income of more than 22,000 Euros). Again, the house characteristics and year/month fixed effects are also interacted with the share of high income households. Column (4), Table 7, shows a positive effect of income on the treatment effect although the effect is only statistically significant at the 10% significance level. A possible interpretation that explains the positive effect might be that higher income households live in properties that suffer less from the externalities caused by turbines (e.g. better insulation and therefore less noise; detached properties might be surrounded by trees that limit views on turbines). Given an average share of high income households of 21%, we find that the average treatment effect is virtually identical to the baseline estimate (−1.5%).

Fifth, we test whether the marginal effect of turbines is different between residential areas and non-residential areas. It might be that in residential areas wind turbines are perceived to be more of a nuisance. Using data from Statistics Netherlands we calculate the share of residential land in each neighborhood. We consider an area as residential when more than 75% of the land area is used for residential purposes (about 25% of the data). We interact this indicator with the treatment effect. We also allow the housing characteristics, year and month fixed effects to differ by this indicator. The results are reported in Table 7, column (5). The effect in residential areas is 2.3 percentage points more negative

Table 7
Heterogeneity in the effect of wind turbines on house prices

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Spatial heterogeneity	Urban/rural effect†	Time periods, 1990–2011†	Income-specific effect†	Residential areas†	Turbine density	Multiple turbines	Multiple turbines + Mun.×year trends
Wind turbine ≤2km	See Fig. 6	−0.0003	−0.0136**	−0.0483**	−0.0090		−0.0185***	−0.0110**
		(0.0050)	(0.0057)	(0.0193)	(0.0058)		(0.0064)	(0.0044)
Wind turbine ≤2 km × years 2000–2008			−0.0003					
			(0.0057)					
Wind turbine ≤2 km × years 2009–2011			−0.0021					
			(0.0072)					
Wind turbine ≤2 km × urban area		−0.0316***						
		(0.0105)						
Wind turbine ≤2 km × share high yearly income				0.1579*				
				(0.0941)				
Wind turbine ≤2 km × residential area					−0.0234**			
					(0.0110)			
Wind turbine density *(per sq. km)*						−0.0182		
						(0.0229)		
Wind turbine ≤2 km × 2 turbines							0.0097	0.0015
							(0.0068)	(0.0060)
Wind turbine ≤2 km × 3 turbines							0.0039	−0.0088
							(0.0095)	(0.0075)
Wind turbine ≤2 km × 4 turbines							0.0312*	−0.0158
							(0.0172)	(0.0118)
Wind turbine ≤2 km × ≥ 5 turbines							0.0181*	−0.0016
							(0.0105)	(0.0139)
Housing characteristics (16)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year and month fixed effects (37)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PC6 fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Municipality×year trends	No	No	No	No	No	No	No	Yes
Only obs. ≤3 km of wind turbine in 2012	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	357,745	357,745	345,561	347,400	357,745	357,745	357,745	357,745
Adjusted R^2	0.9232	0.9243	0.9221	0.9253	0.9235	0.9231	0.9232	0.9261

Notes: The dependent variable is the logarithm of house price. Wind turbine ≤2 km is one the first time a wind turbine is constructed (year of construction and all subsequent years) within 2 km of a property. Standard errors are clustered at the PC4 level and in parentheses. *, **, ***, 10%, 5%, 1% significance, respectively. † In these specifications we also interacted the housing characteristics, month and year fixed effects with the specific variable(s) under investigation.

Table 8
Wind turbine characteristics, shadow, and view

	(1)	(2)	(3)	(4)	(5)
	Turbine height	Diameter of the blades	Height and diameter	Shadow	Direct view
Wind turbine ≤2km	−0.0151*** (0.0057)	−0.0113* (0.0059)	−0.0125** (0.0060)	−0.0142** (0.0057)	−0.0145** (0.0057)
Wind turbine ≤2 km × turbine ≥100m	−0.0221** (0.0107)		0.0075 (0.0129)		
Wind turbine ≤2 km × diameter ≥90m		−0.0371*** (0.0104)	−0.0327*** (0.0110)		
Wind turbine ≤2 km × shadow area				−0.0247 (0.0179)	
Wind turbine ≤2 km × direct view					0.0261 (0.0201)
Housing characteristics (16)	Yes	Yes	Yes	Yes	Yes
Year and month fixed effects (37)	Yes	Yes	Yes	Yes	Yes
PC6 fixed effects	Yes	Yes	Yes	Yes	Yes
Only obs. ≤3 km of wind turbine in 2012	Yes	Yes	Yes	Yes	Yes
Number of observations	319,796	357,058	319,270	357,745	357,745
Adjusted R^2	0.9245	0.9233	0.9247	0.9231	0.9231

Notes: The dependent variable is the logarithm of house price. Wind turbine ≤2 km is one the first time a wind turbine is constructed (year of construction and all subsequent years) within 2 km of a property. Standard errors are clustered at the PC4 level and in parentheses. *, **, ***, 10%, 5%, 1% significance, respectively.

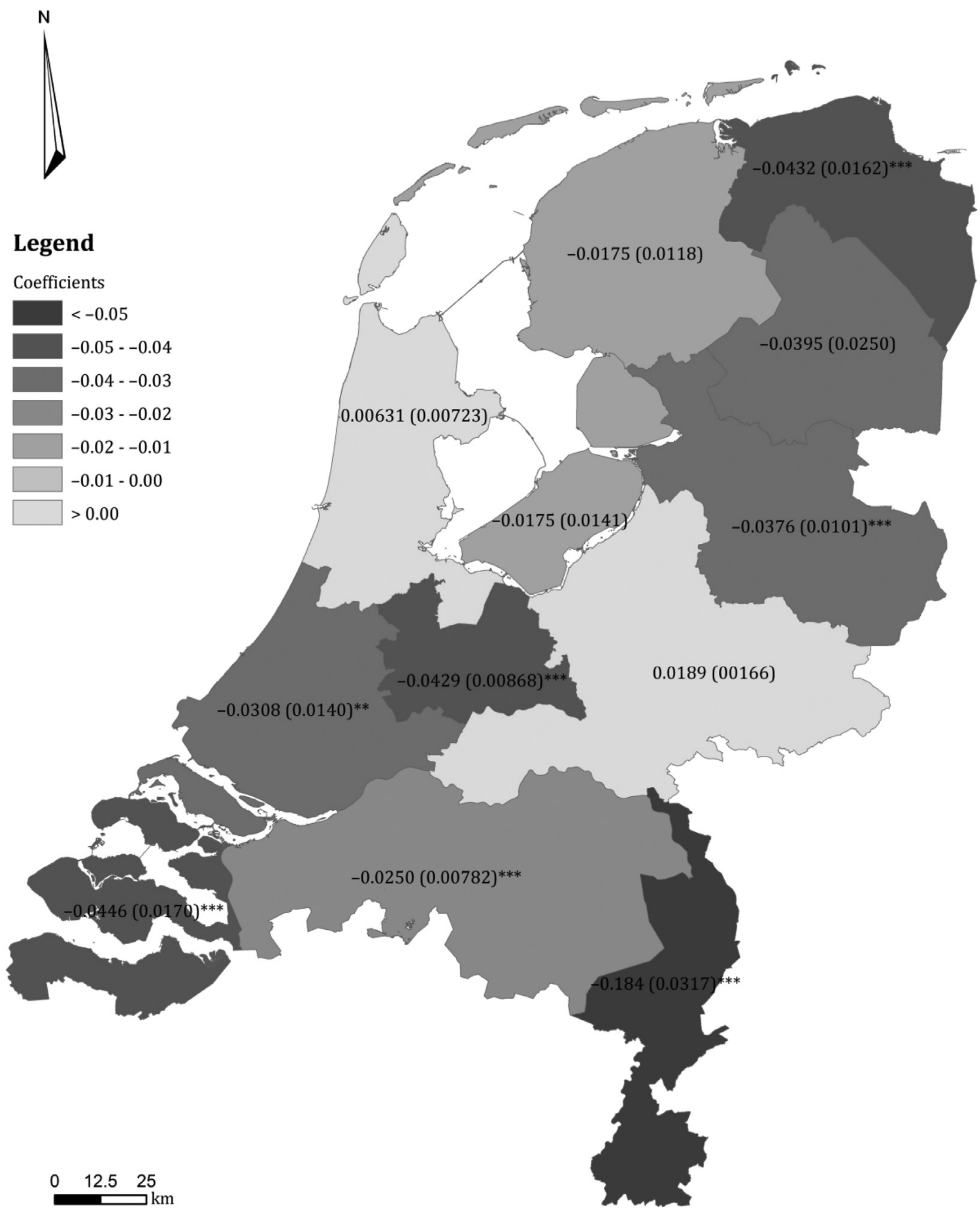


Fig. 6. The treatment effect at the province level. *Notes:* This picture shows the interaction effect between the treatment effect and a dummy variable for each province. Standard errors are clustered at the PC4 level and in parentheses. *, **, ***, 10%, 5%, 1% significance, respectively.

than in non-residential areas. This effect is statistically significant. For non-residential areas the treatment effect is −0.9% (p-value of 0.121). These results are much in line with the differential effect between urban and rural areas (see column (2)), even though the correlation between both measures is only 0.48. Again, the total economic effects of turbines, measured by housing values (we discuss this later on), is dependent on the number of affected houses, so the total effect will of course also be higher in residential areas.

Another issue is that the treatment effect may depend on the number of wind turbines that are constructed. For example, wind parks are likely to have much stronger price effects than single wind turbines (see Linn, 2013; Gibbons, 2015). As we only look at the first and nearest wind turbine we do not capture this effect. In column (6), Table 7, we therefore add a simple measure of wind turbine density. In particular, we calculated the number of wind turbines per square km within a 2 km radius of a house. This results in a time-varying, house-specific measure of wind turbine density. Although this measure has the correct sign (−1.8% per additional turbine) it is statistically insignificant at conventional levels. A particular reason that may explain this result is that not every subsequent wind turbine has the same (statistically significant and linear) effect on house prices.

To investigate this further, we determine the intensity of the treatment effect by interacting the treatment dummy with a set of indicators measuring the number of wind turbines at the time the first wind turbine was constructed. Of the 80,000 'treated' properties, 63% were treated by a single wind turbine, 12% by two turbines, 8% by three turbines, 11% by four turbines, and the remaining 6% by five or more turbines. Column (7), reports the regression results with the interaction effects included. The interaction effects are not statistically significantly different from zero at the five percent significance level. They are also not jointly significant (*F*-value of 1.41). The first wind turbine has a negative effect on house prices of −1.8%. Interestingly, the fourth and fifth (or more) wind turbine has a positive effect on house prices that is marginally statistically significant. It might be that only in case of many wind turbines, homeowners are compensated by the local government, potentially indirectly via investments in neighborhood programs. We aim to control for this by including municipality×year trends, in column (8), Table 7. This results in a statistically significant main effect of −1.1% and insignificant interaction effects. Most of the coefficients now have the expected negative sign. Hence, these results suggest that we do not find evidence that additional wind turbines impose external (price) effects on their surroundings. From a policy perspective, this result implies that to reduce the negative external effects of wind turbines on house prices, it is best to spatially cluster wind turbines.[14]

In the second set of specifications in this subsection we investigate the differential effects of wind turbine characteristics and try to measure the effects of shadow and a direct view. The results are reported in Table 8. We would expect to find that wind turbines that are taller are visually less appealing so that the negative treatment effect on house prices is larger for those turbines. To test this hypothesis, we include an interaction term of the treatment dummy and a dummy that indicates whether the axis height of the turbine is equal or larger than 100 m (top 5 percentile of onshore wind turbines). Note that we lose some observations because the axis height is missing for some turbines. In column (1) we find that for turbines that are relatively tall there is an additional negative effect on house prices of −2.2% on top of the −1.5% treatment effect for the reference category (i.e. turbines lower than 100 m).

In column (2) we include an interaction effect based on the diameter of the blades, expecting that turbines with larger blades impose larger negative externalities. Besides the fact that such a turbine might have a more detrimental effect on the landscape, shadow and flickering are mainly determined by the size of the blades (i.e. not the mast of the turbine itself). We distinguish between those turbines with blades smaller and larger than 90 m (top 5 percentile of onshore wind turbines). The results are reported in column (2). We find that turbines with relatively large blades have a negative price effect of 4.7%, which is much higher than the effect of turbines with smaller blades.

One particular concern is that those turbines that are tall also have large blades. In particular, the correlation between the height of a turbine and the diameter of its blades is 0.79. This suggests that it may be difficult to distinguish between the effect of turbine height and diameter of the blades. Nevertheless, in column (3), Table 8, we include both the indicator for turbine height and diameter of the blades. The results suggest that it is mainly the diameter of the blades that affects house prices, rather than the axis height. This is important because there are already technological improvements that will allow for the construction of bladeless wind turbines. These results suggest that this could substantially decrease the disamenity effect of wind turbines.

Furthermore, there may be direct effects of shadow/flickering of the blades. To measure this effect, we take into account that the Netherlands is located to the north of the equator. Note that only houses in the northern half of each 2 km circle around a turbine are potentially in the shadow of a wind turbine sometime during the day. The shadow area is then defined as 12 times the diameter of the blades of a wind turbine to the north of each wind turbine. Only 0.65% of the 80,000 houses that are within 2 km after the placement of a turbine are in a shadow area. Note that shadow is measured with error, so we are expected to find an effect that is biased towards zero. Column (4) reports the regression estimates where we include the interaction effect with the 'shadow area' indicator. Although we find an additional negative effect of −2.4%, the effect of wind turbine shadow on house prices is not statistically significantly different from zero. This does not imply that there is no effect of wind turbine shadow on house prices but that, even with the quality of data used in this study, we cannot precisely estimate its effect.

Finally, we also tried to estimate the effect of *direct* view on a wind turbine. We use additional information on all buildings in 2011 in the Netherlands obtained from the BAG register (in Dutch: *'Basisadministratie Adresgegevens en Gebouwen'*). Following Koster et al. (2016), we calculate for each property a line of sight from the centroid of each property to the nearest wind turbine and examine whether this line of sight is obstructed by other buildings. If the line of sight is obstructed by other houses, we assume that there is no direct view. According to this measure of direct view, only 0.69% of the treated 80,000 houses have a direct view on a wind turbine. The estimated effect of direct view is reported in column (5), Table 8. The effect is highly statistically insignificant. We note that the direct view indicator is at best a very noisy indicator. For example, buildings are not always of the same height, windows may not be on every side of the house, and wind turbine view may also be obstructed by other objects (e.g. trees, walls). Because direct view is very difficult to measure we decided not to use it as our main source of identifying variation (in contrast to Gibbons, 2015) or to draw strong conclusions from these results.

5.6. Total effect on housing values

In this subsection, we calculate the total economic effect of wind turbines on housing values to gain a better understanding of the quantitative implications of our empirical results. We would like to stress that the results that follow should be interpreted with caution, as we have to make several simplifying assumptions. First, we gather additional data on the number of owner-occupied and total number of housing units from Statistics Netherlands at the neighborhood level in 2012. Using the spatial distribution of NVM transactions (1985–2011), we calculate the number of housing units within 2 km of a wind turbine in 2012 in each neighborhood. Second, we calculate the average housing price of owner-occupied housing units in each neighborhood in 2012 using the NVM data and by inflating house prices by the consumer price index. The average price for *all* housing units is obtained from Statistics Netherlands. One may argue that the effects of turbines may also capitalize into the value of rental housing. To include these costs, we assume an identical percentage treatment effect for the rental market.

Table 9 reports the back-of-the-envelope calculations of the total implied external economic costs that have capitalized in housing values due to the placement of wind turbines. We consider three price effects: a conservative price effect of −0.7% (see column (3), Table 5), the average baseline estimate of −1.4% (see column (4), Table 4), and an upper bound price effect of −3.1% (see column (6), Table 6). The average loss in housing values per property is about 3 thousand Euros if we multiply the average treatment effect of −1.4% with the average house price of owner-occupied housing in each neighborhood. Given that the average housing value of owner-occupied housing units is very similar to that of all housing units, the average loss is very similar if we extrapolate this to all housing units. The total loss for all owner-occupied houses is about

[14] The number of wind turbines within a 2 km radius of a house might also change over time. Our conclusions based on such a time-varying measure are the same. It might also be that wind turbines are placed successively closer to a property. If we exclude those properties (only 303 transactions), we still find a treatment effect of −1.4 percent.

Table 9
Aggregate effect of wind turbines on housing values.

	Owner-occupied houses			All houses		
Assumed price effect	−0.7%	−1.4%	−3.1%	−0.7%	−1.4%	−3.1%
Total loss *(€, in millions)*	450	900	2000	750	1500	3300
Loss/house *(€)*	1500	3000	6700	1500	2900	6500
Loss/turbine *(€)*	250,000	501,000	1109,000	415,000	829,000	1837,000
Loss/turbine/av. construction costs *(in %)*	16	31	70	26	52	116

Notes: All estimates are in 2012 prices.

900 million Euros. This is about 500 thousand Euros per wind turbine (i.e. there are 1802 turbines on land). If we use −0.7% as the treatment effect the total effect is 450 million Euros, about 1500 Euros per house, and about 250 thousand Euros per wind turbine. Similarly, an average marginal effect of −3.1% leads to a total effect on housing values of 2 billion Euros, which is 6700 Euros per 'treated' house, and about 1 million Euros per wind turbine. Even though the marginal effect for each house is not that large, the total external costs of wind turbines are quite substantial because house prices are in nominal terms quite high and relatively a lot of houses have been treated (i.e. 296,410 houses for the owner-occupied market and 510,619 if we take all housing units into account). The total loss in housing values, taking into account rental housing, ranges between 750 million Euros and 3.3 billion Euros. The effect per wind turbine is between 400 thousand Euros and 1.8 million Euros.

Given that the average (onshore) wind turbine produces about 1.2 MW, and assuming 1325 Euros construction costs per kWh installed capacity (ECN, 2008), the average construction costs per wind turbine are about 1.6 million Euros. As a result, we find that the external cost per wind turbine is between 16% (−0.7% treatment effect and only owner-occupied housing) and 116% (−3.1% treatment effect and all housing units) of the average construction costs.

It is important not only to highlight the (external) costs of wind turbines, but also the potential benefits. However, because it is very difficult to measure the economic value of a reduction in CO_2 as a result of wind turbine construction, any result should be interpreted with caution. At least, the calculations provide a sense of the order of magnitude of the CO_2 reduction gains. Based on data from Statistics Netherlands, the CO_2 reduction as a result of wind turbines placed on land ranges from 36 kton in 1990 to 2442 kton in 2012. Between 1990 and 2012 the total CO_2 reduction is about 20,500 kton.[15] Although estimates vary, if we assume that the value of one ton CO_2 reduction in 2012 is worth about 15 to 50 Euros (abatement costs, see Marcantonini and Ellerman, 2013), the total CO_2 benefits have been 310 million to 1 billion Euros. If we add the potential future CO_2 benefits of 15,200 kton, which is based on a 20 year lifespan and a reduction of 0.57 ton CO_2 per megawatt installed (see Hamelink et al., 2012), the total monetary benefits are between 540 million and 1.8 billion Euros. This is in the same order of magnitude as the total loss in housing values. Also considering that the estimated total construction costs are 2.9 billion Euros (1.6 million × 1802 turbines), the net present value of wind turbine construction, at least in a highly urbanized country as the Netherlands, has been most likely negative.[16] However, it is important to note that alternative ways of energy production (e.g. power plants) may also imply negative external effects on the surroundings (see Davis, 2011). Further research should thus compare the social costs of energy production by wind turbines with other ways of energy production.

6. Conclusion and discussion

This paper has investigated the effect of wind turbines on house prices. The results show that, on average, house prices decrease by 1.4% after the construction of a wind turbine within a 2 km distance from a property. A variety of robustness checks suggest that the negative effect ranges from 0.7 to 3.1%. House prices, on average, start to decrease about two years before a nearby wind turbine becomes operational. After 10 years the effect is still statistically significant and negative (−2.2%). Moreover, we calculate that, given a range of assumptions, the external costs of a wind turbine are at least 16% of its construction costs. In addition, the total loss in house value as a result of wind turbine construction is considerable and seems to be in the same order of magnitude as the CO_2 benefits of wind turbines. Our results suggest that the external costs of wind turbines should at least be fully taken into consideration when building turbines close to urban areas.

The CO_2 reductions caused by wind turbines benefits everyone, but the external costs are spatially concentrated and borne by a specific group of homeowners. An important question is whether homeowners should be compensated for the loss in house value and by whom. In our opinion, this is mainly a political question. The Dutch government already has a compensation scheme to compensate for loss resulting from any government planning decisions. This only applies to losses up and above two percent. If we compensate negative externalities, it also raises the (difficult) question whether homeowners should be taxed for positive ones (e.g. as a result of public investments in the neighborhood). Alternatively, economic theory suggests that the external costs of wind turbines in terms of reductions in housing values should be taken into account by those who own wind turbines. One way would be to apply 'the polluter pays' principle. This principle is currently being applied to compensate homeowners in the north of the Netherlands for the physical damage to their houses as a result of natural gas extraction (see Koster and Van Ommeren, 2015).

Given our finding of a local external effect of wind turbines on house prices, the results in this paper further imply that the external effects of future wind turbine construction can be largely avoided by constructing wind turbines further away from urbanized areas. A concern is whether this is possible in a densely populated country as the Netherlands. An alternative is to construct offshore wind parks, but this is still very costly. It might therefore be the case that the external costs of onshore wind turbines would be offset by the additional costs of constructing wind turbines offshore. An option would be to coordinate the placement of wind turbines not at a national level, but at a supranational level and to place wind turbines in those countries where the opportunity costs are lowest (e.g. low density areas) and subsequently buy the electricity from those countries.

Another business strategy that is currently being implemented in the Netherlands is that homeowners can become a shareholder

[15] Before 1990 the CO_2 gains are likely small (i.e. we round up the total CO_2 gains). The CO_2 gains are likely an overestimate because there has been an EU emission trading system as of 2005.

[16] This result stands in stark contrast to those results reported by Lang et al. (2014) who conclude that the CO_2 benefits offset the (external) costs of wind turbine construction, but without adjusting for wind turbine construction costs.

of a wind turbine. This potentially increases the (local) support for the placement of wind turbines. It can also partly compensate homeowners for the loss in housing values as a result of wind turbine construction. Moreover, there are currently many technological improvements regarding wind turbines that could influence the magnitude of the effect of wind turbines on house prices. For example, bladeless wind turbines have already been proposed. This might substantially decrease the disamenity effect of wind turbines on house prices.

Finally, we showed that many wind turbines are currently placed in rural areas. This, however, does not mean that such turbines have no external economic effects. In particular, the value of nearby land is expected to decrease since the option value of the land decreases (i.e. no houses are allowed to be constructed very close to wind turbines). On the other hand, land owners typically get compensated by the owners of wind turbines. Hence, examining the net effect of wind turbines on land values would be an interesting avenue for future research.

Appendix

Figs. A1–A7 and Table A1.

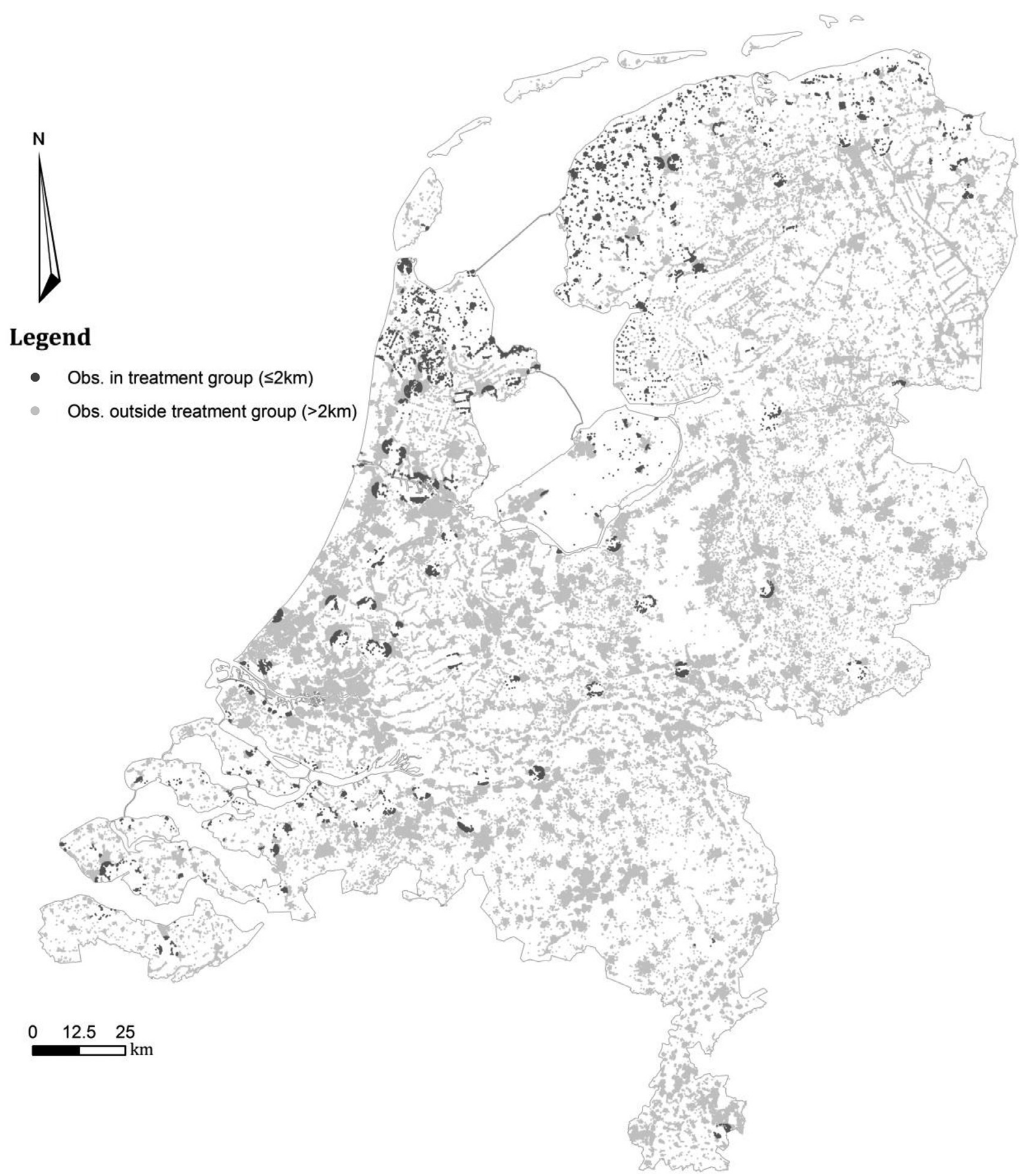
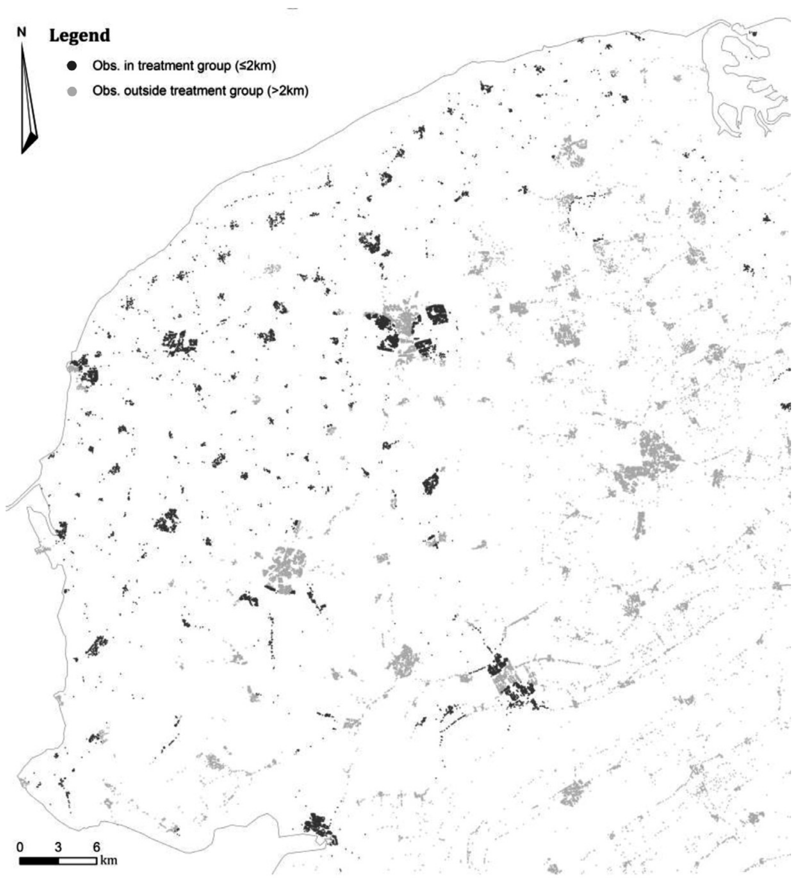
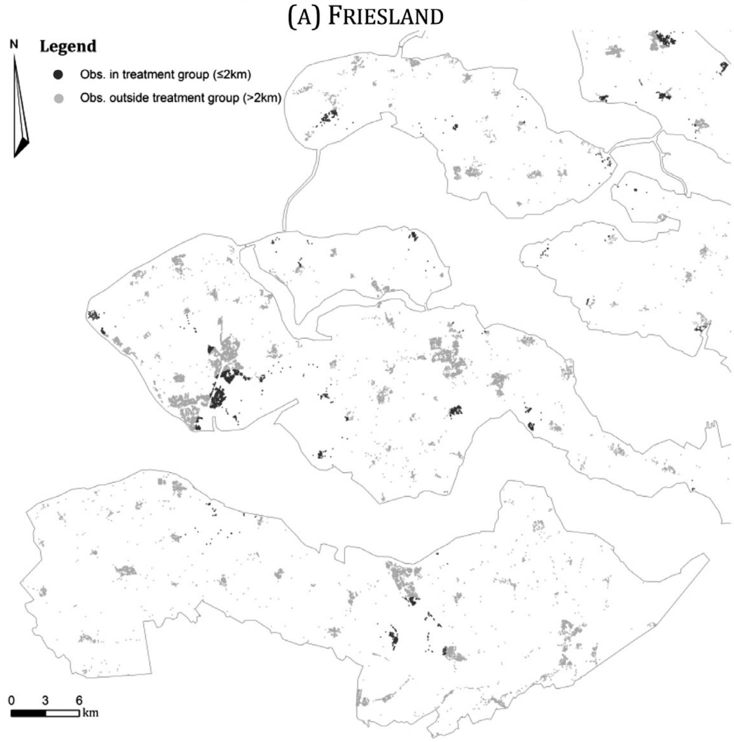


Fig. A1. Spatial distribution of treated observations. *Notes:* This map shows the transactions within 2 km of a wind turbine (treatment group) versus those transactions that are further away.



(A) Friesland



(B) Zeeland

Fig. A2. Spatial distribution of treated observations in Friesland and Zeeland.

Fig. A3. Designated areas where future wind turbines will be placed. *Source:* Trouw, October 29, 2014.

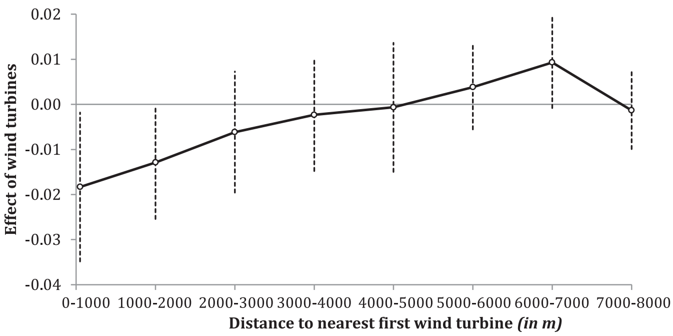


Fig. A4. Distance profile treatment effect, until 8 km. *Notes:* The dots represent conditional averages for a given distance band. The vertical dashed lines represent 95% confidence intervals. The reference category consists of houses that are located further away than 8 km of a wind turbine.

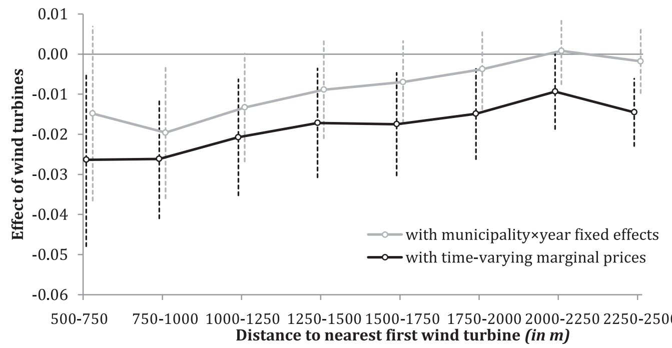


Fig. A6. Distance profile treatment effect, sensitivity. *Notes:* The dots represent conditional averages for a given distance band. The vertical dashed lines represent 95% confidence intervals. The reference category consists of houses that are located further away than 2.0 km (but within 3.0 km) of a wind turbine. The effect for the category <500 is not depicted.

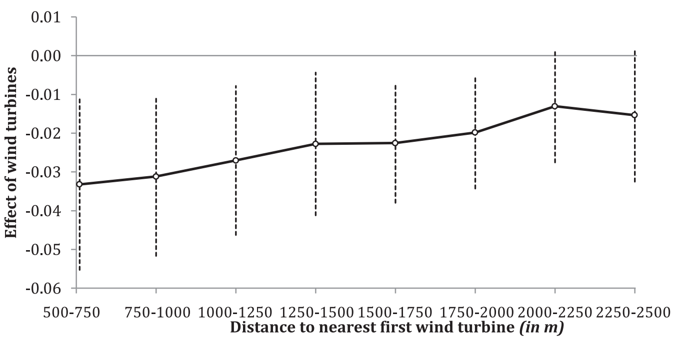


Fig. A5. Distance profile treatment effect, control group 3–5 km. *Notes:* The dots represent conditional averages for a given distance band. The vertical dashed lines represent 95% confidence intervals. The reference category consists of houses that are located further away than 3.0 km (but within 5.0 km) of a wind turbine. The effect for the category <500 is not depicted.

Fig. A7. Anticipation and adjustment effects with time-varying marginal prices. *Notes:* This figure depicts the difference in house price changes between the control (2–3 km of a turbine) and treatment group (within 2 km of a turbine) in years to/after placement of a wind turbine. Interaction terms between the control variables and year dummies were included. In addition, we added treatment group times year fixed effects. The vertical dashed lines represent 95% confidence intervals.

Table A1
Descriptive statistics: extra set of neighborhood control variables.

	Treatment + control group		<2 km of a wind turbine *in 2012*		2-3 km of a wind turbine *in 2012*	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Population density	5253	3986	4736	3441	5625	4298
Share of young population (<25 years)	18.745	5.134	19.171	5.159	18.438	5.095
Share of elderly population (≥65 years)	13.115	7.387	13.050	7.299	13.162	7.449
Share of foreign population	8.478	10.305	7.275	9.308	9.346	10.886
Household size	2.539	0.500	2.576	0.485	2.512	0.509
Residential land use	0.541	0.256	0.510	0.265	0.564	0.247
Industrial land use	0.095	0.126	0.094	0.127	0.096	0.125
Infrastructure	0.054	0.037	0.052	0.035	0.055	0.039
Open space	0.263	0.246	0.292	0.257	0.241	0.235
Water	0.047	0.067	0.052	0.071	0.044	0.063
Distance to nearest highway ramp (*km*)	4.828	4.583	5.046	4.895	4.671	4.338
Distance to nearest train station (*km*)	3.418	4.029	3.621	4.240	3.270	3.964
Number of observations	357,745		149,939		207,806	

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